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A SOUNDSCAPE ASSESSMENT OF THE OAK FORESTS IN THE NATIONAL PARK "HOMILSHANSKI LISY" (NORTHEASTERN UKRAINE)

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Abstract

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We investigated the properties of the sounds recorded on the territory of the National Park "Homilshanski Lisy" (Kharkiv region, Ukraine). Recordings were made at five points (in mature, middle-aged, and young oak forests, overgrown clear-cut and aspen forests). Data collection was carried out using on-site positioning of AudioMoth autonomous recorders, located on trees at a height of 1.5 m. The recording was made from April 11 to July 10, 2020, for 3 h in the morning and evening with a 5-min duration followed by a 10-min pause (24 recordings per day). Six acoustic indices (AIs) were calculated: Acoustic complexity index (ACI), acoustic diversity index (ADI), acoustic evenness index (AEI), bioacoustic index (BI), normalized difference soundscape index (NDSI), and acoustic entropy index (H). For the analysis, we used the Friedman test as well as a nonparametric analysis of the variance of the distance matrix and Tukey's test. The results of the analysis showed the statistical significance of the influence of forest type, date and time of recording, as well as the effect of their pairwise interactions on all six acoustic indices, both in the morning and evening. For three indices – ACI, BI, and NDSI – the highest average values were noted in a mature oak forest and the lowest was in overgrown clear-cuts. We performed a PCA to reduce the number of variables and obtain insight into the variable relevance. The cumulative percentage of variance, explained by the first three principal components, is 84.5%. The first principal component is associated with H, BI, AEI, and ADI. The second and third principal components are associated with NDSI and ACI. The obtained results correspond to the results of quantitative bird counts carried out earlier in this area.

Key words: ecoacoustics, acoustic indices, AudioMoth, oak forests, protected area.

Introduction

Biodiversity monitoring is of great importance for assessing global changes caused by human activity and climate change. Rapid indicators of biodiversity and the state of ecosystems are important for planning conservation activities (Stem et al., 2005; Joppa et al., 2016). Traditional methods of studying biodiversity are often limited due to being resource intensive and invasive. Therefore, remote-sensing methods are now being used more and more, since they can be applied over large areas and have a large time coverage (Kerr, Ostrovsky, 2003): satellite imagery (Turner, 2014; Bonthoux et al., 2018), camera traps (Steenweg et al., 2017; Fontúrbel et al., 2021), unmanned aerial vehicles (UAVs) (Anderson, Gaston, 2013; Nowak et al., 2019), and passive acoustic systems (Froidevaux et al., 2014; Wrege et al., 2017; Sugai, Llusia, 2019).

Passive acoustic monitoring (PAM) is a noninvasive method that uses autonomous recording units (ARUs) to provide data on large spatial and temporal scales, as well as collect long-term information about animal distribution and community dynamics (Sueur et al., 2008; Obrist et al., 2010; Marques et al., 2013; Farina, Gage, 2017). The method does not depend on the presence and number of observers and allows monitoring in hard-to-reach areas (Sueur et al., 2014). It can be used to study the temporally and spatially changing constellation of biological, geological, and anthropogenic sounds (Pijanowski et al., 2011a) and diagnose the state of ecosystems and assess species diversity (Tucker et al., 2014). Three approaches are used to analyze the acquired data: 1) species identification by listening to recordings or visualization of spectrograms, 2) automatic species recognition using classification algorithms, and 3) the use of acoustic indices (AIs).

AIs have been developed to extract biological information from large volumes of acoustic data (Buxton et al., 2018a, b). The use of AIs as environmental indicators is based on the assumptions that the acoustic community is representative of the wider ecological community and the measurable changes in the acoustic environment are of ecological importance (Gasc et al., 2013; Eldridge et al., 2018). Based on these assumptions, it is assumed that higher species richness will elicit a wider range of signals, resulting in greater acoustic diversity (Sueur et al., 2008; Gasc et al., 2013; Bateman, Uzal, 2021). AIs are obtained by postprocessing audio frequencies and levels to extract specific audio characteristics. In some cases, AIs are based on environmental indices. The most used AIs are as follows:

- ***Acoustic complexity index*** (ACI): Created for quantification of the bird's vocalizations by processing the intensities registered in audio files (Farina, Morri, 2008; Pieretti et al., 2011). The formula of ACI is developed based on the assumption that biotic sounds are characterized by an intrinsic variability of intensities, while human-generated noise presents constant intensity values.
- ***Acoustic diversity index*** (ADI): Calculated as the Shannon index using the proportions of the signals in each bin above the threshold value (Pijanowski et al., 2011a, b; Villanueva-Rivera et al., 2011).
- ***Acoustic evenness index*** (AEI): Estimates the diversity of sounds with the Gini index (Villanueva-Rivera et al., 2011).
- ***Bioacoustic index*** (BI): Calculated as the area under the mean frequency spectrum. Proposed by Boelman et al. (2007) as a measure of the number of birds.
- ***Normalized difference soundscape index*** (NDSI): Evaluates the level of anthropogenic disturbances, calculating the ratio of biophony and anthropophony (Kasten et al., 2012).
- ***Acoustic entropy index*** (H): Is a product of spectral and temporal entropies, which are calculated on the mean spectrum and Hilbert amplitude envelope of a time wave, respectively (Sueur et al., 2008).

The National Park "Homilshanski Lisy" is located in the central part of the Kharkiv region (Northeastern Ukraine) and covers primary forests in the Donets River valley. The park was created in 2004, but ornithological research has been carried out in this area since the 1950s (Bukachenko, Naglov, 1954; Volchanetskiy et al., 1954). From 2007 to 2009, quantitative censuses of nesting birds were carried out in the oak forests. During the entire period of research, 47 species of birds were recorded, of which 42 species were nesting. The total population density ranged from 3295 to 3870 pairs/km^2 (Atemasov et al., 2010, 2011).

Soundscape ecology research was started in 2018 (Atemasov, Atemasova, 2019 [as National Nature Park "Gomilshansky forests"]). To establish the suitability of the acoustic method for monitoring the state of forest ecosystems, we conducted studies on seven plots different from each other by stand age and species composition in a maple–linden–oak forest. For the analysis, 5-min recordings made in May and June were used. The results of our research revealed that AIs showed a correlation not only with the species richness of birds, but also with different stand variables which characterize the structure and species composition of the plant cover. In addition, the values of the indices differed for sites with different stand ages and species composition. The smallest values of the indices were noted on the overgrown clear-cuts. The present study is a continuation of the work. The difference lies in the use of stand-alone sound recording devices that allow recording for a long time. This avoids the influence of random factors. The objective of this study was to use AIs as a method for comparing the differences in the soundscape between the forest areas that differ in age and species composition of the stand.

Material and methods

Study site and sample plots

The research was conducted on the territory of the National Park Homilshanski Lisy (N49°35´, E36°20´). It is located in the northeastern part of Ukraine, in the central part of the Kharkiv region, on the territory of the Chuguev and Lozova districts, and occupies an area of 14,314.8 ha. The park covers a large forest area on the right bank of the Siversky Donets River, the floodplain of the river, and the left-bank borough terrace. Description of the study area is published in our previous article (Atemasov, Atemasova, 2019).

We recorded sounds in five sites on the territory of the Koropovske forestry. Sampling sites were randomly selected (but no closer than 100 m from edges, stand boundaries, roads, and settlements) in five types of forest. Sampling site A was a mature oak forest composed of common oak (*Quercus robur*) and common ash (*Fraxinus excelsior*). Undergrowth was composed of Norway maple (*Acer platanoides*), field maple (*A. campestre*), small-leaved lime (*Tilia cordata*), and common hazel (*Corylus avellana*). Sampling site B was a middle-growth oak forest composed of oak and common ash. Undergrowth was composed of Norway maple, field maple, small-leaved lime, common hazel, and euonymus (*Euonymus verrucosus*). Sampling site C was a young forest composed of common ash, common oak, Norway maple, and small-leaved lime. Undergrowth was composed of field maple and common hazel. Sampling site D was an overgrown clear-cut composed of small-leaved lime, common hazel, and field maple. Sampling site E was an old-growth aspen forest composed of common aspen (*Populus tremula*) and common ash. Underground was composed of small-leaved lime, Norway maple, elm, small-leaved lime, euonymus, Tatar maple (*Acer tataricum*), elm (*Ulmus* sp.), and common hazel.

Distance between the sites was from 260 to 2200 m. The distance from the closest road and locality was 1500, 220, 2170, 2415, and 1400 m for the sites A, B, C, D, and E, respectively.

Data collection

Investigations were conducted from April 11 to July 10, 2020, to cover the periods of activity of all nesting bird species (Banik et al., 2014a, b; and others). The study period corresponds to the late spring and summer-nesting aspects of the annual cycle of the avifauna on the territory of Ukraine (Loparev, 1997). We collected data using the on-site positioning of AudioMoth (version 1.1.0) autonomous recorders (Hill et al., 2018, 2019). The devices were placed in trees at a height of 1.5 m in wooden containers to protect against adverse influences. The geographic position of each recorder was marked with a handheld GPS Garmin eTrex 30x. We made records in the morning (beginning 1 h before, ending 2 h after sunrise) and in the evening (beginning 2 h before, ending 1 h after sunset) for 5 min every quarter of an hour. A total of 2184 five-minute records were obtained for each device (12 morning and 12 evening records per sampling day, 91 days). The recorders were set at a sampling rate of 48 kHz and saved in the audio file format Microsoft .wav, mono 16-bit uncompressed. The total recording duration was 910 h (182 h for each of the five sites). High-pass filters were set to 500 Hz to reduce low-frequency noise.

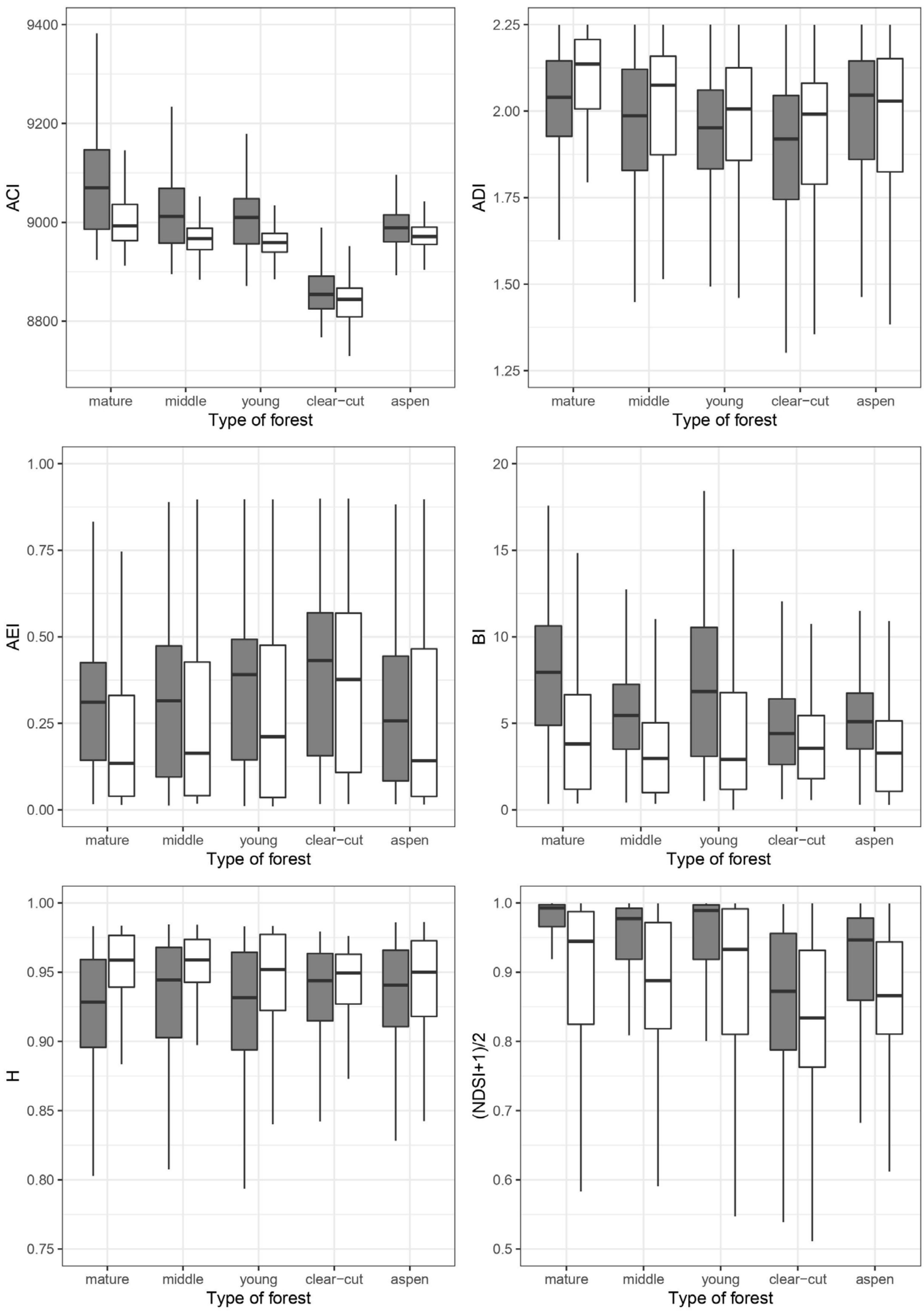

Fig. 1. The boxplot of the five sites with the separation of the morning (gray color) and evening (white color) hours.

Acoustic indices

We calculated six AIs (ACI, ADI, AEI, BI, NDSI, and H) for each record. The soundecology package (Villanueva-Rivera, Pijanowski, 2018) for R (R Core Team, 2021) was used for AI calculations. Default parameters were used for all AIs (Fairbrass et al., 2017; Bradfer-Lawrence et al., 2020). NDSI is bounded from − 1 to 1, and so was scaled using (NDSI + 1)/2 (Fairbrass et al., 2017; Ross et al., 2021).

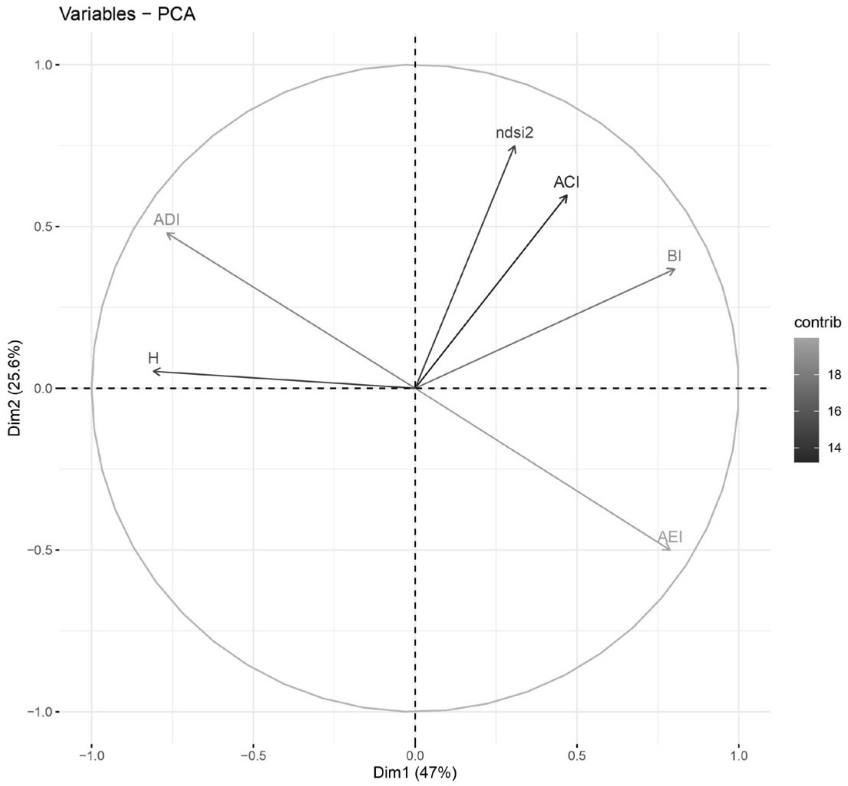

Fig. 2. Correlation plot of the principal component analysis.

Data analysis

Acoustic recordings were taken at five sampling sites 2184 times, so repeated measures analysis of variance (ANOVA) was used. A Shapiro–Wilk test for normality revealed that data was not normally distributed. Therefore, for further analysis, we used the Friedman test as well as nonparametric ANOVA of the distance matrix and the Tukey test. The vegan package (Oksanen et al., 2020) for R was used for analysis. The average values for each AI in the morning and evening hours were compared among the five points. To determine the quantitative characteristics of the degree of severity of the influence of forest type on AIs, the effect size was calculated. There was used Cohen's f. Cohen's f can take values between zero, when the population means are all equal, and an indefinitely large number, as the standard deviation of means increases relative to the average standard deviation within each group. The values of 0.10, 0.25, and 0.40 represent small, medium, and large effect sizes, respectively (Cohen, 1969). G*Power 3.1 software was used for Cohen's f calculation (Faul et al., 2007).

In addition, we used principal component analysis to analyze the matrix of six AIs. The factoextra (Kassambara, Mundt, 2020) and FactoMiner (Le et al., 2008) packages for R were used.

Results

We received about 315 Gb of acoustic data (about 691.2 Mb of data per sampling day/site). We analyzed a total of 10,920 recording files (24 files per sampling day/site). The distribution of AIs among sites in the morning and evening hours is shown in Figure 1. Results of the ANOVA showed the statistical significance of the influence of forest type, date and time of recording, as well as the effect of their pairwise interactions on all six AIs, both in the morning and evening hours. For three indices – ACI, BI, and NDSI – the highest average values were noted in a mature oak forest and the lowest was in an overgrown clear-cut. The index values in young and middle-aged oak forests and aspen forests occupied an intermediate value. At certain time intervals, the picture may change: for example, in the first decade of June, the highest ACI value was noted in the middle-aged oak forest, in the third decade of June, it was noted in the young oak forest, and in the first half of July, it was noted in the aspen forest; in the second and third decades of June, the highest value of BI was noted in a young oak forest. The highest evenness (AEI index) was noted in the overgrown clearing, which is probably due to the low species composition and number of birds in this area.

Values of effect size, which provide information about the magnitude of the differences between groups (in our case, between the values of AIs in various types of the forest), are presented in Table 1. The effect size for ACI is large, for ADI, BI (in the morning) and NDSI is medium, and for AEI, BI (in the evening), and H is small.

We performed a PCA to reduce the number of variables and obtain insight into the variable relevance. The results for the six variables show that components 1 and 2 have eigenvalues Ei >1 (Table 2). Table 3 shows the contribution of different variables to principal components (PC) 1–5. PC1 describes 47.0%, PC2 describes 25.6%, and PC3 describes 11.9% of the data variability. The cumulative percentage of variance explained by these three PCs is 84.5%. Figure 2 shows the correlation plot representing the contributions of the variables in accounting for the variability of the first two PCs. PC1 is associated with H, BI, AEI, and ADI. PC2 is associated with NDSI and ACI. ADI and AEI are anticorrelated. ADI (AEI) and ACI (NDSI) are not correlated.

We used the correlation coefficient between factor scores and soundscape indexes to interpret factor scores. Correlation coefficients between PC1, PC2, PC3, and AIs are presented in Table 4. We plotted sites on the PC axes (three variants – PC1&PC2, PC1&PC3, and PC2&PC3) for morning and evening. This allowed us to visually examine the differences in the soundscape of each site (Fig. 3).

Discussion

The natural sound conditions in different types of forests were measured in the territory of the National Park Homilshanski Lisy (northeastern Ukraine). We made audio recordings from April 11 to July 10 to cover the vocal peaks of all nesting birds. Diurnal variations in song intensity are typical of passerines in temperate forests, with song peaking before and during sunrise and sunset (Armstrong, 1963). Therefore, we made recordings only in the morning and evening hours (before, during and after sunrise, and before, during, and after sunset). We evaluated six AIs that are often used in soundscape investigations (ACI, ADI, AEI, BI, H, and NDSI) for five types of forest. All indexes showed differences in the soundscape of the different types of forest both in the morning and evening. ACI showed the clearest pattern of the increase in the index value with increasing forest age. This is also confirmed by the largest effect size. A similar pattern, but not as pronounced, was noted for NDSI and BI (only for the morning time). The similarity between ACI and BI is explained by the fact that both indices are calculated based on the change in the spectral amplitude, but when calculating ACI, sounds in the anthropophonic range (0–2 kHz) are taken into account, while when calculating BI, they are not taken into account. It is believed that the values of these indices correlate with the abundance and vocal activity of birds (Boelman et al., 2007; Sueur et al., 2008; Pieretti et al., 2011; Depraetere et al., 2012; Buxton et al., 2018a; Müller et al., 2020; Shaw et al., 2021). Given this, it can be assumed that our results are consistent with previous findings that the number of species and density of birds increase during succession (Petty, Avery, 1990). However, some researchers believe that ACI's ability to serve as an indicator of bird diversity remains unclear (Farina et al., 2011, 2015; Eldridge et al., 2018; Ross et al., 2018). After analyzing some studies, Bateman and Uzal (2021) concluded that the claims about the relationship between ACI and bird diversity are not convincing. To establish whether there is a relationship between ACI and species richness in the oak forests of the National Park Homilshanski Lisy, it is necessary to determine the species composition and vocal activity of birds in our records, which will be the subject of further research. Results of previous studies based on the analysis of 5-min recordings made in various types of forests have shown a correlation between AIs and species richness of birds in the studied areas (Atemasov, Atemasova, 2019).

Table 1. Effect size (Cohen's f) of the type of forest on AIs in the morning and evening.

AIs	Morning	Evening
ACI	0.63	0.71
ADI	0.25	0.30
AEI	0.20	0.23
BI	0.34	0.14
H	0.10	0.17
NDSI	0.34	0.38

Table 2. Properties of the six principal components.

	Eigenvalue	Percentage of variance	Cumulative percentage of variance
PC1	2.82	47.0	47.0
PC2	1.54	25.6	72.6
PC3	0.71	11.9	84.5
PC4	0.45	7.6	92.1
PC5	0.30	5.0	97.1
PC6	0.17	2.9	100.0

Table 3. Contributions of each AI to the first five principal components.

	PC1	PC2	PC3	PC4	PC5
ACI	7.78	23.17	43.40	24.48	0.99
ADI	20.88	15.00	5.87	12.84	1.72
AEI	22.00	16.29	0.39	7.47	0.01
BI	22.78	8.83	2.05	4.64	61.29
H	23.22	0.18	8.46	50.02	17.89
NDSI	3.34	36.53	39.82	0.56	18.09

Table 4. Correlation coefficients between the first three PCs and acoustic indices (Spearman's rank correlation coefficient).

	ACI	ADI	AEI	BI	H	NDSI
PC1	0.47	−0.89	0.86	0.80	−0.85	0.55
PC2	0.61	0.25	−0.33	0.41	0	0.69
PC3	−0.48	−0.20	0.15	0.22	0.13	0.34

NDSI is calculated using anthrophony and biophony and is often used as an indicator of anthropogenic sound disturbance. NDSI takes a value from −1 to +1. A value of +1 indicates the presence of only biophonic sounds, and a value of −1 indicates the presence of only anthropophonic sounds (Kasten et al., 2012). All the points where we made recordings are in the territory of the national park, where the anthropogenic sound disturbance is small. The recording point, which is closest to the sources of anthropogenic noise, is a point in a middle-aged oak forest. It is located 220 m from a rural settlement and a road with little traffic. All other points are located much further (up to 1.5–2.5 km). High NDSI values (from 0.656 ± 0.005 in clear-cut to 0.843 ± 0.005 in a mature forest) indicate the predominance of biophon-

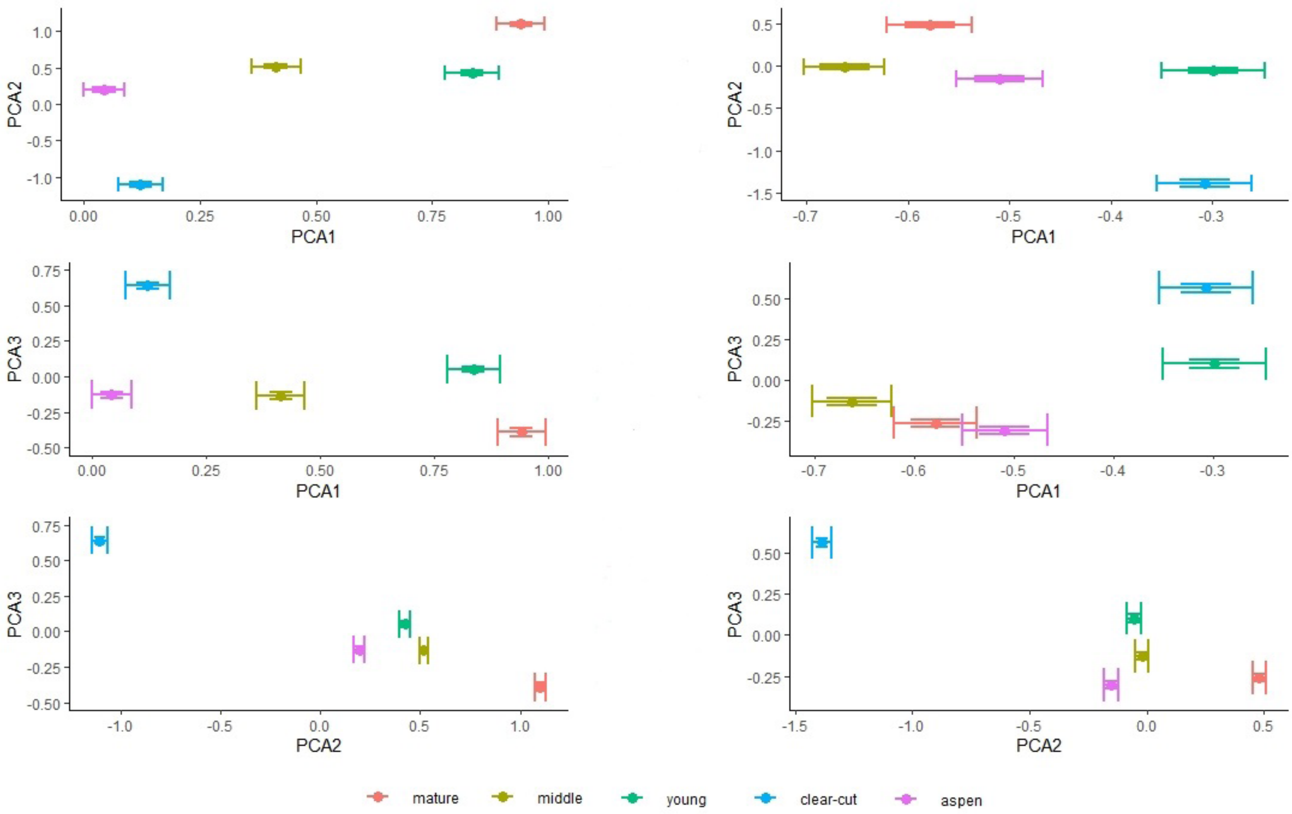

Fig. 3. Sites plotted based on average values on the first three principal component axes from the principal component analysis, with error bars denoting the standard error: in the morning (left) and in the evening (right).

ic sounds. These values may also reflect bird diversity, as NDSI reflects anthropogenic noise at low values (Gage, Axel, 2014) and bird species diversity at high values (Fuller et al., 2015).

Values of diversity-based indices (ADI and H) also increased with forest age. However, for these indexes, the effect size was medium and small, respectively. Unlike ACI, BI, and NDSI, the values of these indices were higher in the evening than in the morning for all types of forest. The values of the AEI were the opposite of H and ADI. They decreased with the increasing age of the forest. This pattern is attributed to the fact that the Gini coefficient, on which the ACI is based, is a mirror opposite of the Simpson diversity index, which is similar to the Shannon Index, on which H and ADI are based (Fuller et al., 2015).

It has been established that combinations of AIs are more effective for predicting bioacoustic activity than individual indices (Towsey et al., 2014; Buxton et al., 2018b). On the other hand, some indices are correlated with each other (Cifuentes et al., 2021; Lawrence et al., 2022). We grouped the indices using principal component analysis, which allowed us to reduce the number of variables while retaining a significant part of the variance of the original variables (≥80% for three PCs). When visually examining our plots along the first three axes of the PC, both in the morning hours and in the evening hours, we observed that the points corresponding to mature forest and clear-cut were located on opposite sections of the graph. The remaining plots (middle, young oak and aspen forests) occupied an intermediate position. This pattern was especially clearly observed in the morning hours along the PC2 and PC3 axes, which are associated with the ACI and NDSI indices. Our future work will be aimed at understanding the activity of which bird species cause such a pattern.

Ecoacoustics explores the sound landscape, which can be defined as the totality of sounds emanating from the landscape, consisting of sounds from physical (geophony), biological (biophony), and anthropogenic (anthrophony or technophony) sources (Pijanowski et al., 2011a; Farina, 2013). Biological sources include all living beings, regardless of their taxonomic affiliation. In the studied forests, the basis of biophony is the sounds of birds. Therefore, we tried to compare the values of AIs with the results of ornithological studies that were carried out earlier in this area.

In 2007-2009, point counts were carried out on this territory to obtain data on the species composition and population density of nesting birds. On an area of about 400 ha, 108 points were laid, and a threefold count was carried out during each nesting season (Atemasov et al., 2010, 2011). During these studies, there was no separation of credentials by age categories of the forest. However, primary accounting data allow us to calculate the population density and establish the number of species and density in oak forests of different ages (Fig. 4). Both the population density and the number of bird species were higher in mature, maturing and middle-aged oak forests and lower in young oak forests and overgrown clear-cuts. Aspen occupied an intermediate position. Thus, the results of the counts showed the same trend as the AIs, that is, the values decreased from old and middle-aged forests to younger forests and overgrown clear-cuts.

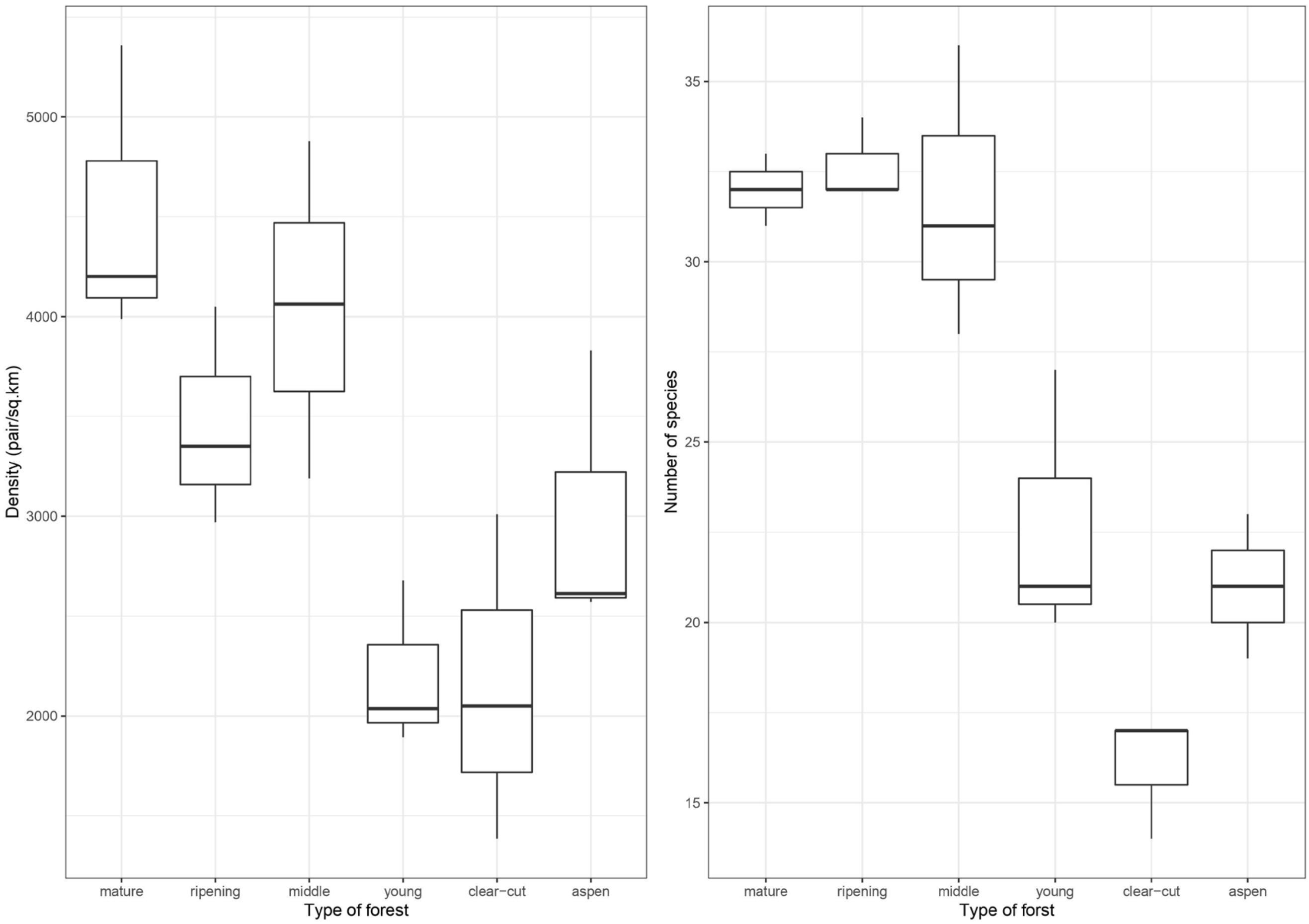

Fig. 4. Density (a) and number of species (b) of breeding birds in oak forests of different ages (calculated based on data from Atemasov et al., 2010, 2011).

It should be noted that both the census results and the values of the AIs obtained in the overgrown clear-cut are obviously somewhat overestimated. The clearing where the censuses were carried out and where the autonomous recorder was placed has a small area (5 ha) and an elongated shape (approximately 450 × 110 m). Both the researcher and the autonomous recorder registered birds singing outside the clearing in areas of old and maturing oak forests. Since the census option was used without limiting the registration band, species nesting on trees were recorded during the census: great spotted woodpecker (*Dendrocopos major*), Eurasian wryneck (*Jynx torquilla*), Eurasian nuthatch (*Sitta europaea*), great tit (*Parus major*), blue tit (*Cyanistes caeruleus*), collared flycatcher (*Ficedula albicollis*), hawfinch (*Coccothraustes coccothraustes*), Eurasian golden oriole (*Oriolus oriolus*), European goldfinch (*Carduelis carduelis*). The same species were registered on recordings made with the autonomous recorder.

Despite the many benefits of acoustic monitoring, there are also several potential limitations. One such limitation is the high cost of acoustic recording devices (Rhinehart et al., 2020; Toenies, Rich, 2021). However, in recent years, low-cost sound recorders based on microcomputers and microcontrollers have been developed. The most widely used among low-cost devices is AudioMoth (Hill et al., 2018, 2019). Despite its small size and price, AudioMoth has proven itself in a variety of acoustic monitoring projects (Prince et al., 2019). In some cases, the average number of species identified using AudioMoths exceeded the average number of species identified using more expensive recorders, as well as the results of point counts (Toenies, Rich, 2021). Our results also show that the data obtained with AudioMoth devices is generally consistent with both data obtained with more expensive devices (Atemasov, Atemasova, 2019) and the results of point counts (Atemasov et al., 2010, 2011).

Conclusion

The results of studies carried out using low-cost autonomous recorders show that the highest values of AIs were recorded in a mature oak forest and the lowest in an overgrown clearing. The results obtained are consistent with both the results of quantitative bird counts conducted earlier in this area and the results of studies obtained using more expensive devices. Thus, the values of AIs calculated for records obtained using low-cost autonomous recorders can serve as an indicator of the state of both bird communities in oak forests and ecosystems of oak forests in general.

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