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Soundscape preferences at Mount Kilimanjaro reveal differing perceptions of non-material nature's contributions between residents and tourists

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ABSTRACT

Soundscapes provide a powerful means for understanding how the acoustic dimension of biodiversity contributes to non-material Nature's Contributions to People (NCP), including therapeutic and aesthetic experiences. Despite growing interest in soundscape ecology and human–nature interactions, limited research has examined how specific acoustic characteristics—particularly those quantified through acoustic indices—are associated with the perception of non-material NCP, and whether these associations vary across social groups. Using soundscapes from seven diverse habitats at both dawn and dusk in Mount Kilimanjaro (Tanzania), we aimed to investigate which soundscapes residents and tourists preferred and which context-specific non-material NCP they associated with their preferences. We applied generalized linear mixed models to identify acoustic indices associated with non-material NCP selection. We found that dawn soundscapes were generally preferred, likely due to the prominence of bird vocalizations and greater acoustic diversity compared to louder, insect-dominated dusk soundscapes. However, these preferred soundscapes originated from different habitats: residents favored soundscapes of familiar, human-shaped habitats such as homegardens, whereas tourists preferred soundscapes with minimal human-generated sounds, particularly sub-alpine habitats. Further, we found distinct associations of soundscape preferences with non-material NCP, such as *cultural heritage* for residents and *restorative experiences* for tourists, reflecting distinct ways of acoustically experiencing nature. Six acoustic indices were significantly associated with seven of the eleven non-material NCP assessed, highlighting their potential as indicators for capturing soundscape attributes relevant to culturally and experientially meaningful environments. Overall, our study advances soundscape-based approaches to assess non-material NCP and offers insights relevant to inclusive conservation and landscape management.

1. Introduction

Soundscapes encompass biological, geophysical, and anthropogenic sounds (Pijanowski et al., 2011) and serve as one of the primary pathways for experiencing nature (Ratcliffe, 2021). As the audible dimension of landscapes, soundscapes can be associated with the provision of non-material Nature's Contributions to People (NCP), which include the psychological and physical contributions of nature to people's quality of life, such as inspiration, recreation, and cultural heritage (Díaz et al., 2018). Listening to nature can evoke cognitive and emotional

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responses that shape how we perceive and experience NCP, and this likely varies with people's cultural backgrounds and knowledge systems (Hill et al., 2021; Soga and Gaston, 2022; Lehnen et al., 2022; Fisher et al., 2023). However, little research has examined how soundscape preferences and associated NCP vary across social groups, and the factors that can explain potential variations (Buxton et al., 2021; Chen et al., 2022). Bridging this gap requires identifying the specific non-material NCP that different groups associate with particular soundscapes, and understanding the acoustic characteristics that shape these associations. Such insights can inform conservation efforts to protect both ecologically and culturally significant soundscapes for diverse social groups and thereby foster more inclusive conservation approaches.

Natural sounds hold deep cultural and emotional significance for people (Moscoso et al., 2018; Ferraro et al., 2020). For instance, people residing on Mount Kilimanjaro, Tanzania, consider the call of the African wood owl (*Strix woodfordii*) a bad omen, while the song of the common bulbul (*Pycnonotus barbatus*) evokes greetings in the local language (Hemp and Hemp, 2009). More broadly, the significance of sounds can vary across cultures. For example, owl species may also be regarded as symbols of wisdom, divinity, or wealth in other contexts (Buthelezi et al., 2026). Even within the same culture, a species' vocalization like the one of the laughing kookaburra (*Dacelo novaeguineae*) in Australian Aboriginal storytelling, can carry both positive and negative meanings (Tidemann and Whiteside, 2010). Beyond individual components, people usually experience soundscapes holistically, generally preferring combinations of natural sounds, such as wind, water, birds, over isolated sounds (Bai and Zhang, 2024). As such, soundscapes can evoke a wide range of emotions, from calmness and awe to fear and anxiety, depending on their composition and the listener's background (Moscoso et al., 2018; Smalley et al., 2023). The acoustic makeup of a soundscape can shape people's perception of it. For instance, anthropogenic interference (e.g., traffic sounds) in natural soundscapes is often perceived as disruptive to restorative experiences (Uebel et al., 2021). At the same time, soundscape perception is influenced by social and cultural factors (Farina, 2014). For example, communities living near forested areas may experience a broad range of emotions, whereas individuals residing farther away primarily associate natural soundscapes with calmness (Moscoso et al., 2018). Understanding these differentiated experiences and preferences is essential for integrating soundscapes into conservation and landscape planning efforts that support diverse experiences of non-material NCP (Erfanian et al., 2019; Buxton et al., 2021; Chen et al., 2022).

Bioacoustics provides a powerful tool to quantify soundscape compositions and their role in supporting non-material NCP. Passive acoustic monitoring, i.e., the use of autonomous recording units to collect audio data in the field (Gibb et al., 2019), enables researchers to characterize soundscapes across spatial and temporal scales (Farina, 2014) using acoustic indices (Sueur et al., 2014; Eldridge et al., 2016). These acoustic indices vary with vocalizing species abundance, diversity, and community composition. Hence, they have been used to characterize diel and annual patterns in soundscape structure (Morrison et al., 2021) and to detect differences across habitats and landscapes (Fuller et al., 2015; Dröge et al., 2024). Acoustic indices are also applied to assess the impacts of global change and monitor ecosystem health, thus informing biodiversity conservation decisions (McGrann et al., 2022; Müller et al., 2023). More recently, researchers have begun to explore the relationship between acoustic indices and human experiences of nature. For example, Zielonka et al. (2024) found that aesthetic enjoyment increased with higher Acoustic Complexity Index (ACI) and Bioacoustic Index (BIO) in English vineyards, while Fisher et al. (2021) linked aesthetic enjoyment to the Normalized Sound Difference Index (NDSI) in Guyana's urban green spaces. However, these studies have limitations in that (i) they focus on single benefits like aesthetic enjoyment, and thus, tend to overlook other non-material NCP, (ii) their scope is restricted to human-dominated landscapes, and (iii) they often adopt single group's perspectives, neglecting potential differences across different social groups.

Here, we used 13 acoustically distinct soundscapes representing the diverse habitats of Mount Kilimanjaro during dawn and dusk to investigate soundscape preferences of residents and tourists, and associated non-material NCP. We specifically asked the following research questions (RQ): (1) Do soundscape preferences, and their associated non-material NCP, differ between residents and tourists? and (2) What acoustic indices are associated with the selection of non-material NCP?

2. Methods

2.1. Mount Kilimanjaro social-ecological system: sampling approach

In October 2021, we sampled soundscapes across 13 plots on the southern slopes of Mount Kilimanjaro, Tanzania. Mount Kilimanjaro, standing at 5895 m altitude, hosts diverse habitats along its elevational gradient, shaped by varying climatic conditions and anthropogenic impacts. Our sampling included habitats within and outside the Kilimanjaro National Park (KINAPA; Fig. 1; Fig. S1). Within KINAPA, habitats included natural vegetation types across the elevation range: the alpine zone at 4000–4600 m (hel1, i.e., the plot used for sampling in this habitat type), the subalpine Erica forest and bushland at 3200–4000 m (fer0 and fed1), and the montane forest at 1800–3200 m. The montane forest included the upper montane Podocarpus forests (fpo1 and fpd2), middle Ocotea forests (foc1 and fod2), and lower natural montane forests (flm1). Outside the park boundaries, we sampled habitats within the lower submontane zone (1100–1800 m), including managed semi-natural grasslands (gra0), homegardens (hom4), and coffee plantations (cof3), as well as in the lowlands (700–1100 m), which included natural savanna (sav4) and agricultural fields (mai1).

We deployed one Song Meter Micro recorder (Wildlife Acoustics) at breast height in the center of a 50x50m plot within each habitat type (Fig.1). The recorders were programmed for continuous, autonomous recording over at least four days, capturing soundscapes at a 44.1 kHz sampling rate and 18 dB gain.

While the lower submontane zone and lowlands support residence and smallholder farming by Chagga communities and commercial agriculture such as coffee plantations (Hemp, 2006), the National Park, beginning at approximately 1800 m, is one of Tanzania's main attractions for international tourists (Holroyd, 2016). Therefore, residents with deep cultural and livelihood ties to the mountain and tourists seeking recreational opportunities (Masao et al., 2022; Degano et al., 2025; Sanya et al., 2025; Gross et al., 2025; Pearson et al., 2024) allow us to explore the role of soundscapes for two actor groups, distinct in experiencing Mount Kilimanjaro's non-material NCP. Where and how these groups engage with Kilimanjaro's nature along its elevational gradient has been shaped by the conservation history of Mount Kilimanjaro. Since the early 1900s, protection efforts have evolved from a forest reserve encompassing high-elevation habitats (> ca. 2700 m), to the formal designation of a National Park (> ca. 2700 m) in 1973 (Sanya et al., 2025; Newmark, 1991). Importantly, residents were not permitted to extract resources from the forest reserve itself; instead, regulated resource use was permitted only in certain periods within a buffer forest below the reserve, established to support local livelihoods. In 2005, the National Park was expanded to lower elevations, thereby incorporating the buffer forest. Different efforts were established to regulate residents' access to forest products until this access was banned in 2021. By including the perspectives of residents and tourists at Mount Kilimanjaro, we aimed to uncover a broader range of non-material NCP and place-based meanings.

We conducted face-to-face surveys with residents and tourists between August and November 2022 using ArcGIS Survey123 (Version 3.15.165). Residents were selected from 14 villages across Mount Kilimanjaro's altitudinal and longitudinal gradients, capturing variation in climate, vegetation, and land use. Within each village, households were selected using a geospatial random sampling approach and village

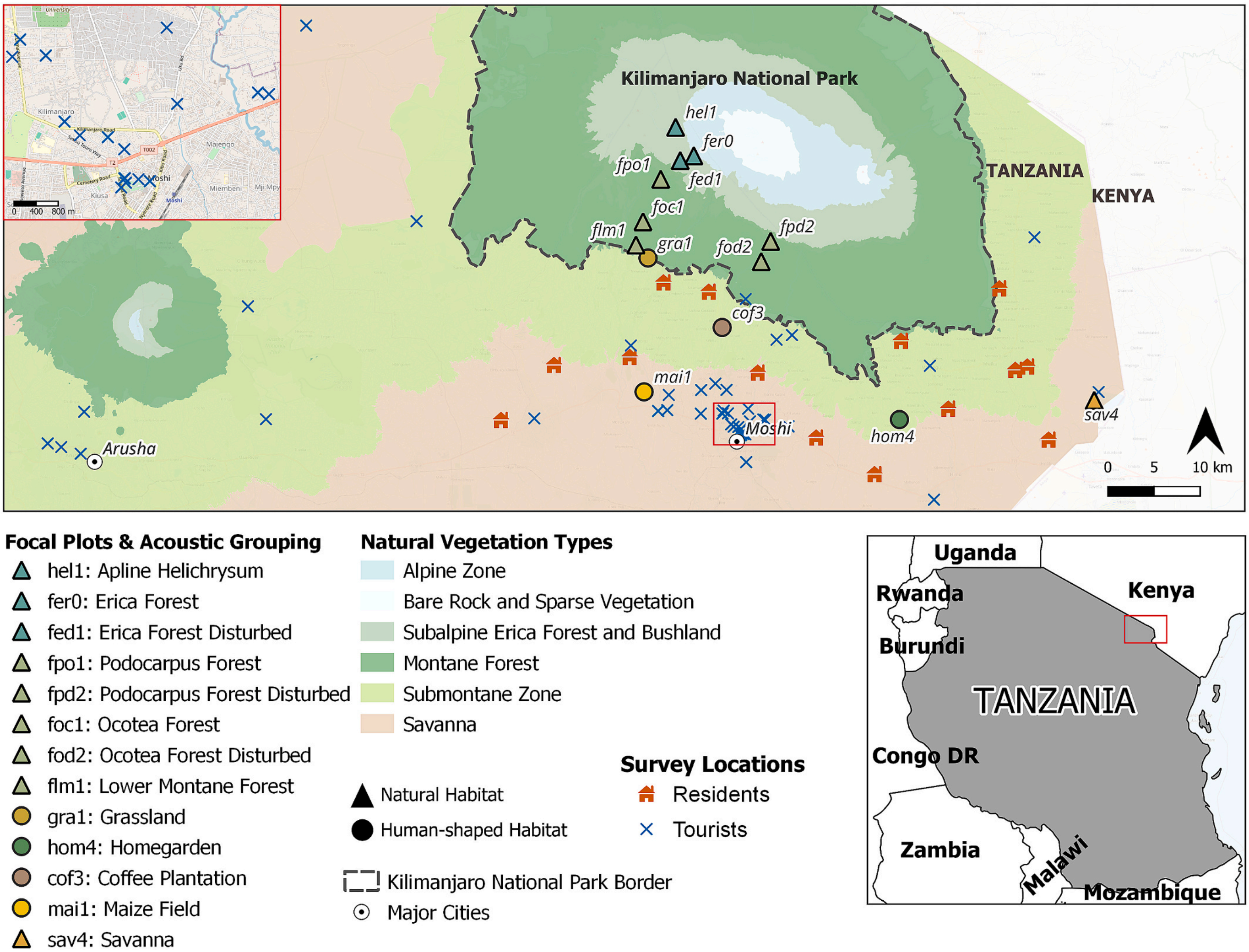

Fig. 1. Study area on the southern slopes of Mount Kilimanjaro, Tanzania. Acoustic data were collected from 13 focal plots representative of key habitat types with eight plots within the National Park borders (Fig. S1). These plots were grouped into seven acoustically similar habitats (i.e., acoustic grouping), each represented by a specific color. Survey data were collected in 14 villages and multiple spots to target tourists.

executive officers facilitated survey administration (see Sanya et al., 2025 for sampling details; Fig. 1). Tourists were approached at key locations such as National Park gates and during nature-based activities (see Gross et al., 2026 for sampling details; Fig. 1). Sample size calculations, based on a 98% confidence level and a 10% margin of error, used population estimates from the most recent census data for residents and official tourist statistics for Kilimanjaro National Park (see Table S1). The final dataset included responses from 211 residents and 149 tourists.

In addition to the soundscape choice experiment (see below), we collected socio-demographic data (e.g., gender, birth year) and measured how participants perceived nature to be included in themselves using the visual "Inclusion of Nature in Self" scale (Schultz, 2002; see Text S1). Residents had an average age of 54 years (range: 18–87) with a gender distribution skewed toward females (132 females, 79 males). Tourists averaged 35 years of age (range: 18–65) and had a nearly equal gender distribution (70 females, 79 males); over 70% of them came from countries in the Global North (Fig. S2).

2.2. Soundscape tracks

The acoustic recordings were manually edited to be both acoustically distinct and short. We use "acoustic recordings" to refer to the raw recordings collected in each plot, and "soundscape tracks" to refer to the edited acoustic recordings played to participants. Each acoustic recording from the 13 plots was manually categorized based on elevation zones and species vocalization patterns by inspecting spectrograms (i.e., visualization of sound intensity along time and frequency axes) using Audacity software (version 3.1), with species identifications supported by consultations with local experts. Acoustic recordings showing minimal variation in sound composition were grouped; this applied to plots between 1800 and 3200 m (montane forest) and 3200–4600 m (sub-alpine zone), resulting in seven acoustic groupings (Fig. 1). For each grouping, both dawn (seven tracks; 06:30 to 09:30) and dusk (six tracks; 18:30 to 21:30) periods were captured, reflecting biologically significant times of day and the turnover of vocalizing species (Metcalf et al., 2021). Key acoustic features were retained, including calls of *Aerotegmina kilimandjarica*, the loudest known insect (Hemp, 2005), and the eastern tree hyrax (*Dendrohyrax validus*) (Kundaeli, 1976), both endemic to the region. Representative excerpts were then assembled to create short soundscape tracks capturing the dominant acoustic features of each grouping during the target periods. The sub-alpine habitat at dusk was excluded due to minimal biological activity, resulting in 13 tracks lasting 18–27 s each (Table S2). All tracks were processed in Audacity (version 3.1) using a 12 dB noise reduction to minimize background noise.

2.3. Soundscape choice experiment

To assess soundscape preferences and associated non-material NCP, we developed a pairwise choice experiment programmed in ArcGIS Survey123 (Version 3.15.165), in which participants selected their preferred soundscape from two soundscape tracks and subsequently identified the non-material NCP that best explained their preference. First, we created 78 unique pairs of soundscape tracks comprising all possible pairwise combinations of the 13 unique soundscape tracks. In the choice experiment, we asked participants to listen to a pair of two tracks and select their preferred track (see Text S2). To reduce time investment and participants' fatigue, each participant evaluated a maximum of five pairs, collectively referred to as a "set". The pairs within each set were randomly assigned and manually rearranged to prevent any single track from appearing more than twice per set. Out of the 16 sets created for the survey, nine sets included a track that was repeated only once (Table S3). These sets were then randomly assigned to participants, with each set being used an average of 13 times for residents and nine times for tourists during the surveys. Individual soundscape tracks were evaluated between 147 and 179 times (average: 154) by residents and between 101 and 122 times (average: 107) by tourists.

After participants selected their preferred soundscape track from a pair, they were asked to select up to two reasons for their preference from a list of prompts associated with 11 context-specific non-material NCP (Fig. 3; Table S4). These non-material NCP had been identified through previous social media analyses and interviews with former tourists (Degano et al., 2025; Pearson et al., 2024), and with people living and working in situ (Gross et al., 2025). *Intergenerational benefits* is generally considered as an NCP in the category "maintenance of options", which spans across all NCP categories (IPBES 2019). For simplicity, we refer to *intergenerational benefits* as a non-material NCP in this manuscript. To mitigate potential biases toward the first prompts, we developed three randomly organized lists of prompts (Table S4). We pre-tested the soundscape section with seven individuals, including residents and people foreign to Mount Kilimanjaro—Brazilian, Egyptian, German, and Nepalese citizens—to reflect the tourist group. Their feedback helped us clarify language issues and improve the soundscape experience.

2.4. Ethical considerations

We informed respondents about the goals of the survey and their rights as research participants (Text S3). All data were collected pseudo-anonymously after obtaining prior written informed consent. Our research was approved by the ethics committee of Leuphana University Lüneburg (reference number: EB-Antrag_202206_Martín-López), and respective Tanzanian institutions, including Tanzania Commission for Science and Technology, Tanzanian Wildlife Research Institute (TAWIRI), and Tanzania National Parks (TANAPA) granted research permits (COSTECH No. 2021-358-NA-2021-09 and 2022-530-NA-2021-09). As required by research protocols in Tanzania, written or oral permission was obtained from executive commissioners at the regional, district, and village levels, as well as from tour guides, tour operators, or tour agents. To address potential language barriers and cultural considerations, Tanzanian researchers and field assistants surveyed residents, while both non-Tanzanian researchers and Tanzanian field assistants surveyed tourists to manage the effort required to achieve a representative sample size. As part of the collective effort within the Kili-SES project (DFG: FOR 5064), each surveyor participated in a week-long project-specific training in August 2022.

2.5. Soundscape preference assessment

To assess the preferred soundscape by residents and tourists (RQ1), we used an Elo algorithm to rank the tracks according to preference for each social group (Clark et al., 2018; Tribot et al., 2018). The Elo algorithm calculates a preference rating for each soundscape track, based on participant choices during comparisons. Initially, all soundscape tracks start with the same arbitrary rating (zero). The algorithm processes each pairwise comparison sequentially, adjusting the ratings of the soundscape tracks according to the comparison outcome and the probabilities of each track being selected. The order in which comparisons are entered into the Elo algorithm affects the ratings, as scores are updated based on previous outcomes. To minimize the impact of sequence effects and achieve reliable and consistent rankings, we computed the Elo rating for each soundscape track 10,000 times, with the order of comparison exercises randomized in each iteration, and then calculated the mean rating for each soundscape track (mElo) across the 10,000 iterations. Residents completed 1001 comparisons, while tourists completed 697. To account for this difference in sample size, we bootstrapped the residents' comparisons 1000 times to match the number of tourists' comparisons.

2.6. Acoustic indices associated with the selection of non-material NCP

First, we characterized each soundscape track by calculating a set of different acoustic indices. As different indices capture distinct acoustic aspects, and their performance when correlated with biodiversity metrics varies (Buxton et al., 2018; Alcocer et al., 2022; Kotian et al., 2024; Mammides et al., 2025), we combined seven indices (Table 1; Table S5), as used in previous studies to describe habitats (Bradfer-Lawrence et al., 2019). For each soundscape track, we calculated the Acoustic Complexity Index (ACI), Acoustic Diversity Index (ADI), Acoustic Evenness Index (AEI), Bioacoustic Index (BIO), Acoustic Entropy Index (H), Acoustic Richness (AR), and Normalized Difference Sound Index (NDSI) (Sueur et al., 2014; Bradfer-Lawrence et al., 2019; Bradfer-Lawrence et al., 2025). These calculations were performed using the soundecology version 1.3.3 (Villanueva-Rivera et al., 2018) and seewave version 2.1.6 R-packages (Sueur et al., 2008). All parameters used in the calculations of acoustic indices were set to their default values as specified in the software package, with the following exceptions: we adjusted the maximum frequency to 12 kHz for ACI, AEI, ADI and BIO and the minimum frequency to 500 Hz for ACI (Dröge et al., 2021). This frequency range encompasses most sounds from birds, amphibians, and non-flying mammals while minimizing potential interference from

Table 1
Summary of the seven acoustic indices used in this study. For additional details, references, comparisons with other studies, and correlations among indices and auxiliary data, see Table S5.

Acoustic index	*Short description*
Acoustic Complexity Index (ACI)	Measures temporal variability in biotic sounds distinguishing them from more constant geophonic or anthropogenic sounds; higher values usually mean more animal activity, particularly birds' vocalizations.
Acoustic Diversity Index (ADI)	Measures the richness of sound sources across frequency bands; higher values indicate higher acoustic and potentially ecological diversity.
Acoustic Evenness Index (AEI)	Measures how evenly different sounds are spread across frequencies; higher values indicate that a few sounds dominate; lower values indicate that many sounds contribute equally.
Normalized Difference Soundscape Index (NDSI)	Compares natural to human-made sounds; higher values indicate more natural sound, while lower values suggest more anthropogenic interference.
Bioacoustic Index (BIO)	Measures how rich and lively natural sounds are; higher values mean more complex and vibrant soundscapes.
Acoustic Entropy Index (H)	Measures how evenly sound is spread over time and frequencies; higher values mean a more complex and balanced soundscape.
Acoustic Richness (AR)	Measures how rich and varied a soundscape is over time; higher values suggest higher sound richness.

microphone self-noise (Bradfer-Lawrence et al., 2019). We also increased the dB-threshold for ADI and AEI to −40 dB to effectively exclude background noise (Dröge et al., 2021). Second, because soundscapes are influenced by multiple components beyond biophony (i.e., biological sounds), we incorporated auxiliary data to support the interpretation of the acoustic indices (Alcocer et al., 2022). We manually inspected each soundscape track and annotated the presence or absence of insects, birds, mammals, and anthropogenic sounds (Table S2). We also determined whether the soundscape's habitat was natural or human-shaped; and noted its location in- or outside the National Park. This information was used to provide a clearer characterization of the acoustic composition of the stimuli presented to participants (for more details see Fig. S3, S4).

To assess acoustic indices associated with the selection of non-material NCP in preferred soundscapes (RQ2), we used generalized linear mixed models (GLMMs) with a binomial distribution and a logit link function. Each non-material NCP was treated as a binary response variable (1 for selected or 0 for non-selected). We used participant ID as a random effect to account for individual variability. Alongside acoustic indices and auxiliary ecological data (i.e., natural/human-shaped habitat and their relation to the National Park), we incorporated socio-demographic predictors to capture variation arising from the subjective perception of non-material NCP. These included birth year, social group (resident or tourist), gender, and perceived inclusion of nature in self. For each of the 11 non-material NCP, we constructed six global models in which all non-acoustic predictors were held constant, while only acoustic indices with collinearity <0.75 were alternated across models (Fig. S3; Tables S6). We then used Akaike's Information Criterion for small sample size (AICc) to identify the optimal model for each non-material NCP. Subsequently, we performed model selection across all possible combinations of predictor variables within this optimal model using the function "dredge" from R package MuMIn (Bartoń, 2023). Finally, we performed model averaging for all models within a two AICc unit range of the best model to determine the factors associated with each non-material NCP.

3. Results

3.1. Soundscape preference and associated non-material NCP (RQ1)

Overall, residents and tourists preferred soundscape tracks from dawn over dusk times, but from different habitats (Fig. 2).

For residents, the distribution of mean soundscape track scores, i.e., mElo rating, followed a normal distribution (Shapiro-Wilk test *p-value* = *0.77*), with scores ranging from −99.3 to 114.9 and a mean standard deviation of 0 ± 67.7. Residents exhibited a strong preference for dawn soundscape tracks from coffee plantations, maize fields, montane forests, and homegardens (Fig. 2a). Conversely, sub-alpine/dawn soundscape tracks and dusk tracks from montane forests, grasslands, maize fields, and savannas were rated lower.

For tourists, the mean soundscape track scores also followed a normal distribution (Shapiro-Wilk test *p-value* = *0.52*), with scores ranging from −51.8 to 69.3 and a mean standard deviation of 0 ± 38.9. Tourists expressed a strong preference for dawn soundscape tracks from grasslands, coffee plantations, and sub-alpine habitats (Fig. 2b). In contrast, the soundscapes from maize/dusk, homegarden (both dawn and dusk), savanna/dawn, and grassland/dusk were less preferred.

Furthermore, residents and tourists associated different non-material NCP to their preferred soundscapes. Residents associated them with *intergenerational benefits* (2.8 times more than tourists), *cultural heritage* (1.9 times more), *affective experiences* that trigger diverse emotions (1.6 times more), *aesthetic experiences* (1.5 times more), and *connectedness with nature* (1.2 times more). Conversely, tourists were more likely to associate preferred soundscapes with *new & unique experiences* (3.5 times more than residents), *therapeutic experiences* (2.4 times more), and *recreation* (1.5 times more) (Fig. 3, Table 2). For other non-material NCP, we did not find any statistical differences between residents and tourists (Table 2).

3.2. Acoustic indices associated with the selection of non-material NCP (RQ2)

Among the 11 NCP assessed (Fig. 3), seven NCP were significantly associated with acoustic indices (Table 2). *Cultural heritage* was linked to soundscapes with high ADI, AR, and BIO values—reflecting diverse acoustic sources (ADI), particularly bird (AR) and mammal (BIO) vocalizations (Table S5). This NCP was most frequently associated with maize fields (selected 28 times; AR: 0.65) and montane forest at dawn (selected 19 times; ADI: 1.93 and BIO: 27.10), both characterized by rich bird and mammal vocal activity (Table S2). *Affective experiences* related to remembering past experiences were also associated with high ADI values (Table 2), with tourists most often selecting maize fields (20

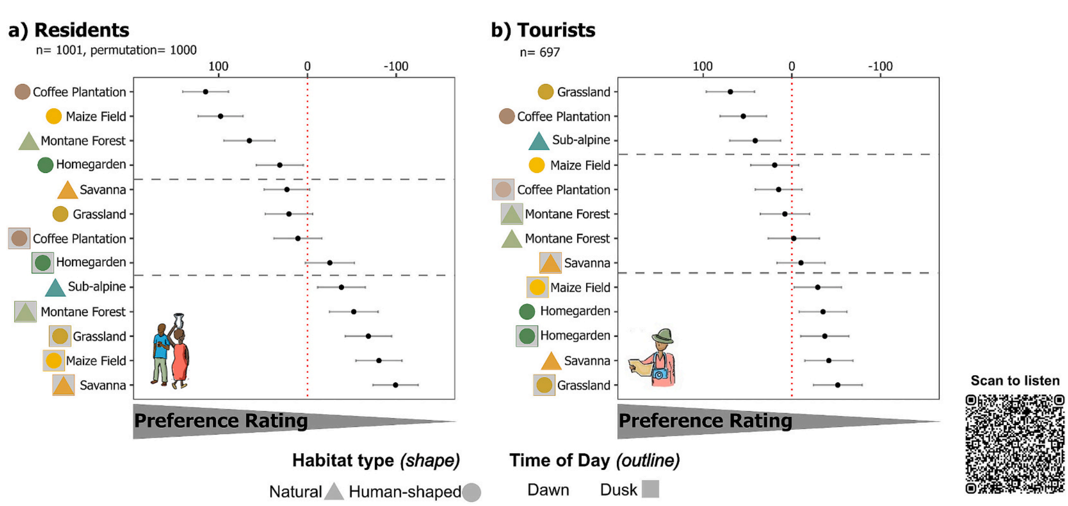

Fig. 2. Preference assessment: mean preference scores per soundscape track for (a) residents and (b) tourists. Preference Assessment: black dots represent the mean preference scores based on mElo rating, and shaded whiskers show standard deviations. Positive values indicate more preferred soundscapes; negative values less preferred ones. Values not different from zero (i.e., dots whose whiskers cross the dashed vertical zero 0-line) indicates that there is no clear preference trend. n represents the number of comparisons of soundscape track pairs completed by each social group. For residents, a permutation was conducted to ensure a sample size comparable to that of tourists (see Data Analysis). Icons design credit: Jelke Meyer.

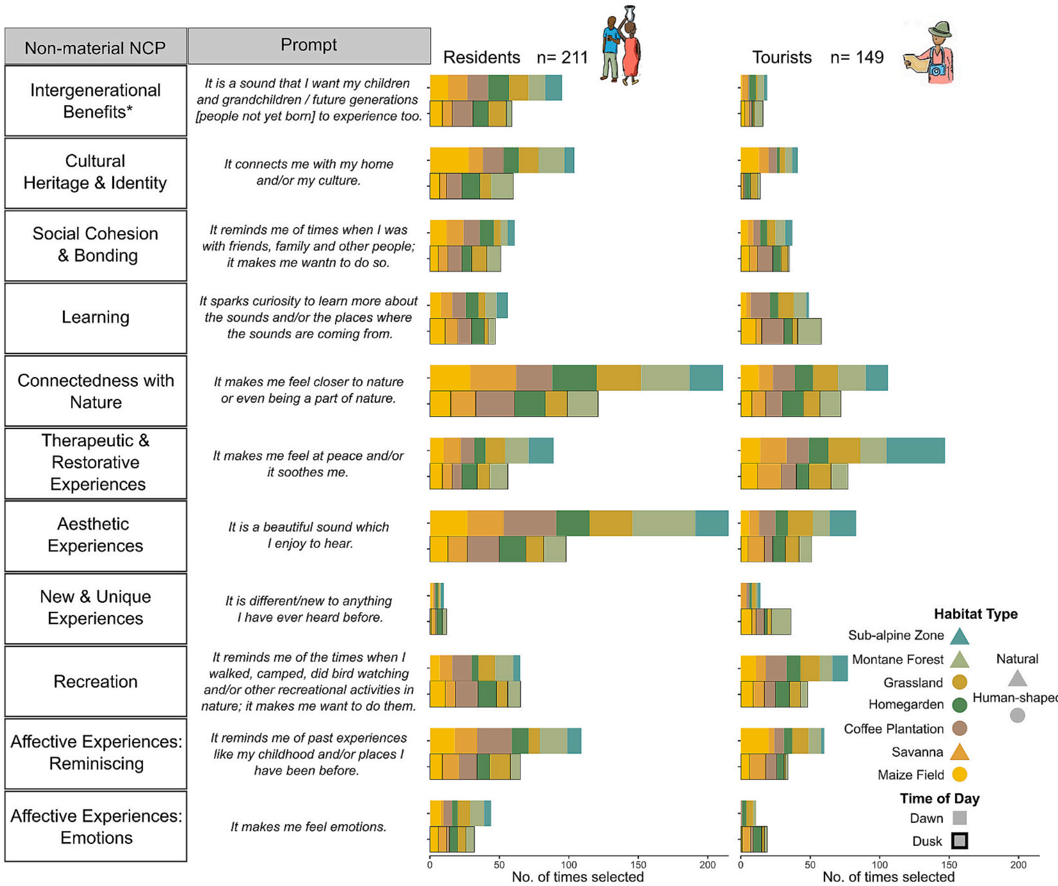

Fig. 3. Non-material Nature's Contributions to People (NCP) associated with the 13 soundscape tracks from different habitat types and times of day for residents and tourists. For each non-material NCP evaluated, the figure provides an associated prompt presented to participants, and number of times it was selected for each soundscape track by residents and tourists. *Maintenance of Options NCP. Icons design credit: Jelke Meyer.

times, ADI: 1.81) and residents coffee plantations (25 times, ADI: 1.90) and montane forests at dawn (20 times). These latter two soundscapes also aligned with those supporting *aesthetic experiences* for residents (Fig. 3) given their rich bird vocalizations, as suggested by the association of this NCP with high ACI values (Table 1; Table S2). *Affective experiences* that trigger diverse emotions was linked to soundscapes with high H values, particularly those from montane forest (selected 10 times; H: 0.57) and grassland (selected 9 times; H: 0.60) at dawn (Fig. 3), which were characterized by a diversity of vocalizing sources (Table S2). In contrast, *therapeutic experiences* were primarily selected for soundscapes characterized by high ACI and AEI values, particularly within the National Park (Table 2). This NCP was selected 20% more often to justify the choice of sub-alpine soundscape preferences (Fig. 3), which had the highest ACI values observed. *New & unique experiences* were selected to justify the choice of soundscapes that had high H values, primarily montane forest soundscapes during dusk (Fig. 3). *Learning* was associated with soundscapes featuring high H values (Table 2). For residents, this association was consistent across time of the day, whereas for tourists, it was specifically triggered by dusk soundscapes (Fig. 3).

Gender was the only socio-demographic variable associated to whether an NCP was selected, which was the case for *aesthetic experiences*, *affective experiences* linked to memories and *cultural heritage* (Table 2). Specifically, men preferentially selected *aesthetic experiences*, whereas women preferentially selected the other two NCP when choosing soundscapes. Perceived inclusion of nature in self did not explain the selection of any NCP (Table 2), even though residents had significantly higher scores of nature connectedness than tourists (Welch's *t*-test, $t = 6.98$, df $= 1666.1$, $p < 0.001$). However, residents selected *connectedness with nature* as an NCP associated with soundscape preference more often than tourists (Table 2).

4. Discussion

This study reveals that soundscape preferences and their associated non-material NCP vary significantly between different habitats on Mount Kilimanjaro and between residents and tourists. Our findings suggest that these differences might reflect residents' deeper cultural ties to the region and tourists' demands from natural areas, highlighting the varied ways through which soundscapes can contribute to human well-being. By integrating acoustic indices such as AR, BIO, H, ACI, ADI, and AEI (Table 2) in the analyses of these relationships, we demonstrated the potential of bioacoustics as a tool for monitoring and potentially predicting NCP supply across habitats.

4.1. Differing soundscape preferences across social groups

Residents' soundscape preferences can be explained by three (not mutually exclusive) reasons: (1) familiarity with the habitats from which the sounds originate, (2) the inherent acoustic characteristics of the soundscapes, and (3) cultural perceptions on specific vocalizing species. A sense of familiarity can enhance enjoyment and connectedness when listening to nature (Ednie and Gale, 2021), which may explain why residents favored soundscapes from human-shaped habitats such as coffee plantations, maize fields, and homegardens (Fig. 2). These are habitats where residents live and work and its soundscapes tend to have lower NDSI values, indicative of higher anthropogenic sounds (Table 1, Fig. S4). Interestingly, residents also favored the montane forest/dawn soundscape from within the National Park (Fig. 1, Fig. 2). Access to

Table 2
Factors associated with the selection of non-material Nature's Contributions to People (NCP) in preferred soundscapes. For each NCP, predictor effects and their confidence intervals (values in brackets) were quantified using Generalized Linear Mixed Models with NCP selection (yes/no) as a binary response variable. Predictor variables included categorical factors (social group and gender), integer variables (INS: Inclusion of Nature in Self; and year born), binary variables (natural habitat and National Park), and continuous variables (acoustic indices). Predictors excluded from the best-fit model for a given non-material NCP are indicated as "NA" (see global models Table S6). Significant predictor effects are in bold and marked with stars indicating the significance level (*$p < 0.05$, **$p < 0.01$, ***p < 0.001). For a summary of the acoustic indices, see Table S5.

Predictors	Intergenerational benefits	Cultural heritage	Social cohesion & bonding	Learning	Connectedness with nature
Social Group: Local Resident	**1.40 (0.82, 1.98)***	**0.87 (0.44,1.31)***	0.007 (−0.11, 0.13)	−0.16 (−0.63,0.32)	**0.49 (0.09, 0.89)***
Gender: Male	0.002 (−0.10, 0.10)	**−0.46 (−0.86, −0.06)***	−0.07 (0.0.37, 0.24)	0.01 (−0.13, 0.15)	0.35 (−0.07, 0.77)
Year Born	−0.06 (−0.29, 0.17)	0.008 (−0.09, 0.10)	−0.02 (−0.14, 0.10)	NA	NA
Inclusion of Nature in Self (ins)	−0.0003 (−0.03, 0.03)	−0.006 (−0.06,0.05)	−0.002 (−0.04, 0.03)	0.002 (−0.03, 0.03)	0.07 (−0.06, 0.20)
Natural Habitat	NA	NA	0.002 (−0.11, 0.12)	0.02 (−0.17, 0.22)	−0.007 (−0.10, 0.10)
National Park	−0.03 (−0.26, 0.19)	−0.008 (−0.15, 0.14)	**−0.49 (−0.94, −0.04)***	0.005 (−0.09, 0.10)	0.004 (−0.08, 0.09)
Acoustic Entropy Index (H)	NA	NA	−0.002 (−0.05, 0.05)	**0.30 (0.10, 0.50)****	NA
Acoustic Diversity Index (ADI)	NA	**0.19 (0.01, 0.36)***	0.005 (−0.05, 0.06)	NA	NA
Acoustic Complexity Index (ACI)	−0.005 (−0.07, 0.06)	−0.02 (−0.15, 0.10)	NA	−0.06 (−0.26, 0.13)	NA
Acoustic Evenness Index (AEI)	NA	NA	NA	NA	NA
Acoustic Richness (AR)	−0.03 (−0.19, 0.13)	**0.55 (0.32, 0.79)*****	NA	NA	0.001 (−0.03, 0.04)
Bioacoustic Index (BIO)	−0.04 (−0.22, 0.14)	**0.38 (0.15, 0.61)****	NA	NA	0.004 (−0.04, 0.05)
Normalized Difference Soundscape Index (NDSI)	0.0004 (−0.04, 0.04)	NA	NA	−0.13 (−0.34, 0.07)	0.08 (−0.06, 0.23)

Predictors	Therapeutic Experiences	Aesthetic Experiences	New & Unique Experiences	Recreation	Affective Experiences: Reminiscing	Affective Experiences: Emotions
Social Group: Local Resident	**−1.22 (−1.61, −0.83)*****	**0.77 (0.45, 1.09)*****	**−1.18 (−1.82, −0.55)*****	**−0.50 (−0.90, −0.10)***	0.14 (−0.26, 0.54)	**0.96 (0.30, 1.63)****
Gender: Male	0.16 (−0.22, 0.55)	**0.29 (−0.04, 0.62).**	0.003 (−0.13, 0.14)	0.08 (−0.20, 0.36)	**−0.50 (−0.90, −0.12)****	0.35 (−0.22, 0.92)
Year Born	0.01 (−0.07, 0.01)	0.001 (−0.04, 0.05)	0.17 (−0.14, 0.17)	−0.09 (−0.30, 0.11)	0.02 (−0.10, 0.13)	0.22 (−0.12, 0.55)
Inclusion of Nature in Self (ins)	NA	0.002 (−0.02, 0.03)	−0.015 (−0.12, 0.09)	−0.004 (−0.05, 0.04)	0.001 (−0.02, 0.03)	0.001 (−0.04, 0.04)
Natural Habitat	−0.10 (−0.54, 0.33)	0.03 (−0.13, 0.18)	0.57 (−0.17, 1.31)	−0.093 (−0.41, 0.23)	**0.76 (0.11, 1.41)***	−0.01 (−0.18, 0.16)
National Park	**0.55 (0.06, 1.04)***	0.06 (−0.17, 0.30)	0.09 (−0.50, 0.70)	NA	**−1.20 (−1.89, −0.50)*****	−0.01 (−0.19, 0.16)
Acoustic Entropy Index (H)	NA	−0.01 (0.07, 0.06)	**0.52 (0.16, 0.90)****	0.11 (−0.06, 0.30)	−0.04 (−0.20, 0.12)	**0.24 (0.02, 0.46)***
Acoustic Diversity Index (ADI)	NA	−0.01 (−0.07, 0.05)	−0.08 (−0.38, 0.22)	NA	**0.31 (0.10, 0.54)****	NA
Acoustic Complexity Index (ACI)	**0.27 (0.08, 0.47)****	**0.16 (0.02, 0.30)***	−0.12 (0.43, 0.19)	−0.004, −0.06, 0.05)	0.05 (−0.10, 0.20)	0.001 (−0.07, 0.08)
Acoustic Evenness Index (AEI)	**0.37 (0.19, 0.55)*****	NA	NA	0.0008 (−0.03, 0.03)	NA	NA
Acoustic Richness (AR)	−0.21 (−0.52, 0.09)	NA	NA	NA	NA	NA
Bioacoustic Index (BIO)	−0.18 (−0.44, 0.07)	NA	NA	NA	NA	NA
Normalized Difference Soundscape Index (NDSI)	NA	NA	NA	NA	NA	0.21 (−0.05, 0.47)

habitats within the National Park, including sub-alpine habitats, are limited to residents due to factors such as entry fees; indeed, over 79% of residents reported never visiting the Park (Text S1). Therefore, although montane forest might lack the familiarity of human-shaped habitats, the shared acoustic characteristics (i.e., complex vocalizations from both birds and mammals; Fig. S4), might explain residents' preference. Hence, residents seemed to prefer soundscapes with a rich and diverse acoustic composition over quieter habitats with fewer vocalizing species, as seen in the sub-alpine zone (Fig. 2, Fig. S4, Table S2). The third reason might explain residents' lower preferences for soundscapes dominated by insect modulations, such as the savanna at dusk (Fig. 2). This aversion might owe to cultural perceptions of insects, particularly the Orthoptera order, in Eastern Africa. For instance, children in Chagga communities often fear the sound of crickets due to their inability to identify where the sound is originating, and in other ethnic groups in Tanzania, crickets are viewed as a bad omen, believed to damage crops (van Huis, 2022). Similarly, the highly unfavored savanna and maize dusk soundscapes (Fig. 2) feature calls from nightjars (e.g., *Caprimulgus clarus*, Table S2) whose night call symbolizes hardship or struggle (Hemp and Hemp, 2009). Furthermore, dusk soundscapes from coffee plantations and homegardens include vocalizations from bushbabies (*Otolemur garnettii*; Table S2), which are unpopular among residents due to their tendency to damage crops (Hemp and Hemp, 2009). These multifaceted perceptions likely influence the preferences expressed by residents when evaluating soundscapes at Mount Kilimanjaro.

By contrast, tourists' preferences can be explained by a combination of (1) birdsong characteristics, (2) anthropogenic interference, (3) loudness, and (4) the urbanization-disgust hypothesis. Tourists favored dawn recordings from coffee plantation, grassland, and sub-alpine habitats, which featured rich and diverse birdsongs (Fig. 2, Table S2). These preferences likely reflect sensitivity to perceptual features such as melodic variation, rhythmic patterns, complexity, and birdsong dominance which are key drivers of perceived acoustic diversity (Rozario et al., 2025). This rich bird activity of tourists' preferred soundscapes underscores the contribution of diverse birdsongs to human well-being (Methorst et al., 2021; Hammoud et al., 2022). Interestingly, while the savanna/dawn soundscape was bird-dominated, it was less preferred, likely due to its lower bioacoustic richness (BIO and ADI) and higher acoustic evenness (AEI; Fig. S4, Table S5). This suggests that tourists prefer soundscapes with more diverse bird sounds, which supports findings that varied birdsong offers greater psychological benefits than just a few species singing (Hedblom et al., 2014; Ferraro et al., 2020; Douglas and Evans, 2022). Homegarden/dawn recordings, though rich in birdsong, were also less preferred potentially due to human-generated sounds like music, hammering, and people talking, showcasing lower NDSI values associated with anthropogenic interference (Fig. S4, Table S5). This interference may have challenged tourists' expectations of an "idealized" or "desired" natural experience with minimal human interference (Marselle et al., 2021; Schwarz, 2013). Least favored were also dusk soundscapes from maize, homegardens, and grasslands (Fig. 2), which shown high acoustic entropy values (H; Fig. S4). High H can be associated with louder or chaotic soundscapes which in turn are often perceived as less pleasant (Soeta and Kagawa, 2020), or were disliked because of dominant insect sounds (Fig. S4; Table S5). The latter aligns with the "urbanization-disgust" hypothesis, which suggests that individuals from urbanized areas (like most tourists from the Global North) tend to dislike insects, possibly due to frequent indoor encounters and limited ecological familiarity (Fukano and Soga, 2021). These findings suggest that tourists' soundscape preferences are shaped by an interplay between expectations of natural settings and the acoustic diversity of vocalizing species, specifically birdsongs. Yet this also reveals an important tension, as recreational activity itself can alter acoustic environments along trails (Vaughn and Quinn, 2025), potentially affecting the very soundscape qualities visitors value.

Overall, the preference for dawn soundscapes expressed by both residents and tourists (Fig. 2) may partly reflect societal biases favoring birds over insects (Troudet et al., 2017). Given that birds are typically more active at dawn, whereas insects dominate dusk periods, diel patterns of species activity likely shape opportunities for human–nature interactions and, consequently, familiarity with dawn soundscapes (Soga and Gaston, 2022).

4.2. Differing non-material NCP associations across social groups

The non-material NCP associated with soundscape preferences at Mount Kilimanjaro differed between residents and tourists (Table 2), highlighting the varied ways through which soundscapes can contribute to human well-being. For residents, the association of soundscapes with *cultural heritage* and *intergenerational benefits* (Table 2) indicates that soundscapes resonate with their cultural roots and deep ties to the place (Smalley et al., 2023) and serve as a medium for preserving traditions and fostering a sense of continuity. In contrast, tourists may experience soundscapes as a means of disconnection from their daily lives and relaxation, emphasizing their therapeutic and recreational benefits (Marin et al., 2011; Table 2). While our findings support previous research on the restorative effects of natural sounds, particularly among individuals from Global North contexts (i.e., tourists, Fig. S2), they also reveal that people from different socio-cultural backgrounds (i.e., residents) associated distinct meanings to soundscapes (Table 2; Buxton et al., 2021). These different associations underscore the importance of socio-cultural factors, such as daily interactions with nature, cultural identity, and dependence on natural resources, in shaping how people perceive non-material NCP (Peter et al., 2022; Martín-López et al., 2012).

The association of non-material NCP with soundscapes differing between residents and tourists may also be influenced by the spatial dimension of their preferred soundscapes. Residents and tourists tended to favor soundscapes from different habitat types (Fig. 2). For example, sub-alpine soundscapes were frequently associated with *therapeutic experiences* by tourists, but were neither a preferred soundscape nor a non-material NCP considered relevant by residents (Fig. 2, Fig. 3). These spatial divergences in NCP perception have also been observed in other contexts. Ghermandi et al. (2020) noted that locals and tourists often associate different cultural benefits with different locations. Similarly, participatory mapping studies in Norway revealed that even when spatial preferences overlap, residents and tourists derived different types of benefits from the same places (Muñoz et al., 2019). In our study, both groups ranked the coffee plantation/dawn soundscape high (Fig. 2), but likely for different reasons (Fig. 3). These differences highlight how soundscapes meet different expectations and social needs, depending on the listener's background and relationship with the landscape (i.e., place attachment). Incorporating such insights into conservation decision-making can help design interventions that both maintain local identities and enhance tourist experiences.

4.3. Acoustic indices associated with the selection of non-material NCP

Our study shows that seven non-material NCP can be directly associated with acoustic indices (Table 2), positioning these indices as a promising tool for assessing the role of soundscapes in supporting human well-being. Few studies have explored the relationship between acoustic indices and human experiences of nature (Zielonka et al., 2024; Lawrence et al., 2023; Fisher et al., 2021), and our findings contribute to a growing body of evidence that such associations can provide a robust framework for linking acoustic patterns to the diverse ways people experience and derive benefits from natural environments.

Cultural heritage was positively associated with BIO, ADI and AR (Table 2), indicating that diverse soundscapes rich in bird and mammal vocalizations were an important cultural component (Table S5), in particular for female residents. While BIO can increase with insect activity (Bradfer-Lawrence et al., 2019), it also captures the presence of non-avian species such as mammals (Retamosa Izaguirre and Ramírez-Alán, 2018). Similarly, high ADI values reflect a variety of sound sources, suggesting that no single sound source dominates the soundscape. When paired with high AR values—driven largely by bird vocalizations (Table S5)—this acoustic combination helps distinguish culturally preferred, bird-rich soundscapes from those dominated by insects (Fig. S4). Montane forest soundscapes at dawn characterized by high BIO and ADI values (Fig. S4) features vocalizations of species like the black-and-white colobus monkey (*Colobus guereza*), the eastern tree hyrax and variety of birds such as the Hartlaub's turaco (*Tauraco hartlaubi*; Table S2), and hence could theoretically contribute to *cultural heritage* (Fig. 3). However, access to these forests has become increasingly restricted for residents due to National Park regulations and entrance fees (see Sanya et al., 2025, and references therein), yet residents might now associate these soundscapes with memories of past experiences (i.e., *affective experiences* NCP, Table 2), reinforcing their cultural significance and preference (Fig. 2). While a strong sense of attachment and identity can persist despite lack of access (e.g., Lau et al., 2019), prolonged exclusion may erode these cultural ties, potentially reducing local engagement in forest conservation efforts (e.g., Cuni-Sanchez et al., 2019). Overall, familiarity with habitats seems to be a key driver of *cultural heritage*: soundscapes from familiar maize fields (high AR) were often associated with this NCP, in contrast to less familiar ones like sub-alpine habitats (Fig. 2, Fig. 3). This supports the role of acoustic, place-based experiences in nature in shaping connections to *cultural heritage*.

While *cultural heritage* was uniquely reported by residents, *affective experiences* linked to past memories were shared across groups but also showed a gender difference, with women reporting it more frequently, aligning with evidence on stronger autobiographical memory and emotional recall for women than men (Davis, 1999). Interestingly, this NCP differed in the associated soundscapes between social groups: residents selected montane forest soundscapes, whereas tourists more often chose maize field soundscapes (Fig. 3). These contrasting soundscape preferences reflect differing formative experiences with nature—one grounded in natural habitats (residents), the other in human-shaped environments (tourists). Despite ecological differences, familiar acoustic elements like roosters, ravens, and cuckoos (Table S2) in maize fields may evoke childhood or past memories in tourists, contributing to their emotional resonance.

Therapeutic experiences were selected twice as often by tourists compared to residents and were associated with soundscapes characterized by rich avian choruses (high ACI) but minimal acoustic overlap (high AEI) (Table 2; Table S5). In contrast, *aesthetic experiences*, more frequently reported by residents, were associated with high ACI alone, reflecting an appreciation for soundscapes rich in bird diversity, regardless of their acoustic saturation. For example, sub-alpine/dawn soundscapes (high ACI and AEI) were linked to *therapeutic experiences*, while more acoustically saturated montane forest soundscapes (high ACI, low AEI) were more often associated with *aesthetic experiences* (Fig. 3). This distinction is supported by previous research: while birdsong generally enhances perceived restorativeness (Ratcliffe et al., 2016; Ferraro et al., 2020; Uebel et al., 2021), overly dense soundscapes may reduce this benefit (Douglas and Evans, 2022). Higher AEI values, indicative of lower acoustic intensity and reduced complexity, are strong predictors of how people assess the quality of natural environments (Morrison et al., 2021). These findings emphasize the balance required in bird-dominated soundscapes, rich in vocalizations yet not overly complex, to maximize *therapeutic experiences* (i.e., high AEI; Lawrence et al., 2023) whereas *aesthetic experiences* tend to value complexity and diversity of bird vocalizations, even at the expense of a restorative effect.

The other three NCP—*new & unique experiences*, *affective experiences*, and *learning*—were all positively associated with H values (Table 2). Tourists predominantly reported *new & unique experiences; affective experiences* were more commonly preferred among residents, and *learning* showed no significant difference between the two groups. High H values indicate insect-dominated soundscapes (Ross et al., 2021) or soundscapes with numerous vocalizing species (Bradfer-Lawrence et al., 2019). This association was particularly evident in dusk soundscapes from montane forests, which were linked to both *new & unique experiences* and *learning* (Fig. 3). The presence of two endemic species to Mount Kilimanjaro, *Aerotegmina kilimandjarica* and the eastern tree hyrax (Table S2), may stimulate curiosity and provide opportunities to learn about these endemic acoustic sources. For tourists, these unfamiliar sounds likely reflect the novelty of the environment. In contrast, *affective experiences* were particularly associated with dawn soundscapes from montane forests (Fig. 3), characterized by a rich diversity of species (Table S2). These findings highlight that this diversity of vocalizing species can enhance the emotional resonance of the soundscape, fostering a deeper connection to these environments (Moscoso et al., 2018).

5. Conclusion

A soundscape-based approach that integrates both social and bioacoustic dimensions can offer powerful insights into the role of natural sounds in supporting non-material NCP for different socio-cultural groups. By moving beyond single-metric assessments (e.g., "avian diversity") and employing a comprehensive suite of acoustic indices (i.e., i.e., ACI, AEI, H, BIO, AR, ADI), we show *which* soundscapes social groups may prefer and *why*. These findings carry direct implications for inclusive conservation and nature-based experience management. In the Kilimanjaro region, *therapeutic experiences* appear best supported at dawn and at higher elevations, while *learning*-focused activities may be better suited to montane forests at either dawn or dusk. National Park managers and tour guides can use this evidence to design targeted interventions, such as sound walks calibrated by timing, location, and intended outcome, that are responsive to the needs of different visitor groups. Equally important, understanding why residents prefer specific soundscapes can strengthen sense of place, support cultural continuity and promote stewardship. Co-management of culturally meaningful areas could provide a pathway to inclusive conservation that respects and integrates local values rather than merely accommodating them. Beyond site-level management, these findings open productive avenues for future research. The acoustic properties identified here as salient to non-material NCP could be tested in contexts where access to physical nature is limited. For instance, through tailored soundscape interventions designed to support quality of life among individuals with limited mobility in clinical or care settings. Ultimately, this study underscores that soundscapes are not acoustically neutral backdrops, they are culturally and emotionally significant environments. Their conservation demands the same pluralistic sensitivity that is increasingly asked of landscape management.

CRediT authorship contribution statement

M. Eugenia Degano: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Katrin Böhning-Gaese:** Writing – review & editing, Funding acquisition, Conceptualization. **Hamadi Iddi Dulle:** Writing – review & editing, Funding acquisition, Data curation. **Milena Gross:** Writing – review & editing, Investigation. **Claudia Hemp:** Writing – review & editing, Funding acquisition, Data curation. **Neema Robert Kinabo:** Writing – review & editing, Investigation. **Lisa Lehnen:** Writing – review & editing. **Berta Martín-López:** Writing – review & editing, Funding acquisition. **Thomas Mueller:** Writing – review & editing, Funding acquisition, Conceptualization. **Ugo Arbieu:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGTP-4o in order to improve the readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2026.115175.

Data availability

Soundscape tracks are available in SoundCloud (scan QR in Fig. 2, Fig. S4). All data used for this study will be available at doi:https://doi.org/10.5281/zenodo.18832991 as of the date for publication.

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