

## Article

# Evaluation of Soundscape Perception in Urban Forests Using Acoustic Indices: A Case Study in Beijing

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**Abstract:** Soundscape is an essential component of urban forest landscapes, acoustic indices can be effectively used to monitor biodiversity, but whether they can be used for soundscape perception assessments needs to be further explored. In this study, soundscape recordings were collected in Beijing Eastern Suburban Forest Park, and acoustic indices were used to explore the relationship between the acoustic environment and soundscape perception, as well as the possible effects of temporal changes. To achieve this, audio recordings collected in spring and summer were divided, and a total of 90 audio segments were extracted from three time periods—morning, afternoon, and evening—to calculate the acoustic index and complete a questionnaire survey. The urban forest soundscape was evaluated according to the eight perceptual attribute quality indicators of ISO 12913, and generalized linear models were constructed to quantify the relationships between the acoustic indices and perception. The results showed that the temporal variation of the soundscape influenced the subjective evaluation, with the highest overall evaluation relating to the morning soundscape. The combination of acoustic indices explained the soundscape pleasantness ( $R^2 = 0.58$ ) better than the soundscape eventfulness ( $R^2 = 0.54$ ), demonstrating the utility of these indices in soundscape assessment. Linking acoustic indices to human perception generates innovative ideas and theoretical support for soundscape enhancement, contributing to a more pleasant acoustic environment and maximizing the social value of urban forests.

**Keywords:** soundscape evaluation; subjective perception; acoustic indices; temporal change; urban forest; human wellbeing



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## 1. Introduction

Sound plays an important role in ecosystems [1]. Each landscape has distinct acoustic patterns, and combinations of sounds over a specific temporal scale are collectively referred to as soundscapes, including geophony (non-biological ambient sounds), biophony (sounds created by organisms), and anthrophony (sounds produced by humans) [2]. Humans are surrounded by sound and use auditory perception to establish a relationship between sound and the environment [3,4]. Part of the sound research focused on the negative effects of noise, such as reduced attention span, increased stress, effects on biodiversity, and noise reduction techniques [5–8]. The International Organization for Standardization defines “soundscape” as an “acoustic environment as perceived or experienced and/or understood by a person or people, in context” [9]. Rather than equating sound with noise, more researches gradually focus on the meaningful components of sound, emphasizing the relationship between human perception and the acoustic environment [3,10–12]. Related findings also imply that natural sounds play an important role in ecosystem service functions and that exposure to natural sounds benefits human health and well-being [5,13–16].

The perception of soundscapes is closely related to the characteristics of the environment, time, and space in which people live [17–19]. Urban forest parks are usually

natural spaces adjacent to cities and connected to residential areas [20,21]. While performing ecological functions, urban forests provide a valuable opportunity for people to feel and experience the sounds of nature. Studies have shown that forest soundscapes can help reduce stress, improve mood, and enhance cognition [13,22], thereby providing an opportunity to improve the health of urban residents. Exploring the relationship between soundscape perception and the natural environment from multiple perspectives will help further improve people's perceptions of the urban forest landscape [10].

Commonly used soundscape evaluation methods include soundwalks, questionnaires, semantic analysis, interviews, and laboratory experiments [23–26]. These are used to explore the characteristics and cultural values of soundscapes in different places [18], the sound preferences of various user groups [25,27], the resilience of natural soundscapes [22], and the influence of specific sound sources or landscapes on soundscape preference and perception [28,29]. Quantitative soundscape analysis can help better understand the sound composition of the surrounding environment, the significance of sound sources, landscape characteristics, and the interaction between user perceptions [19,30,31]. Multisensory soundscape studies, such as combined visual and audio studies, have shown that visual stimuli can influence sound perception and evaluation [32,33].

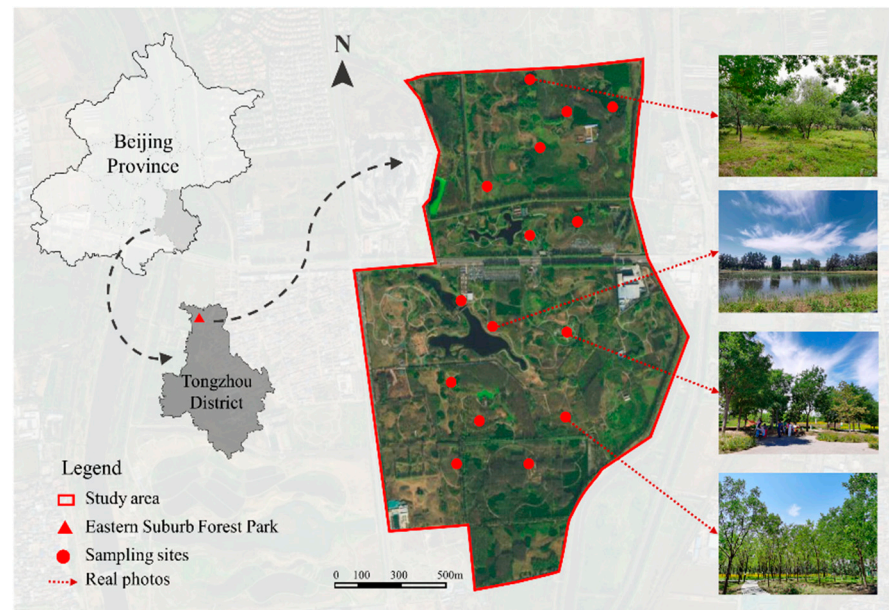
A combination of methods has also been considered in soundscape evaluation studies to reflect soundscape patterns and human perceptions from various perspectives and levels [34,35]. Physical soundscape properties and subjective human perception interact and can affect or restrict each other [36,37]. Most previous studies used sound level (Leq, LAeq, etc.) to describe objective components of the soundscape and rarely represented the overall acoustic environment from the perspective of time and frequency domains [34,38]. Acoustic indices can reflect the temporal or frequency distribution features of acoustic energy in fixed-duration digital audio [39], and various indices indicate different soundscape characteristics such as frequency, amplitude, and saturation [40]. Acoustic indices have been shown to have the potential to predict ecological values, such as biodiversity in urban forests [41,42], with the ability to connect people to ecosystems through soundscapes [4,16]. If a clear relationship between acoustic indices and subjective evaluations can be established, it has the potential to serve as a useful tool for inferring people's perceptions and preferences for soundscapes, providing a reliable basis for urban forest soundscape planning. However, human well-being perceptions are complex, and people have a limited ability to correctly perceive objective measures of the urban natural environment [43,44], which may result in a mismatch between perceptions and objective measures. It is still unclear whether soundscapes with higher ecological values can be rated better, and whether there is a potential link between acoustic indices and subjective perceptions [4]. Furthermore, studies have shown that soundscape evaluation is constrained by weather, time, and cost, and research on differences in soundscape preferences due to environmental factors such as seasonal changes is lacking [10,45]. However, sound varies over space and time, reflecting important ecosystem processes and human activities [2,42,46]. Therefore, it is necessary to explore the effects of temporal variation on soundscape perception.

To gain a more comprehensive understanding of how humans evaluate urban forest soundscapes at different times, and to clarify the link between acoustic indices and soundscape perception, we collected continuous recordings in the Beijing Eastern Suburban Forest Park and then conducted indoor evaluation and analysis. The following two questions were addressed in this study: (1) Do temporal changes affect people's subjective evaluation of the soundscape? and (2) Are acoustic indices effective for explaining people's perceptions of soundscapes? We hypothesize that there are temporal differences in urban forest soundscape perception, with higher evaluations at times when the vocal communities are active. In addition, there is a significant association between acoustic indices and perception, which allows for preliminary speculation on the perception of urban forest soundscape.

## 2. Materials and Methods

### 2.1. Sound Collection and Processing

The study area was in the Beijing Eastern Suburban Forest Park (Figure 1). It is a typical and representative urban forest park in the eastern suburbs, with a diverse range of biological resources and soundscape types [42]. The park was divided into two sections, with Xu Yin Road as the boundary. A total of 15 sampling sites were used for sound collection in this study; seven were selected in the northern area, and eight in the southern area. On 20 April and 20 August 2021, sound recordings were made throughout the day.



**Figure 1.** Study area and real photos of typical sampling sites.

Audio files collected from 15 sampling sites in the two seasons were segmented using Python 3.7.3 and Adobe Audition CC 2019 software. The audio was randomly intercepted for 15 s during in the morning (6:00–8:00), noon (12:00–14:00), and evening (17:00–19:00). The audio clips were broken up and renumbered to avoid any effects of the order. The final total of 90 15 s audio files constituted the audio settings for the subsequent evaluation experiment.

### 2.2. Subjective Evaluation

#### 2.2.1. Participants

Previous studies have shown that more than seven trained participants are required to achieve adequate and accurate results [31,47]. Thirty volunteers were recruited for this study, and all participants were confirmed to be free of any hearing impairment at the time of recruitment. Among them, 10 were male, and 20 were female, with ages ranging from 18 to 28 years. Prior to the start of the experiment, each participant was trained in the soundscape assessment method and fully understood the purpose of the experiment, as well as the meaning of the evaluation indicators. All participants provided written consent.

#### 2.2.2. Questionnaire

A questionnaire was used to collect participant evaluations of the soundscape presented by each audio segment. According to ISO 12913-2 [48] and the previous research [49], a questionnaire was developed to evaluate urban forest soundscape perception from eight aspects: pleasant, chaotic, vibrant, uneventful, calm, annoying, eventful, and monotonous (Table 1). Participants assessed the soundscape on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). We asked one question after the participants

completed the questionnaire: “Are you able to clearly distinguish between the season and time of appearance of the above audio?” and recorded based on the participants’ feedback.

**Table 1.** Soundscape questionnaire. After listening to the audio clips, participants rated the following 8 indicators.

|            | Strongly Agree           | Agree                    | Neither Agree, Nor Disagree | Disagree                 | Strongly Disagree        |
|------------|--------------------------|--------------------------|-----------------------------|--------------------------|--------------------------|
| Pleasant   | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/>    | <input type="checkbox"/> | <input type="checkbox"/> |
| Chaotic    | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/>    | <input type="checkbox"/> | <input type="checkbox"/> |
| Vibrant    | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/>    | <input type="checkbox"/> | <input type="checkbox"/> |
| Uneventful | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/>    | <input type="checkbox"/> | <input type="checkbox"/> |
| Calm       | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/>    | <input type="checkbox"/> | <input type="checkbox"/> |
| Annoying   | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/>    | <input type="checkbox"/> | <input type="checkbox"/> |
| Eventful   | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/>    | <input type="checkbox"/> | <input type="checkbox"/> |
| Monotonous | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/>    | <input type="checkbox"/> | <input type="checkbox"/> |

To simplify the results for analysis, according to the procedure in ISO 12913-3 [50], the eight perceived indicators were triangulated and reduced to two dimensions: pleasantness and eventfulness. The calculation formulas are as follows:

$$\text{Pleasantness} = (\text{pleasant} - \text{annoying}) + \cos 45^\circ * (\text{calm} - \text{chaotic}) + \cos 45^\circ * (\text{vibrant} - \text{monotonous}) \quad (1)$$

$$\text{Eventfulness} = (\text{eventful} - \text{uneventful}) + \cos 45^\circ * (\text{chaotic} - \text{calm}) + \cos 45^\circ * (\text{vibrant} - \text{monotonous}) \quad (2)$$

To adjust the coordinate range to  $(-1, 1)$ , we divide the coordinates by  $(4 + \sqrt{32})$ . This conversion is described in detail in ISO 12913-3.

### 2.2.3. Procedure

This study was conducted in a laboratory to ensure a quiet and comfortable experimental environment. Laboratory settings help to eliminate the influence of the visual environment on soundscape evaluation and control for potential influencing factors [22]. The experimental sound samples were played when the participants put on their headphones. After participants listened to each recording, the questionnaire was completed online and evaluated. To minimize physical discomfort, the duration was limited to 1 h, and sufficient rest periods were provided at the request of the participants. A total of 450 valid soundscape datasets were collected for this experiment.

### 2.3. Objective Measure

In this study, six commonly used acoustic indices that were initially validated in the study of soundscape ecology were used: acoustic entropy index (H), acoustic complexity index (ACI), acoustic diversity index (ADI), acoustic evenness index (AEI), bioacoustic index (BIO), and normalized difference soundscape index (NDSI). These acoustic indices were calculated using the “Seewave” and “Soundscape” R packages (Table 2).

**Table 2.** Description of the acoustic indices used in this study.

| Acoustic Indices                 | Description                                                                                                                                                                                                                                                          |
|----------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Acoustic complexity index, (ACI) | This index is used to measure changes in amplitude between adjacent frequency bands, reflecting the variability and irregularity of sound intensity, especially bird calls. The index is relatively unaffected by a constant intensity of a sustained sound [51,52]. |
| Acoustic diversity index, (ADI)  | The spectrogram is divided into frequency bands (default 10), and the percentage of sounds in each band that exceed the threshold is calculated using the Shannon index [53].                                                                                        |

Table 2. *Cont.*

| Acoustic Indices                               | Description                                                                                                                                                                                                                                                                                             |
|------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Acoustic evenness index, (AEI)                 | The spectrogram is divided into bands (default 10), and the Gini index is used to calculate the proportion of sounds in each band that exceeded the threshold [53].                                                                                                                                     |
| Bioacoustic index, (BIO)                       | The sound intensity in the specified frequency range is measured. The area of the above-threshold portion of the spectrum is related to the frequency range and sound intensity of most birds' calls [54]. It is calculated for sounds between 2 and 11 kHz in this study.                              |
| Normalized difference soundscape index, (NDSI) | NDSI is assessed by calculating the ratio of anthrophony (1–2 kHz) to biophony (2–11 kHz). The range is from −1 to 1, and the values closer to 1 indicate that biophony is more dominant [55].                                                                                                          |
| Acoustic entropy index, (H)                    | The audio is divided into multiple frequency bands, and the Shannon index is used to calculate the temporal entropy (Ht) and spectral entropy (Hf), which are multiplied to obtain the acoustic entropy index, reflecting the complexity of the acoustic signal in the time and frequency domains [56]. |

#### 2.4. Statistical Analysis

To understand the effect of temporal change on soundscape assessment, the mean values of participants' soundscape perception ratings were calculated. The Kruskal–Wallis H test (the data were non-Gaussian distributed) was used to determine whether there were significant differences in the soundscape evaluation at different times. The same test was used to measure the temporal variability of the soundscape in the urban forest. As a post hoc analysis, we used Dunn's multiple comparison test with Benjamini–Hochberg correction to determine which periods had significant differences in the soundscape [57].

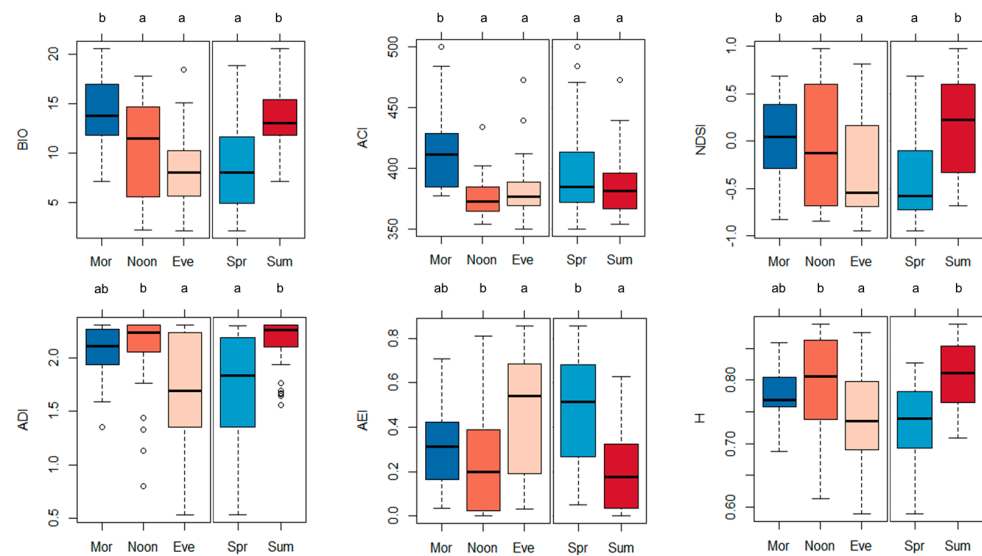
To investigate the relationship between subjective soundscape perception and the assessment results of the objective acoustic indices, we built two generalized linear models. The rotated pleasantness and eventfulness values were used as response variables, and the acoustic indices and day were used as independent variables. To facilitate comparison of the effects of different acoustic indices on soundscape pleasantness and eventfulness, the acoustic indices were standardized. The variance inflation factor (VIF) was calculated to check the multicollinearity among the acoustic indices, and the factors with VIF > 10 were deleted. Finally, a total of five acoustic indices (H, ACI, ADI, BIO, and NDSI) participated in the model analysis. All statistical analysis was processed and completed in R version 4.2.2.

### 3. Results

#### 3.1. Temporal Difference of Objective Acoustic Indices

Differences in the urban forest soundscape characteristics were measured using two temporal dimensions, daily and seasonal variation (Figure 2). In terms of daily variation, BIO and ACI showed significant differences between the early morning and other periods, whereas NDSI showed a significant difference between morning and evening soundscapes. The NDSI is influenced by both biophony and anthrophony. Combining the performance of BIO and ACI revealed that biophony was more dominant in the morning acoustic environment of the urban forest with higher sound complexity. ADI, AEI, and H showed significant differences between the evening and midday soundscapes, with more uneven variation between bands in the evening soundscape. Except for ACI, all acoustic indices showed significant differences in soundscape characteristics between seasons. The summer acoustic environment had similar sound complexity to that of the spring, but the biophony was more intense and varied more uniformly across frequency bands.

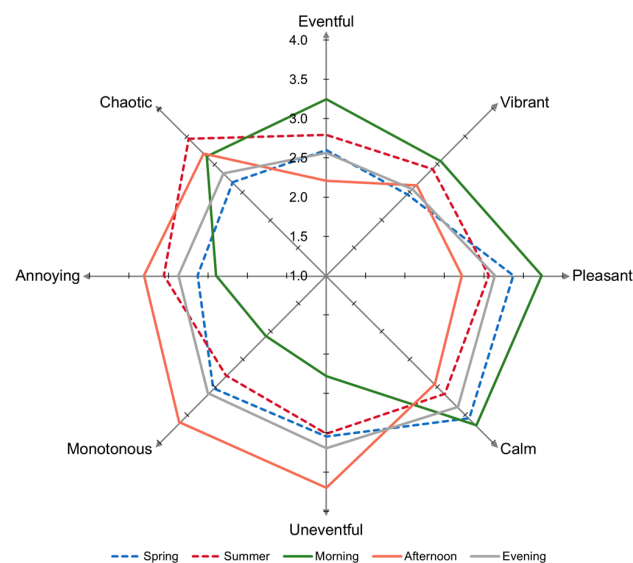




**Figure 2.** Differences of urban forest soundscape characteristics in the two-time dimensions of daily and seasonal. Mor = Moring (6:00–8:00), Noon = afternoon (12:00–14:00), Eve = evening (17:00–19:00). Dots represent outliers. Different letters above the box indicate significant differences at  $p < 0.05$ .

### 3.2. Temporal Variation of Subjective Soundscape Evaluation

The results of this study have shown that people's perceptions of soundscapes in urban forests vary depending on the time of day or season (Figure 3, Table 3). Except for chaotic, there were significant differences in the evaluation results of the other 7 indicators in the morning, afternoon, and evening. There were seasonal perceptual differences in the evaluation results of vibrant, chaotic, and clam. Figure 3 showed that the morning soundscape was perceived to be the most satisfying of the daily variations, with the highest mean scores for the four positive perceptual attributes. The morning soundscape was perceived as pleasant, calm, and eventful. In contrast, the midday soundscape had a high average score in negative attributes, leading to monotonous and uneventful feelings. The evening soundscape was perceived less strongly, and the soundscape perception attribute scores were basically in the middle range.

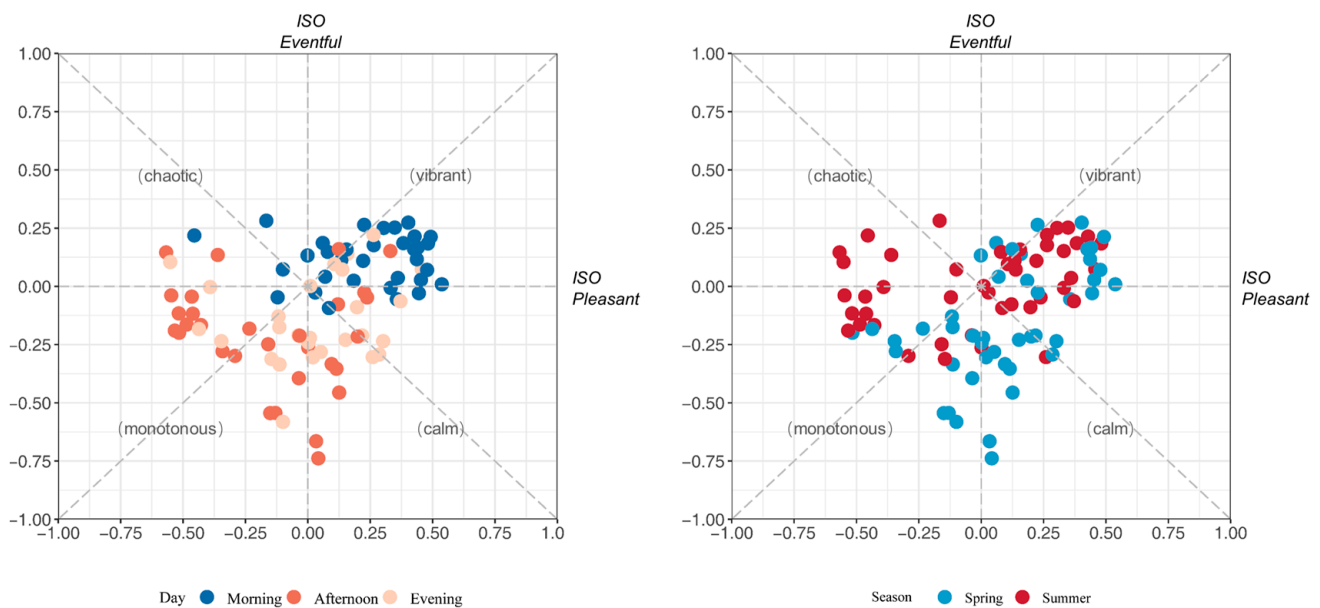


**Figure 3.** Mean scores of the subjective perceptual attribute of urban forest soundscapes at different times. The radar plot is drawn with reference to the model proposed by Axelsson [49], and higher scores imply higher agreement with the perceived attributes.

**Table 3.** Results of the test for significance of temporal differences in the perceived attributes of urban forest soundscape.

|        | Pleasant   |          | Chaotic  |          | Vibrant  |          | Eventful   |          |
|--------|------------|----------|----------|----------|----------|----------|------------|----------|
|        | $\chi^2$   | <i>p</i> | $\chi^2$ | <i>p</i> | $\chi^2$ | <i>p</i> | $\chi^2$   | <i>p</i> |
| Season | 1.80       | 0.18     | 18.93    | <0.001   | 20.11    | <0.001   | 1.49       | 0.22     |
| Day    | 25.68      | <0.001   | 3.65     | 0.16     | 7.36     | 0.03     | 39.95      | <0.001   |
|        | Uneventful |          | Calm     |          | Annoying |          | Monotonous |          |
|        | $\chi^2$   | <i>p</i> | $\chi^2$ | <i>p</i> | $\chi^2$ | <i>p</i> | $\chi^2$   | <i>p</i> |
| Season | 0.02       | 0.89     | 5.39     | 0.02     | 3.54     | 0.06     | 1.44       | 0.23     |
| Day    | 39.02      | <0.001   | 15.61    | <0.001   | 18.76    | <0.001   | 45.75      | <0.001   |

A comparison of the scoring results between the two seasons revealed that the spring soundscape provided a more pleasant and calm sense. Summer soundscapes tend to be more chaotic and annoying, and strong sound levels can also draw attention. Combined with Figure 4, the soundscape at noon and evening in spring felt monotonous and calm, while the summer noon and evening soundscape felt chaotic and annoying. Most of the participants could judge the soundscape appearing to be in the summer based on loud cicadas but were not sensitive to the specific sampling time of day.

**Figure 4.** Scatter plot of the same assessments on the soundscape circumplex, transformed according to ISO 12913-3. Every data point in the scatter plot represents one sound recording clip. The plot is drawn with reference to the paper by Mitchell [58].

### 3.3. Relationship between Acoustic Indices and Perceptual Dimensions

The combination of acoustic indices fitted the soundscape pleasantness ( $R^2 = 0.58$ ) slightly better than the eventfulness ( $R^2 = 0.54$ ). In the pleasantness model, all five acoustic indices involved in the model construction were significantly correlated with perception. Among them, NDSI, ACI, and ADI were positively correlated with pleasantness, but BIO and H enhancement led to a decrease in pleasantness (Table 4).

**Table 4.** Generalized linear model parameters for acoustic indices and perceptual dimensions.

| Variables     | Estimates | Std. Error | CI          | <i>p</i> |
|---------------|-----------|------------|-------------|----------|
| Pleasantness  |           |            |             |          |
| Intercept     | −0.47     | 0.14       | −0.74–−0.21 | <0.001   |
| H             | −0.32     | 0.14       | −0.59–−0.04 | 0.024    |
| ACI           | 0.49      | 0.09       | 0.30–0.67   | <0.001   |
| ADI           | 0.24      | 0.11       | 0.03–0.46   | 0.029    |
| BIO           | −0.56     | 0.13       | −0.80–−0.31 | <0.001   |
| NDSI          | 0.51      | 0.11       | 0.28–0.73   | <0.001   |
| Day [Evening] | 0.38      | 0.19       | 0.00–0.76   | 0.049    |
| Day [Morning] | 0.97      | 0.21       | 0.57–1.38   | <0.001   |
| Eventfulness  |           |            |             |          |
| Intercept     | −0.53     | 0.14       | −0.80–−0.25 | <0.001   |
| H             | 0.04      | 0.15       | −0.25–0.32  | 0.796    |
| ACI           | −0.08     | 0.10       | −0.28–0.11  | 0.389    |
| ADI           | −0.17     | 0.12       | −0.40–0.05  | 0.137    |
| BIO           | 0.59      | 0.13       | 0.33–0.84   | <0.001   |
| NDSI          | 0.01      | 0.12       | −0.22–0.25  | 0.92     |
| Day [Evening] | 0.53      | 0.20       | 0.14–0.93   | 0.008    |
| Day [Morning] | 1.00      | 0.22       | 0.58–1.43   | <0.001   |

In the soundscape eventfulness model, only BIO was significantly associated with eventfulness. When the BIO value was higher, the urban forest soundscape was vibrant and chaotic. In addition, both models showed that soundscape perception was significantly influenced by time differences.

#### 4. Discussion

##### 4.1. Effects of Soundscape Temporal Patterns on Perception

Soundscape perceptions and objective measurements were compared to gain insight into public responses to urban forest soundscape characteristics. Consistent with previous studies, acoustic indices can objectively reflect changes in the urban forest soundscape [41,59]. This study also confirmed that there are temporal differences in human perceptions of urban forest soundscapes. Due to financial and personnel constraints, field experiments such as soundwalks are rarely conducted throughout the day or across multiple seasons [10]. The effects of time are relatively poorly explored, and only a few studies have focused on human preferences for birdsong in different seasons [60]. Temporal changes in soundscapes are closely related to the natural rhythms of vocalizing organisms, particularly birds and insects [42,61]. From the interviews, we found that most participants could only identify seasons based on season-specific sounds (e.g., the association of cicadas with summer). However, overall satisfaction with the soundscape was low in summer, possibly due to the loud and constant sound of cicadas, which can lead to negative perceptions, irritability, and anxiety. Therefore, soundscapes with strong bioacoustics may not necessarily provide a positive soundscape experience.

Continuous acoustic recordings can visualize dynamic changes in the soundscape [62], whereas short-term, randomly sampled audio may weaken the differences in daily soundscape changes. However, we also discovered that soundscapes are more pleasant and vibrant in the morning, which may be due to the perceived dominance of certain sound types at a specific time of day influencing participant evaluations [63]. For example, researchers have confirmed the restorative effect of birdsong on human emotions and that bird chorus at dawn may enhance this positive effect, which may explain why mornings are more enjoyable [22,31,64]. Therefore, we speculate that the reason for the differences in urban forest soundscape perception at different times is related to biological sound sources—that is, the impact of changes in the acoustic activity of vocalizing communities on soundscape perception.



#### 4.2. Ability of Acoustic Indices for Urban Forest Soundscape Evaluation

The quality of the urban forest acoustic environment is important for human well-being and sustainability. Unlike most studies that use Leq, LAeq, loudness, and sharpness to measure the acoustic environment [25,30,34], this study focused on acoustic indices and subjective perceptions. According to the ISO evaluation guidelines, we explored the patterns of participants' perceptions of urban forest soundscape in two dimensions: pleasantness and eventfulness. This attempt to couple objective indices with human well-being broadens the scope of the application of acoustic indices.

All acoustic indices were significantly correlated with pleasantness. Previous studies have shown that ACI, NDSI, and ADI are good predictors of biodiversity [65–68], and this study also found that human perception of soundscape pleasantness in the urban forest was significantly positive correlated with them. It means that the more complex and diverse sounds in the urban forest are, the more pleasant the acoustic environment tends to be. Biological sound types and perceptual advantages are key considerations [31]. Fisher et al. also reported that NDSI could accurately reflect the types of sounds heard and enjoyed by participants [16]. However, when H and BIO are higher, too much sound intensity will make people feel annoyed and reduce the pleasantness of the soundscape perception. Not all types of natural sounds were perceived positively, such as strong cicada calls that could generate negative psychological feelings [10,30,69]. The effectiveness of the BIO in explaining the eventfulness of the soundscape was also confirmed. BIO was directly related to the bioacoustics intensity of sound in the environment [54] and reported in some areas as a valid indicator for exploring bird vocalizations [70,71]. The significant positive correlation between BIO and eventfulness also showed that chaotic and vibrant sounds create eventful soundscapes which correspond to people's perceptions. The multi-dimensional research supports the potential link between biodiversity and soundscape perception.

It is worth that the feedback from the laboratory experiments was in response to brief soundscape stimuli, but soundscape perception judgments may be influenced by subjective experiences and long-term knowledge [26]. From the fitting results of the two models, the five acoustic indices partially explain the human perception of the soundscape. The predictive power of the model was slightly weaker compared to a previous study of the relationship between psychoacoustic indicators and soundscape perception [72]. Incorporating perceptually derived input features (visual factors, etc.) at the time of modeling may achieve better accuracy rates [73,74]. Despite the complexity of factors affecting subjective soundscape evaluation, this study confirms the ability and value of using acoustic indices as a tool to explore indicators of human well-being. In the future, compound indices might be developed with an ability to better link soundscape data to subjective perception.

#### 4.3. Applications and Practical Implications

Understanding human perceptions and attitudes toward soundscapes may be the key to developing soundscape designs that meet the needs of the public [27]. The special characteristics of urban forests allow abundant anthropogenic sound, and natural sounds associated with health benefits are also common. Changes in acoustic indices such as NDSI, ACI, and ADI can initially predict peoples' perception of the soundscape and help guide urban forest planning and management. For example, reasonable zoning in park planning is able to accommodate the soundscape needs of a wider range of individuals. NDSI can be used as a good index to classify natural areas (quiet areas) and artificial areas (active areas). By installing signage or other visible reminders in quiet areas, visitors can be encouraged to visit quietly [11], thereby increasing their exposure to and appreciation of natural sounds.

The findings of the acoustic indices in biodiversity research and attempts in the field of soundscape perception provide several perspectives for interpreting urban forest soundscapes. Higher ADI and ACI values may not only represent rich sound diversity but also imply to some extent that the soundscape provides a pleasant and positive perceptive experience. Soundscape tracking and the measurement of multiple urban forest sample

sites using acoustic indices has the potential to assess the effectiveness of landscape planning. In addition, the perception of soundscapes influences people's sense of place and identity because it serves as a conduit for humans to experience nature [26]. The use of acoustic indices in urban forests to predict people's perception ratings and incorporate human perceptions into planning or measurement can aid in the development of more targeted management recommendations. Forestry policymakers must develop soundscape strategies based on public expectations and different needs to enhance human well-being in a holistic and multi-dimensional manner.

#### 4.4. Limitations and Future Research

The participants in this study were all youth, and the experimental population may be relatively limited. Residents of various ages may have different uses for urban forest parks [27]. Seniors prefer recreational activities, such as square dancing in the park, which may influence their subjective evaluation of anthrophony. Future work should include participants of different ages and behavioral levels.

Furthermore, this study focused on subjective evaluations of the acoustic environment obtained through the sense of hearing and explored their correlation with acoustic indices, as well as laboratory experiments that were purposefully designed to exclude the potential influence of visual stimuli on the evaluation of soundscapes. However, it is undeniable that visual influence, scene ambiance, physical comfort, and scene association can all cause differences in evaluations [19,33]. Following our preliminary validation findings, additional work should be conducted to investigate the impact of audition interaction and multisensory stimulation on soundscape assessment. In future studies, we would like to add comparative analysis with field or virtual soundwalk to further explore the importance of considering contextual information.

#### 5. Conclusions

This study clarified the temporal changes affecting soundscape assessments in urban forests, established a link between subjective evaluations and acoustic indices, and highlighted the application value of acoustic indices for assessing soundscape perception. Participants rated soundscapes higher in the morning and spring, and the dominance of sound sources at specific periods (e.g., the dawn chorus of birds, strong cicadas in summer) influenced the subjective evaluation results. Furthermore, as an objective indication, acoustic indices can predict perceptions of the pleasantness and eventfulness of the soundscape to some extent. This also implies that soundscape perception is intrinsically linked to urban forest biodiversity. Our study provided evidence linking soundscape perception and acoustic indices, which can help forestry managers assess human perception of sound in urban forests more rationally. The use of soundscapes as a valuable natural resource, a better understanding of public needs for soundscapes, as well as increased awareness and conservation of soundscapes, will all contribute to the sustainable development of urban forests.

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