Using acoustic indices in a protected wetland: a case study from Dragoman Marsh, Bulgaria

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Abstract. Protected areas are of crucial importance for biodiversity conservation, but reliable monitoring is often associated with great costs in terms of both funding and working hours. While in recent years a number of acoustic indices have been implemented for the purpose of passive monitoring of vocally active animal species, there is still insufficient data on the effects of interactions between different taxa and the influence of anthropogenic noise. This is especially true for diverse ecosystems such as wetlands, which provide a variety of habitats for both aquatic, semi-aquatic and terrestrial animals, and are generally characterized by high species richness. The aim of this study was to establish whether three commonly used acoustic indices would be able to differentiate between vocal activity of birds and other animals, as well as traffic noise generated by passing vehicles in the protected wetland of Dragoman Marsh, Bulgaria. Using recordings from a SongMeter SM4, we registered a total of 47 bird species from 27 families, and a single frog species. We calculated three acoustic indices: ACI, ADI and AE. Although some indices (i.e., ACI) correlated with species diversity and could potentially be used to detect increase in traffic intensity, they are unlikely to differentiate between avian and anuran vocal activity.

Keywords: anurans, bioacoustics, birds, species richness, traffic noise, wetlands.

1. Introduction

The establishment and management of protected areas is a key strategy in biodiversity conservation, and identifying conservation priorities is essential for balancing species protection with the often limited funds (Qu & Lu, 2018). Wetlands in particular play a crucial role in sustaining biodiversity of both terrestrial and aquatic species and at the same time are one of the most vulnerable and rapidly declining habitats in recent decades (Revenga et al., 2005). In recent years anthropogenic sound has become an ever-increasing threat to biodiversity on a global scale. Deteriorating acoustic conditions due to human activity can have a pronounced negative effect on animal communities, especially if they rely on vocalization in their social interactions (Pieretti & Farina, 2013). While there are a number of studies focused on individual response to anthropogenic noise in various animal taxa (reviews in Roca et al., 2016; Sordello et al., 2019), there is still a need of a focus shift from individual to community and landscape level, as these aspects have been largely neglected until very recently.

The relatively new subject area of soundscape ecology, i.e., the study of the relationship between a landscape and its sound composition, was first introduced by Pijanowski et al. (2011a,b) and later included in the main discipline of ecoacoustics (Sueur & Farina, 2015). The simple process of passive audio recording, combined with the appropriate analyses, could allow for the effective monitoring of complex animal communities, including their interactions with external influences, such as human activity (Farina et al., 2011; Pieretti & Farina, 2013).

A novel methodology to estimate vocal activity in avian communities using the newly developed Acoustic complexity index (ACI) was proposed by Pieretti et al. (2011). Since then, there has been a growing number of studies on soundscape and community acoustics, introducing various other indices and testing their correlation to bird diversity in different habitats, as well as their use in long-term monitoring (review in Alcocer et al. 2022). While there are studies focusing on the implementation of indices in urban environments (Fairbass et al., 2017), and on animals other than birds (Bolgan et al., 2018), there is currently a significant knowledge gap regarding monitoring complex ecosystems in terms of overall biodiversity assessment and anthropogenic pressure. A recent study on frog communities established that acoustic indices outperformed species richness and abundance metrics in estimating diversity from passive recordings (Desjonquères et al., 2020). This supports the idea that ecoacoustic measures can capture structural elements of community composition beyond simple taxonomic counts.

We tested three acoustic indices to assess (1) their correlation with avian species diversity, (2) their ability to distinguish between bird and frog vocal activity, and (3) their sensitivity to traffic noise. We postulate that in order for a passive acoustic monitoring to be effective, indices should not only be correlated to species diversity, but also be able to differentiate between bird and other (prominently, anuran) vocal activity and technophonies generated by passing vehicles.

2. Materials and methods

2.1 Study sites

The Dragoman Marsh is the biggest karst marsh in Bulgaria and the largest natural wetland in the Sofia district. It is situated 38km to the North-west of the capital city of Sofia, in a large valley surrounded by limestone ridges, and has a total surface area of 350 hectares (it spreads 2.5km in West-East direction and 1.2km in North-South direction). Hills around the marsh provide grassland and forest habitats, ensuring that other species are present in addition to the typical wetland inhabitants. A total of 237 bird species and seven anuran species have been observed there (Shurulinkov et al., 2007; Balkani Wildlife Society database – unpubl.). It is part of the NATURA 2000 network of protected areas (as a part of two protected areas – Rayanovtsi for birds and Dragoman for habitats), as well as a site listed under Ramsar Convention on Wetlands of International Importance (“Dragoman Marsh Karst Complex”).

The bird taxonomy used in the present paper follows HBW & BirdLife International (2024).

2.2 Data collection

We used a SongMeter SM4 digital recording device (WildlifeAcoustics, Maynard, MA, USA) to obtain records of vocal activity during the months of April and October 2018. Recordings were made as PCM-WAV files (48 kHz sampling rate, 16 bits, stereo mode) divided into recordings of 30 min duration. The location to position the recorder was specifically chosen to be in close proximity to the marsh, the surrounding heights and an asphalt road (Fig. 1). Mean value for sound pressure level (SPL) of the environmental noise (generated mainly by wind, birds and frogs, with only occasional passing vehicle) during the course of the study was 40 dB(A). Fuller et al. (2015) postulate the need to better understand temporal partitioning of the soundscape by specific taxonomic groups, including amphibians, insects and birds during a 24 h cycle, and for this reason recordings were made on a continuous basis during the study period (equal samples of 42 hours in April and 42 hours in October).

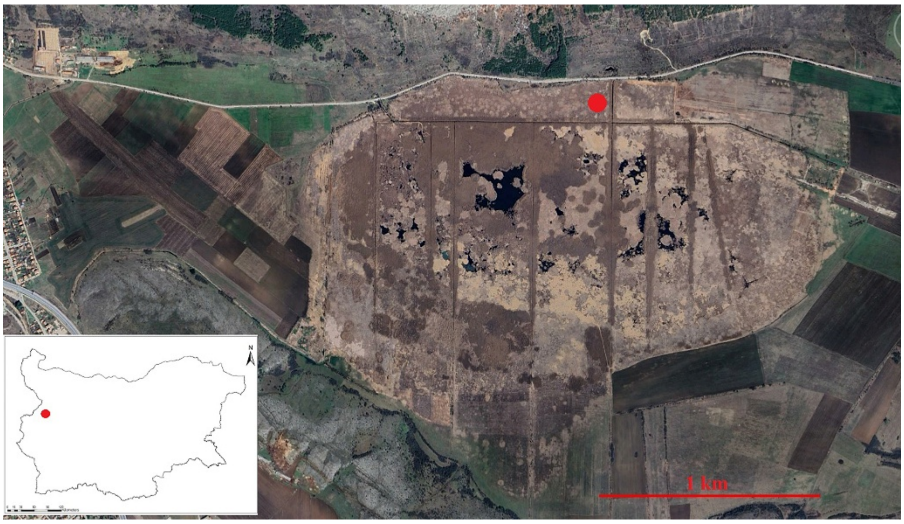

Figure 1. Location of the study site and position of the audio recorder.

2.3 Data analysis

Recordings were analysed manually and automatically. During the manual analysis, specific effort was made to distinguish audio files with predominant frog choruses, which were then analysed separately from the others. A sample with duration of 5 min was randomly selected from each audio file. The procedure consisted of listening to recorded sounds and simultaneously analysing a spectrogram created with Soundruler v. 0.9.6.0 software (Gridi-Papp et al., 2007). When possible, all records were identified to a species level, after which species richness and species diversity were estimated separately for each month. Diversity was calculated using the Shannon-Wiener Diversity index, $H' = -\sum(pi * \ln(pi))$, where pi =

proportion of species i. During manual analysis, special effort was made to identify recordings dominated by frog choruses, which were subsequently analyzed as a separate category. This separation was necessary to examine whether acoustic indices can differentiate between taxonomic groups (birds vs. frogs), given their potentially overlapping frequency ranges. Identifying frog-dominant segments ensured that comparisons were not confounded by mixed-source recordings. To stabilize variance and normalize the distribution of the index for regression analysis, we applied a natural logarithmic transformation to the H′ values prior to statistical analysis and visualization.

For the automated acoustic analysis, we used WaveSurfer version 1.8.8 with the SoundMeter plugin (Farina et al., 2012), which provides calculations of several ecoacoustic indices. Specifically, we extracted three indices: Acoustic Complexity Index (ACI), Acoustic Diversity Index (ADI), and Acoustic Evenness (AE). ACI estimates the variability in amplitude between successive time steps within frequency bins, and reflects the complexity of the soundscape. In our analysis, we used a variation of ACI that measures complexity occurring within a single amplitude clump inside each frequency bin, as implemented by the plugin. ADI is based on the Shannon entropy of the distribution of sound energy across frequency bands, and captures how diverse the spectral content is in a given recording (Sueur et al., 2008). AE, in this plugin implementation, measures the evenness of ACI values across frequency bands, rather than the raw amplitude distribution — a slightly different formulation from Gini-based versions in other toolkits (Farina et al., 2012).

For each recording, we randomly extracted a 30-second sample and processed it using the plugin's "Compute multiple SCM files" function with the following settings: 1) Noise filter: 5000; 2) FFT window length: 512 samples (as recommended by Farina et al., 2012); 3) Lowest frequency: 100 Hz; 4) Highest frequency: 10,000 Hz. This procedure was applied to five sets of recordings: 1) Birds (April); 2) Birds (October); 3) Frogs; 4) Traffic noise (recorded and calibrated at 40 dB SPL @ 1 m); 5) Control (a baseline recording with no biotic or anthropogenic noise). For the Traffic noise set, we applied a threshold of 1.5 kHz, based on the observation that most vehicular sounds occupy the 1–3 kHz range — a practical proxy for anthropogenic interference (Goodwin & Shriver, 2011; Summers et al., 2011).

The calculations followed published algorithms for these indices (see Farina et al., 2012; Sueur et al., 2008). The goal was not to derive absolute values, but to compare relative patterns of acoustic complexity and diversity across taxonomic groups and recording conditions. The resulting indices were analyzed with the STATISTICA v.7.0 software (StatSoft, Inc. 2004), with chosen alpha level for statistical significance of $p<0.05$. Data were tested for normality with the Shapiro-Wilk test and the null hypothesis was rejected. A Spearman rank correlation coefficient was used to evaluate associations between indices and species richness and species diversity. In order to test for differences between indices calculated from different sets of recordings, a Kruskal-Wallis ANOVA and Multiple comparisons of mean ranks for all groups were performed for the whole dataset with Type as a grouping variable.

3. Results

A total of 47 bird species, belonging to 27 families, were registered from the audio recordings – 34 in April and 24 in October; of these, 13 species were recorded only in October, 11 were observed in both months, and 23 were recorded only in April (Table 1). In April the number of registered bird species per audio file varied between 2 and 15, while for October these were 0 and 10. The only non-avian vocally active species present on the recordings was the Eastern treefrog (*Hyla orientalis*). Frog choruses were prominent in the April recordings, especially during peak calling hours (19h-00h).

Table 1. List of bird species registered in the manual analysis of the audio recordings.

Species	**Family**	**Month**

Mallard (*Anas platyrhynchos*)	Anatidae	April, October
Little Grebe (*Tachybaptus ruficollis*)	Podicipedidae	April
Wood Pigeon (*Columba palumbus*)	Columbidae	April
Western Water Rail (*Rallus aquaticus*)	Rallidae	April, October
Common Cuckoo (*Cuculus canorus*)	Cuculidae	April
Common Moorhen (*Gallinula chloropus*)	Rallidae	April
Eurasian Coot (*Fulica atra*)	Rallidae	April
Eurasian Bittern (*Botaurus stellaris*)	Ardeidae	April
Grey Heron (*Ardea cinerea*)	Ardeidae	October
Eurasian Scops-owl (*Otus scops*)	Strigidae	April
Tawny Owl (*Strix aluco*)	Strigidae	April
Eurasian Eagle-owl (*Bubo bubo*)	Strigidae	April, October
Short-toed Snake-eagle (*Circaetus gallicus*)	Accipitridae	April
Eurasian Buzzard (*Buteo buteo*)	Accipitridae	October
European Bee-eater (*Merops apiaster*)	Meropidae	April
Eurasian Green Woodpecker (*Picus viridis*)	Picidae	October
Lesser Spotted Woodpecker (*Dryobates minor*)	Picidae	April
Eurasian Jay (*Garrulus glandarius*)	Corvidae	April, October
Eurasian Magpie (*Pica pica*)	Corvidae	April
Common Raven (*Corvus corax*)	Corvidae	April
Hooded Crow (*Corvus corone cornix*)	Corvidae	April
Eurasian Blue Tit (*Cyanistes caeruleus*)	Paridae	October
Great Tit (*Parus major*)	Paridae	April, October
Eurasian Skylark (*Alauda arvensis*)	Alaudidae	October
Bearded Reedling (*Panurus biarmicus*)	Panuridae	October
Common Reed-warbler (*Acrocephalus scirpaceus*)	Acrocephalidae	April
Great Reed-warbler (*Acrocephalus arundinaceus*)	Acrocephalidae	April
Savi’s Warbler (*Locustella luscinioides*)	Locustellidae	April
Barn Swallow (*Hirundo rustica*)	Hirundinidae	April
Common Chiffchaff (*Phylloscopus collybita*)	Phylloscopidae	April, October
Long-tailed Tit (*Aegithalos caudatus*)	Aegithalidae	April
Lesser Whitethroat (*Curruca curruca*)	Sylviidae	April
Northern Wren (*Troglodytes troglodytes*)	Troglodytidae	October

Mistle Thrush (*Turdus viscivorus*)	Turdidae	October
Eurasian Blackbird (*Turdus merula*)	Turdidae	April, October
European Robin (*Erithacus rubecula*)	Muscicapidae	October
Common Nightingale (*Luscinia megarhynchos*)	Muscicapidae	April
Common Stonechat (*Saxicola torquatus*)	Muscicapidae	April
Dunnock (*Prunella modularis*)	Prunellidae	October
Water Pipit (*Anthus spinoletta*)	Motacillidae	October
Common Chaffinch (*Fringilla coelebs*)	Fringillidae	April, October
Brambling (*Fringilla montifringilla*)	Fringillidae	October
Hawfinch (*Coccothraustes coccothraustes*)	Fringillidae	October
European Greenfinch (*Chloris chloris*)	Fringillidae	April, October
Common Linnet (*Linaria cannabina*)	Fringillidae	April, October
European Goldfinch (*Carduelis carduelis*)	Fringillidae	April, October
Ortolan Bunting (*Emberiza hortulana*)	Emberizidae	April

As expected, bird species richness and species diversity were highly correlated ($r=0.99$, $p<0.001$), and for further analyses species diversity was used. All three indices demonstrated statistically significant positive correlation to species diversity, and although Spearman's r values were relatively low in the case of ADI, p values were very reliable (Table 2, Fig. 2).

Table 2. Correlations between acoustic indices and bird species diversity for April and October. Value data for the indices is presented as Mean (Min-Max ± SD).

	Spearman - r	**t(N-2)**	**p-value**
ADI	0.396	3.453	p<0.001
ACI	0.533	5.039	p<0.001
AE	0.595	5.927	p<0.001

All three acoustic indices were significantly correlated with bird species diversity. ACI showed the strongest correlation ($r = 0.533$, $p < 0.001$), followed by AE ($r = 0.595$, $p < 0.001$), and ADI (r = 0.396, p < 0.001). Despite ADI's lower correlation strength, the p-value remained highly significant, reflecting a consistent positive trend across recordings from both April and October.

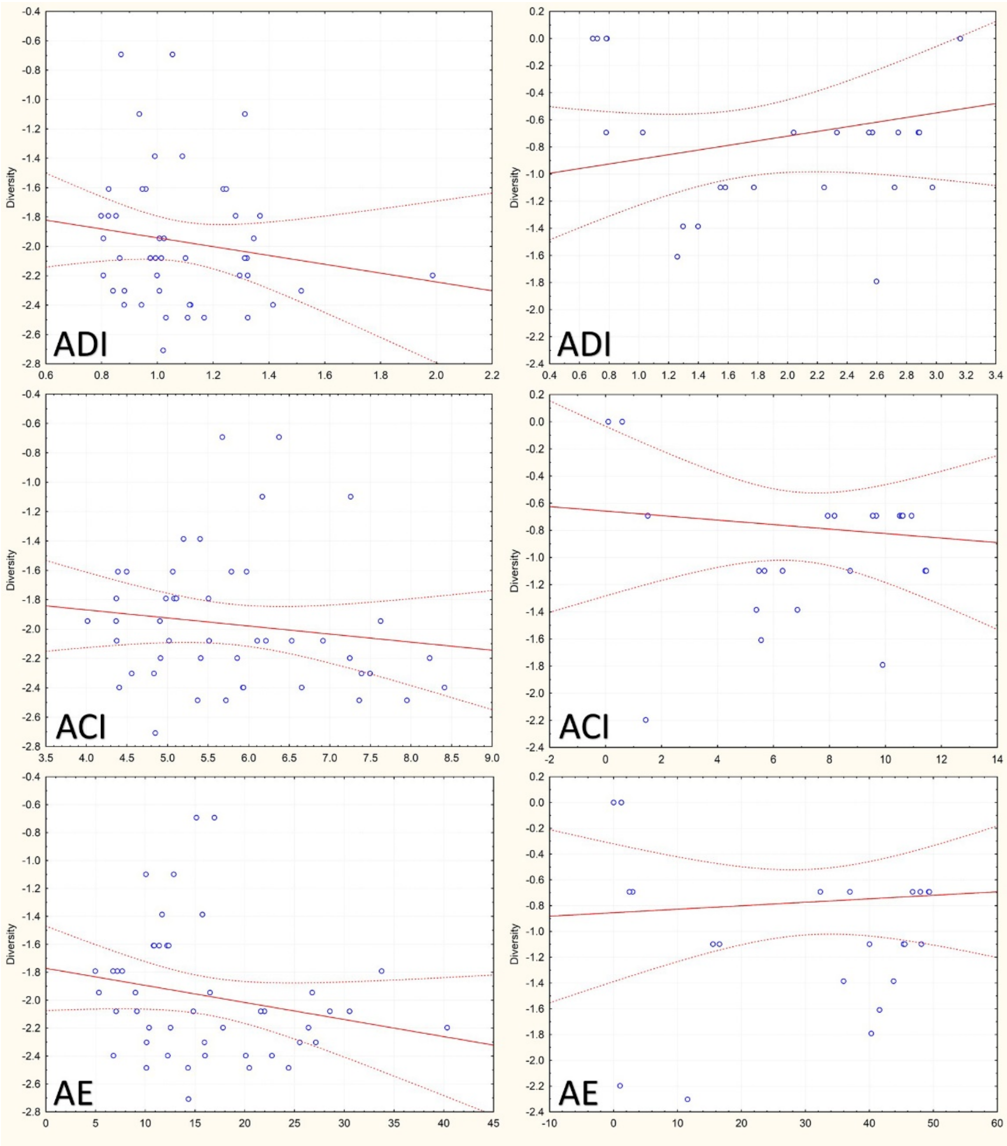

Figure 2. Correlations between the three indices and Shannon-Wiener bird species diversity in April (left) and October (right). Straight lines represent the linear regression slope and curved lines indicate the 95% confidence intervals.

Results from the Kruskal-Wallis ANOVA revealed that indices differed significantly across different sets of recordings (ADI H(4)=91.586, p<0.001; ACI H(4)=57.405, p<0.001; AE H(4)=81.783, p<0.001). All three indices from the control recording were significantly different to all other recordings, while results from the comparison between the other sets of recordings were mixed (Table 3). A Kruskal-Wallis ANOVA revealed significant differences in all three indices across recording types (ADI: H = 91.586, p < 0.001; ACI: H = 57.405, p < 0.001; AE: H = 81.783, p < 0.001). Post-hoc tests showed that all three indices clearly distinguished the Control recordings from other categories (p < 0.001). ADI values for Traffic noise differed significantly from all biotic categories. However, no significant difference was found between bird and frog recordings for any of the indices, except for AE in October (p = 0.034).

Table 3. Multiple comparison of acoustic indices across different sets of recordings. Statistically significant results are in bold and italic. Apr – April, Oct – October.

	Birds (Apr)		**Birds (Oct)**		**Frogs**		**Traffic noise**	
	Z	**p**	**Z**	**p**	**Z**	**p**	**Z**	**p**
ADI								
Birds (Apr)	-	-	3.649	***0.002***	0.935	1.000	6.526	***<0.001***
Birds (Oct)	3.649	***0.002***	-	-	1.302	1.000	4.602	***<0.001***
Frogs	0.935	1.000	1.302	1.000	-	-	4.453	***<0.001***
Traffic noise	6.526	***<0.001***	4.602	***<0.001***	4.453	***<0.001***	-	-
Control	3.937	***<0.001***	6.945	***<0.001***	3.845	***<0.001***	8.678	***<0.001***
ACI	-	-	3.106	***<0.019***	1.531	1.000	1.602	1.000
Birds (Apr)	3.106	***<0.019***	-	-	0.326	1.000	0.304	1.000
Birds (Oct)	1.531	1.000	0.326	1.000	-	-	0.025	1.000
Frogs	1.602	1.000	0.304	1.000	0.025	1.000	-	-
Traffic noise	4.631	***<0.001***	7.300	***<0.001***	4.900	***<0.001***	5.026	***<0.001***

Control								
AE								
Birds (Apr)	-	-	5.585	***<0.001***	0.554	1.000	3.183	***0.015***
Birds (Oct)	5.585	***<0.001***	-	-	2.926	***0.034***	0.223	1.000
Frogs	0.554	1.000	2.926	***0.034***	-	-	2.091	0.365
Traffic noise	3.183	***0.015***	0.223	1.000	2.091	0.365	-	-
Control	3.545	***<0.001***	7.937	***<0.001***	3.210	***<0.001***	5.551	***<0.001***

Three main results could be outlined: 1) All three indices exhibited statistically significant differences between bird recordings from April and October; 2) With a single exception (AE for birds in October), there were no significant differences between indices from bird recordings and frog choruses; 3) ADI was the only index in which values for Traffic noise were significantly different to every other set of recordings.

3. Discussion

Our findings show that none of the tested indices reliably distinguished between bird and frog vocalizations. Results from Indraswari et al. (2018) demonstrated that acoustic indices could not reliably distinguish between frog species with overlapping call frequencies. In our study, the frequency overlap between birds and frogs (~2–3 kHz) likely limited the ability of the indices to separate vocalization types, reinforcing the need for cautious interpretation of index-based diversity estimates. In contrast, ADI consistently yielded significantly different values for traffic noise compared to all other categories ($p < 0.001$), suggesting its potential utility for detecting anthropogenic acoustic disturbances. However, this does not imply species-specific sensitivity — rather, it reflects spectral simplicity and energy concentration in traffic noise. In the decision-making process concerning conservation, there is a certain temptation to use a single and easy to understand value on which to base recommendations and future activities, especially in regards to environmental policy and management plans (Magurran et al., 2010). Perhaps for this reason, in the beginning of soundscape studies, usually a single index was tested, and the existing several indices were rarely used together (Seuer et al., 2014). Still, the development of acoustic indices for biodiversity assessment and landscape ecology could be considered as a new stage of development in the field of ecoacoustics, as collecting reliable data of this type over large areas and long time periods is a major issue in ecology (Greenwood & Robinson, 2006).

In the last few years, there is a positive trend to include and compare different indices in a single study, which provides much better understanding of the complex landscape sound composition. Mammides et al. (2017) used seven acoustic indices and tested whether they were correlated to bird diversity in two regions in the most biodiverse-rich province of China. They established that relationships between the tested indices and bird diversity varied considerably depending on the index examined, the region, and the season; two of the three indices that performed best in their research were also used in the current study – ADI and AE. ADI has also been highlighted as a good indicator for bird species diversity both in the tropical regions of the Brazilian Cerrado (Machado et al., 2017) and in the temperate forests of Poland (Budka et al., 2023). In view of the above, our results of positive correlation between the three tested indices and bird diversity in the study region comes as no surprise. What is surprising is that, with a single exception for October (and even this was only marginally significant at $p=0.034$), all three indices did not differ significantly between bird and tree frog recordings. A possible reason for this result could be that while structurally very different, both bird and tree frog calls fall within roughly the same frequency limits (i.e., around 2-3 kHz; Gerhardt & Schwartz, 2001). When wetlands are considered, one should never expect to record birds only, as these types of habitats are also home to other highly vocal aquatic and semi-aquatic animals such as frogs and insects. To our knowledge, this is the first study that attempts to compare acoustic indices in terms of their ability to differentiate between bird and frog vocalizations.

Although the use of acoustic indices in ecological studies has increased in recent years, there are still very few cases when the influence of anthropogenic noise has been specifically targeted. Fairbrass et al. (2017) employed four indices (incl. ACI and ADI) to measure biodiversity in urban areas, reaching the conclusion that while ACI was positively correlated to biotic activity, the tested indices were not suitable for monitoring biodiversity in anthropogenically dominated habitats. The site in our study exhibited relatively low environmental noise levels, primarily of natural origin, with passing vehicles and airplanes contributing some anthropogenic noise. For this reason, we sought to determine whether the tested acoustic indices could be used to detect increases in traffic intensity. Achieving this would benefit conservation efforts, as traffic intensity is negatively related to species richness and diversity, affecting species composition and population sizes (e.g., Patricelli & Blickley, 2006; Newport et al., 2014). On individual scale, increased noise levels are known to cause shift in frequency not only in birds (e.g., Slabbekoorn & den Boer-Visser, 2006) and anurans (e.g., Zhao et al., 2018), but also in some vocally active invertebrates (e.g, Duarte et al., 2019), negatively affecting species reproduction. Our results indicate that ADI could potentially be useful in such efforts, as measurements from traffic noise were consistently different to all other sets of recordings. However, there is a need for additional research before any definite conclusions could be made – especially considering that bird singing performance could be more active in the presence of more intense noise (Pieretti & Farina, 2013).

The use of a single recording device in a 350-hectare area presents a limitation in spatial coverage. Although the placement was selected to include diverse acoustic sources (marsh, road, hills), the data collected may not be representative of the entire wetland soundscape. Sensor placement significantly affects index outputs, and acoustic conditions can vary substantially over short distances in heterogeneous environments like wetlands. The analysis was based on 84 hours of recordings across two time points (April and October), which is insufficient to capture daily and seasonal variability in acoustic activity. Therefore, our findings should be interpreted as localized and may not generalize across the full extent of Dragoman Marsh. In conclusion, it could be stated that acoustic indices can be used as proxies for evaluating bird species diversity in wetlands, as they reliably differentiate between higher (i.e., April) and lower (i.e., October) species richness and diversity. The Acoustic diversity index also performed well to distinguish biotic (bird songs and calls, frog chorus) from abiotic (traffic noise) sounds, suggesting it could potentially be useful in detecting increased traffic. However, frog choruses should always be considered when monitoring wetland habitats – acoustic indices alone could not reliably differentiate between frog and bird vocal activity. One likely explanation is the spectral overlap between bird and frog vocalizations, particularly in the 2–3 kHz range. Many anuran species produce calls in frequencies similar to passerines, which complicates frequency-based discrimination by acoustic indices. Since the ACI, ADI, and AE are not designed to capture fine-scale spectral or temporal differences, their performance may be inherently limited in multi-taxa environments like wetlands. It is important to emphasize that our results are highly site-specific and context-dependent, reflecting the soundscape and species composition of a single wetland (Dragoman Marsh) during limited time periods. Different ecosystems and seasons may yield different acoustic patterns and index behaviours.

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