

Acoustic monitoring of avifauna in the Bukovynian Carpathians during spring: effectiveness assessment in anthropogenically transformed mountain ecosystems

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Abstract Today, technologies exist that allow for the efficient monitoring of large areas from both economic and practical perspectives. Our study is the first to investigate the species diversity of birds in the anthropogenically transformed ecosystems of the Bukovynian Carpathians by using the Song Meter Micro acoustic receiver from the American company, Wildlife Acoustics. The material analyzed in the study consists of audio files ($n=843$) with a total duration of 204 minutes, recorded in April 2023 at 14 locations in the anthropogenically transformed ecosystems of the Bukovynian Carpathians, Ukraine. The data were analyzed using two approaches: the BirdNET application, which operates based on machine learning algorithms and artificial intelligence, and the Raven Pro software. In the second approach, the resulting sonograms were compared with the reference database of xeno-canto. The similarity of the avifauna species composition at different monitoring points was determined using binary similarity indices such as Jaccard and Sørensen–Czekanowski, as well as the Stugren–Radulescu coefficient. The highest similarity was observed between two sites within the area of a national park (Jaccard = 0.43). In contrast, the lowest similarity was recorded between these sites and a remote site outside the national park (Jaccard = 0.13). The species richness of birds at different locations was analyzed and compared using the Menhinick index. As a result of the study, 58 bird species were identified, 10 of which were recorded for the first time in the research region. These findings highlight the rich avian biodiversity of the study area and emphasize the importance of continued monitoring.

Keywords: ornithofauna, Song Meter Micro, sonograms, audio recordings, acoustic research, transformed landscapes

Összefoglalás Napjainkban olyan technológiák állnak rendelkezésre, amelyek gazdasági és gyakorlati szempontból is hatékonyan teszik lehetővé nagy területek megfigyelését. Tanulmányunk az első, amely a Bukovinai-Kárpátok antropogén módon átalakított ökoszisztémáiban élő madárfajok sokféleségét vizsgálja az amerikai Wildlife Acoustics vállalat Song Meter Micro akusztikus vevőjének felhasználásával. A tanulmányban elemzett anyag 843 hangfájlból áll, összesen 204 percnyi felvétellel, amelyeket 2023 áprilisában rögzítettünk Ukrajnában, a Bukovinai-Kárpátok ember által átalakított ökoszisztémáinak 14 helyszínén. Az adatokat a mesterséges intelligencián alapuló gépi tanulási algoritmusokat alkalmazó BirdNET alkalmazással, valamint a Raven Pro szoftverrel elemeztük. Az így kapott szonogramokat összehasonlítottuk a xeno-canto referenciadatbázisával. A különböző megfigyelési pontokon rögzített madárfauna fajösszetételének hasonlóságát bináris hasonlósági indexek, a Jaccard- és Sørensen–Czekanowski-index, valamint a Stugren–Radulescu-együttható segítségével határoztuk meg. A madárfaj-gazdagságot a különböző helyszíneken a Menhinick-index alkalmazásával elemeztük és hasonlítottuk össze. A vizsgálat eredményeként 58 madárfajt azonosítottunk, amelyek közül 10-et először jegyeztek fel a vizsgált térségben. Ezek az eredmények kiemelik a vizsgált terület gazdag madárbiodiverzitását, és hangsúlyozzák a folyamatos monitorozás fontosságát.

Kulcsszavak: madárfauna, Song Meter Micro, szonogramok, hangfelvételek, akusztikus kutatás, átalakított tájak

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Introduction

Ecosystems worldwide are undergoing global anthropogenic changes due to human interference with their functioning, as well as alterations to the climate and landscape (Maina 2016), which can significantly impact species distribution and, in some cases, lead to extinction (Rajan *et al.* 2024). Traditional approaches to the monitoring of biodiversity involve studying species diversity within the ecosystem of interest (Lawton *et al.* 1998). This requires trained experts to invest substantial time in conducting research.

Monitoring vulnerable species inhabiting mountain ecosystems is an extremely important yet challenging task, enabling the tracking of population trends and the identification of conservation priorities (Serrurier *et al.* 2024). Researchers have long focused on developing more effective approaches to biodiversity monitoring that are less time-consuming (Kerr *et al.* 2000). Passive acoustic monitoring has emerged as a less labor-intensive and more accessible alternative to traditional biodiversity monitoring methods, such as visual observations (e.g. transect or point counts) and mist-netting. It also enables long-term data collection with minimal disturbance to the environment and can accumulate valuable data across large spatial and temporal scales (Serrurier *et al.* 2024). Moreover, data collection can be performed by individuals trained to operate recording devices without the need for expert ornithologists in the field, saving time and resources (Maina 2015, 2016). Audio recordings can be stored indefinitely and analysed later using specialised software by professionals in controlled, non-field environments, which is especially valuable in remote or logistically challenging mountainous ecosystems (Brandes 2008, Celis-Murillo *et al.* 2009, Chamberlain *et al.* 2012, Serrurier *et al.* 2024, Yuzyk 2024). Moreover, the successful application of the method requires proper planning and analysis of the results, which can be used for further biodiversity conservation (Teixeira *et al.* 2024).

Acoustic recordings enable the identification of bird species and their abundance. The recordings can be analysed by an expert or processed using specialised software. Researchers consider acoustic biodiversity monitoring to be a promising research method (Sueur *et al.* 2008, Pieretti *et al.* 2011, Maina 2016, Turner *et al.* 2022), as well as effective for bridging knowledge gaps regarding nocturnal bird migration (Horton *et al.* 2015).

This approach has several advantages: 1) audio recordings may be archived as evidence of the ecosystem's state at the time of research; 2) data collection does not require experts – people making the recordings only need to be trained in using the equipment correctly; 3) acoustic recordings can be used both for large-scale biodiversity assessments (Sueur *et al.* 2008, Pieretti *et al.* 2011) and for the review of individual species (Zwart *et al.* 2014). However, audio data analysis is labour-intensive, requires expert knowledge, and the time required for “scanning” spectrograms can exceed the recording duration by 2–3 times (Pamula *et al.* 2020).

Recording time can influence bird song activity, making proper scheduling important for reliable data collection. This raises a key research question: how effective is acoustic monitoring for detecting and assessing bird diversity during spring in anthropogenically transformed mountain ecosystems of the Bukovynian Carpathians?

In light of the above, the aim of this work was to conduct acoustic research on common bird species, which in this context refers to all bird species that collectively form the prevailing soundscape of the studied ecosystems at the time of recording, in the anthropogenically transformed ecosystems of the Bukovynian Carpathians, in order to determine the species composition of the avifauna, its similarity, and its richness at different monitoring points.

Material and Methods

Study area

Acoustic monitoring of common bird species was conducted at 14 points in the Bukovynian Carpathians (Ukrainian Carpathians, Chernivtsi Region, Ukraine). The coordinates of the locations are as follows:

- I) near the rented administrative building of the National Park (NP) «Cheremoskyi» in the settlement of Putyla – 25.08763 E, 48.00082 N;
- II) a private estate with a small photovoltaic solar power plant – 25.086049 E, 47.992403 N;
- III) along the Sarata River:
 - 24.95854 E, 47.80450 N;
 - 24.96240 E, 47.79931 N;
 - 24.96744 E, 47.79433 N;
 - 24.96562 E, 47.79678 N;
 - 24.98327 E, 47.77551 N;
- IV) near the administrative building of the Perkalab Environmental Research Department (ERD) of the NP «Cheremoskyi»:
 - 24.95964 E, 47.80536 N;
 - 24.98292 E, 47.78368 N;
- V) in the Vakarca tract, quarters 37, 46 of the Selyatyn ERD of the NP «Cheremoskyi»:
 - 25.02868 E, 47.75757 N;
 - 25.02518 E, 47.75667 N;
 - 25.02302 E, 47.75352 N;
 - 25.02177 E, 47.75099 N;
 - 25.01882 E, 47.74924 N (*Figure 1*).

The distance between neighbouring points along the Sarata River, within the Perkalab ERD, and in the Vakarca tract averaged approximately 500 m. The points near the NP “Cheremoskyi” administrative building in Putyla and within the photovoltaic solar power plant area were about 1500 m apart. The monitoring sites were located in areas with different types of land cover, including built-up areas, riparian habitats (floodplain meadows, riverbank shrubs, and wet vegetation), and mountain spruce forests.

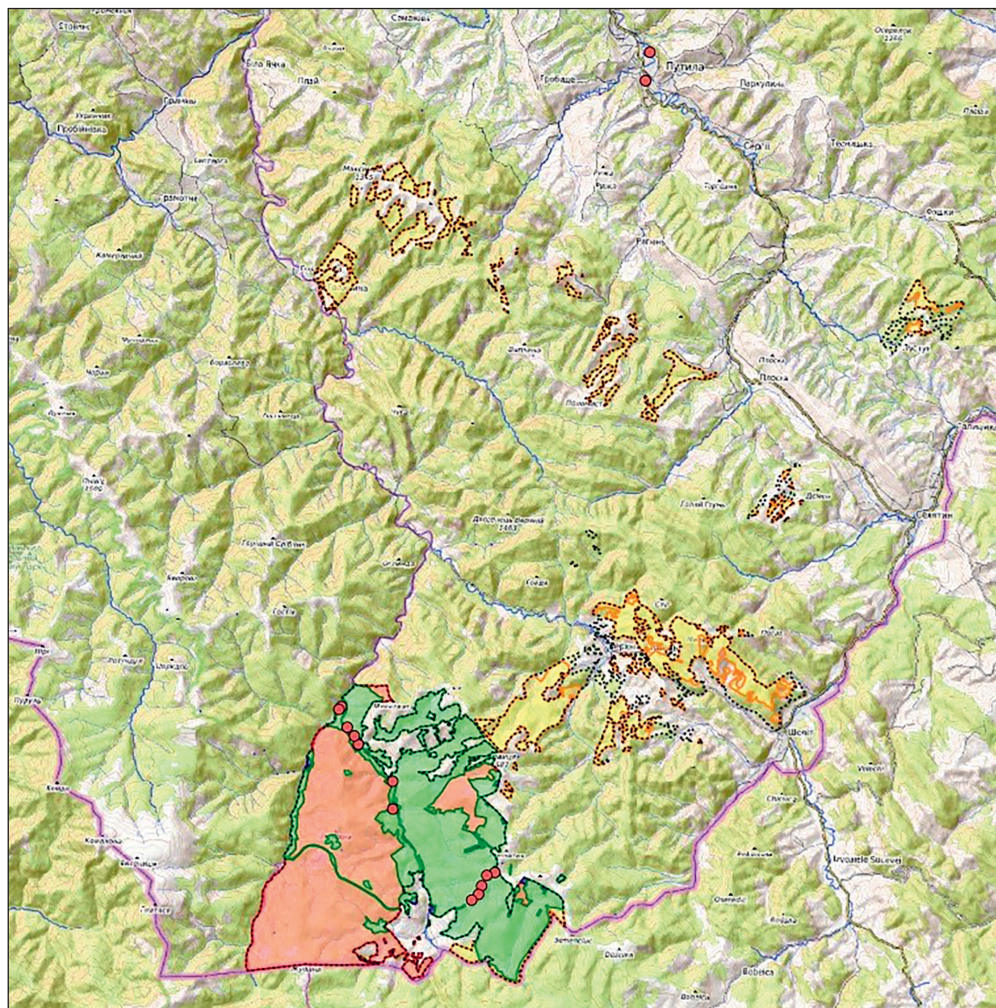


Figure 1. Map of acoustic monitoring sites in the Bukovynian Carpathians, Chernivtsi region, Ukraine. The sites are located near the border with Romania

1. ábra Akusztikus megfigyelési pontok térképe a Bukovinai-Kárpátokban, Ukrajna Csernyivci megyéjében. A helyszínek Románia határához közel helyezkednek el

Sound recording and analysis

The recordings were carried out within the framework of the Pan-European Common Bird Monitoring Scheme (Vysochyn *et al.* 2023, Yuzyk & Yuzyk 2023) using a Song Meter Micro acoustic receiver, provided by the Frankfurt Zoological Society. The receiver was configured outside of field conditions using the Song Meter app.

The analysis is based on research results that include 15 sound recordings made at 14 monitoring points (one point had two recordings). Some recordings were conducted in the morning, others in the evening, between 25 April and 28 April 2023, inclusive. The total

duration of the recordings was 204 minutes, with an average length of approximately 13 minutes per recording. During the identifying process using the BirdNET-Analyzer and Raven Pro software, the recordings were automatically split into separate audio files of about 3 seconds each. This segment length was chosen as it provides sufficient duration for accurate species song recognition while minimizing overlap with vocalizations of other species. A confidence threshold of 0.10 was applied, and no additional noise filters were used during analysis. All other settings were left at their default values. This segmentation approach resulted in a total of 843 individual audio files. The resulting audio and text files were used for further analysis.

The taxonomic affiliation and scientific names of bird species identified from the analysis of sound recordings are provided according to the classification system presented in the Handbook of the Birds of the World (del Hoyo *et al.* 1992–2011), in accordance with scientific work on avian taxonomy in the region (Fesenko & Shydlovskyi 2017), adhering to the International Code of Zoological Nomenclature.

The collection and processing of research materials were carried out in accordance with ethical standards for animal treatment.

Data analysis

Additional data analysis was conducted using Raven Pro software, which specialises in processing and analysing sound recordings. The sonograms obtained from the processed sound files were thoroughly examined and compared with the existing samples in the reference database xeno-canto (Xeno-canto 2024). Xeno-canto is an international database containing a vast collection of bird vocalisations from various parts of the world. Utilising this database allows for the accurate identification of sounds by comparing them with already known samples, thereby enhancing the precision and reliability of bird identification.

To verify the accuracy of species identification based on acoustic data, direct field observations were conducted simultaneously with sound recordings at monitoring locations III, IV, and V, and the results were subsequently compared. Observations were carried out by two experienced ornithologists (the authors of this study) using the point-count method, with a fixed survey strip width of 50 meters. During each session, all bird species detected visually or by ear were systematically recorded in field notebooks. When possible, individual birds were also photographed to document species presence. These observational data were subsequently compared with the results of automated acoustic analyses. Species identified in the recordings were cross-checked against field observations made at the same time and location, allowing for the evaluation and validation of the acoustic identification results.

Statistical analysis

For all bird species identified by the BirdNET and Raven Pro software, the average identification confidence score was calculated. This value includes both correctly and incorrectly identified species, based on expert validation involving comparison with

reference sonograms and auditory examination. In calculating the mean identification value, both correct and erroneous identifications assigned by the software to a given species were considered. Reference recordings from the xeno-canto database were used for verification. The final average confidence scores were calculated in Microsoft Excel. The closer the value is to 1, the higher the probability of correct species identification.

The similarity of the avifaunal composition at different monitoring points was assessed after verification of the automatic recognition results, which included comparison with reference sonograms and expert listening. To quantify the similarity in species composition between pairs of locations, two widely used binary similarity indices were applied: the Jaccard index and the Sørensen–Czekanowski index. These indices were calculated according to the following formulas:

$$Kj = \frac{c}{a+b-c}, Ks = \frac{2c}{a+b}$$

where a is the number of species at the first location, b is the number of species at the second location, c is the number of species common to both the first and second locations (Meharrran 1992). The Jaccard index is often used for its strict mathematical formulation, while the Sørensen–Czekanowski index is more sensitive to shared species due to its weighting. Using both indices allows for a more comprehensive and cross-validated assessment of species similarity, as they emphasize slightly different aspects of faunal overlap.

These coefficients range from -1 (indicating no similarity of the comparative parameters) to +1 (indicating complete similarity).

In addition to the Jaccard and Sørensen–Czekanowski indices, the Stugren–Radulescu Coefficient (Leontiev 2007) was also used to assess species composition differences. This index is known for its higher differential sensitivity, especially in highlighting asymmetries between species sets. It was calculated using the formula:

$$Pst = (X + Y - Z) / (X + Y + Z)$$

where X is the number of species occurring at the first location but absent from the second; Y is the number of species occurring at the second location but absent from the first; Z is the number of species common to both locations (Shmydt 1984). Including this index alongside the other two allows for a more nuanced comparison of avifaunal differences, particularly in cases where the number of shared species between locations is low, and differences in species composition are significant.

This coefficient varies from -1 to +1 (with values from -1 to 0 indicating similarity, and values from 0 to +1 indicating differences between the areas).

The Menhinick Species Richness Index was determined as:

$$DMe = S / \sqrt{N}$$

where N is the total number of identified sound signals at a given location, and S is the number of correctly identified (detected) species at that same location (Hrod & Shevchyk 2020).

Results

Acoustic species identification and expert verification of sound signals

During the research, 843 sounds were recorded. The identification of sounds using the BirdNET-Analyzer software revealed their affiliation with 70 bird species, most of which are typical for the given territory and the research period (Yuzyk 2021, Yuzyk & Yuzyk 2022, 2023, Yuzyk *et al.* 2024), with 22 species being recorded for the first time.

However, when examining the sonograms of the sound signals, including species first detected in the studied area using the RavenPro software and compared with reference specimens, we found that they actually belonged to 58 species of birds. Of these, 10 were newly discovered: Common Teal (*Anas crecca*) (Figure 2), Eurasian Oystercatcher (*Haematopus ostralegus*), Common Ringed Plover (*Charadrius hiaticula*), Common Redshank (*Tringa totanus*), Common Greenshank (*Tringa nebularia*), Eurasian Curlew (*Numenius arquata*), Little Tern (*Sterna albifrons*), Western Barn-Owl (*Tyto alba*), Bluethroat (*Luscinia svecica*) (Figure 3), European Penduline Tit (*Remiz pendulinus*), while 8 species (Great Crested Grebe (*Podiceps cristatus*), Little Bittern (*Ixobrychus minutus*), Black-crowned Night Heron (*Nycticorax nycticorax*), Mute Swan (*Cygnus olor*), Western Marsh Harrier (*Circus aeruginosus*), White-tailed Eagle (*Haliaeetus albicilla*), Short-eared

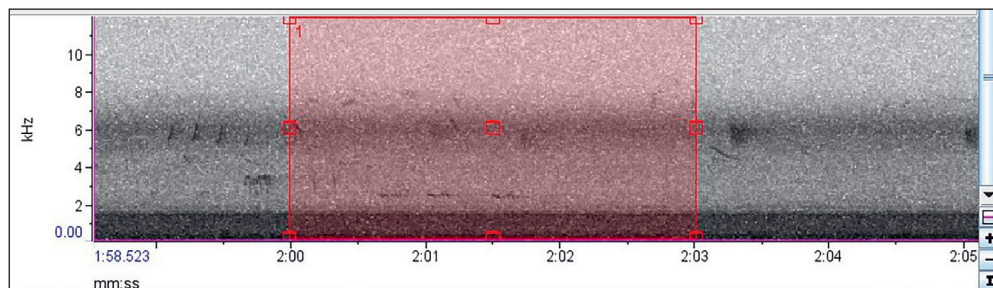


Figure 2. Sonogram of Common Teal (*Anas crecca*) call, 28 April 2023, near Perkalab ERD
2. ábra Csörgő réce (*Anas crecca*) hangjának szonogramja, 2023. április 28., Perkalab ERD közelében

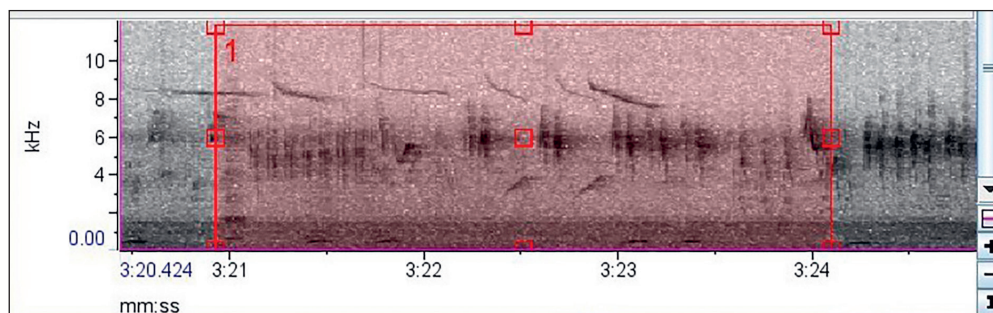


Figure 3. Sonogram of Bluethroat (*Luscinia svecica*) song, recorded on 25 April 2023 in Putyla township on the grounds of a private estate with a small photovoltaic solar power plant
3. ábra A kékbegy (*Luscinia svecica*) énekének szonogramja, 2023. április 25-én rögzítve Putyla településen, egy kis napelemes erőművel rendelkező magánbirtokon

Owl (*Asio flammeus*), Common Kingfisher (*Alcedo atthis*)) were incorrectly identified by the BirdNET-Analyzer programme.

The identification of species such as Little Egret (*Egretta garzetta*), Dunlin (*Calidris alpina*), Grey Plover (*Pluvialis squatarola*), and Common Grasshopper Warbler (*Locustella naevia*) is also contentious. As is well known, the latter two species occur throughout Ukraine during migration (Fesenko & Bokotei 2002), but require special studies in this region, as the sound recording identified as belonging to Grey Plover exhibits a significantly faster tempo than that typically characteristic of the Grey Plover. Interestingly, this tempo is more akin to that of the Song Thrush (*Turdus philomelos*), although the sonogram closely resembles the reference for the Grey Plover. Regarding the identified Common Grasshopper Warbler, it is worth noting that the sonogram is very similar to that characteristic of the Common Grasshopper Warbler; however, the recording does not feature the trilling typical of the species but rather resembles a clicking sound. Concerning Little Egret, there is a possibility of a vagrant occurrence. The closest findings of the species to the study region were recorded in the summer of 1955 in the Storozhynets district of Chernivtsi Region. However, the presence of the Little Egret in the mountainous part of the Bukovynian Carpathians requires additional detailed study and confirmation.

The list of species identified by the software and subsequently verified by experts is presented in *Table 1*.

Table 1. Bird species (including rare ones) identified during acoustic research
1. táblázat Akusztikus kutatás során azonosított madárfajok (beleértve a ritka fajokat is)

No.	Scientific species names	Total number of identifications	Conservation status
Order Anseriformes Family Anatidae			
1	<i>Anas crecca</i>	11	*●
2	<i>Anas platyrhynchos</i>	1	*●
Order Falconiformes Family Pandionidae			
3	<i>Pandion haliaetus</i>	1	*●
Family Accipitridae			
4	<i>Accipiter nisus</i>	1	*●
5	<i>Buteo buteo</i>	5	*
Order Charadriiformes Family Charadriidae			
6	<i>Haematopus ostralegus</i>	2	*●
7	<i>Charadrius hiaticula</i>	1	*
8	<i>Charadrius dubius</i>	3	*
Family Scolopacidae			
9	<i>Tringa totanus</i>	1	*●
10	<i>Tringa nebularia</i>	3	*●
11	<i>Actitis hypoleucos</i>	2	*

No.	Scientific species names	Total number of identifications	Conservation status
12	<i>Numenius arquata</i>	1	*●
Family Sternidae			
13	<i>Sterna albifrons</i>	1	*●
Order Columbiformes Family Columbidae			
14	<i>Columba palumbus</i>	1	*●
15	<i>Streptopelia decaocto</i>	2	*●
Order Cuculiformes Family Cuculidae			
16	<i>Cuculus canorus</i>	2	*
Order Strigiformes Family Tytonidae			
17	<i>Tyto alba</i>	1	*
Family Strigidae			
18	<i>Bubo bubo</i>	2	*●
19	<i>Strix aluco</i>	1	*
Order Caprimulgiformes Family Caprimulgidae			
20	<i>Caprimulgus europaeus</i>	3	*●
Order Coraciiformes Family Upupidae			
21	<i>Upupa epops</i>	1	*
Family Alcedinidae			
Order Piciformes Family Picidae			
22	<i>Dryocopus martius</i>	8	*●
23	<i>Picus canus</i>	2	*●
24	<i>Picus viridis</i>	16	*
25	<i>Dendrocopos minor</i>	1	
Order Passeriformes Family Hirundinidae			
26	<i>Hirundo rustica</i>	1	*
Family Motacillidae			
27	<i>Anthus trivialis</i>	80	*
28	<i>Motacilla cinerea</i>	11	*
29	<i>Motacilla alba</i>	6	*
Family Corvidae			
30	<i>Pica pica</i>	1	*●
31	<i>Corvus cornix</i>	2	
32	<i>Corvus corax</i>	3	*

No.	Scientific species names	Total number of identifications	Conservation status
Family Troglodytidae			
33	<i>Troglodytes troglodytes</i>	6	*
Family Prunellidae			
34	<i>Prunella modularis</i>	1	*
Family Sylviidae			
35	<i>Curruca curruca</i>	6	*
36	<i>Phylloscopus collybita</i>	102	*
Family Regulidae			
37	<i>Regulus regulus</i>	50	*
38	<i>Regulus ignicapillus</i>	4	*
Family Muscipapidae			
39	<i>Ficedula parva</i>	1	*●
40	<i>Ficedula albicollis</i>	2	*●
41	<i>Oenanthe oenanthe</i>	1	*
42	<i>Phoenicurus phoenicurus</i>	11	*
43	<i>Phoenicurus ochruros</i>	2	*
44	<i>Erithacus rubecula</i>	19	
45	<i>Luscinia svecica</i>	2	●
Family Turdidae			
46	<i>Turdus philomelos</i>	3	*●
47	<i>Turdus viscivorus</i>	6	*●
Family Remizidae			
48	<i>Remiz pendulinus</i>	2	*
Family Paridae			
49	<i>Lophophanes cristatus</i>	1	*
50	<i>Poecile montanus</i>	6	*
51	<i>Periparus ater</i>	141	*
52	<i>Parus major</i>	22	*
Family Certhiidae			
53	<i>Certhia familiaris</i>	2	*
Family Fringillidae			
54	<i>Fringilla coelebs</i>	104	*
55	<i>Spinus spinus</i>	117	*
56	<i>Loxia curvirostra</i>	4	*
57	<i>Pyrrhula pyrrhula</i>	24	*
58	<i>Coccothraustes coccothraustes</i>	3	*
Total		843	

Note: * – species listed in the European Red List of Birds; ● – species that is protected under EU Birds Directive
 Megjegyzés: * – a Madarak Európai Vörös Listáján szereplő faj; ● – az EU Madárvédelmi Irányelve által védett faj

During the field surveys at locations III, IV, and V, the presence of 26 bird species was confirmed, including: Mallard (*A. platyrhynchos*), Common Buzzard (*Buteo buteo*), Golden Eagle (*Aquila chrysaetos*) (Akimov 2009), Common Cuckoo (*Cuculus canorus*), Great Spotted Woodpecker (*Dendrocopos major*), Woodlark (*Lullula arborea*), Tree Pipit (*Anthus trivialis*), Eurasian Magpie (*Pica pica*), Common Raven (*Corvus corax*), Eurasian Wren (*Troglodytes troglodytes*), Blackcap (*Sylvia atricapilla*), Common Chiffchaff (*Phylloscopus collybita*), Wood Warbler (*Ph. sibilatrix*), Willow Warbler (*Ph. trochilus*), Black Redstart (*Phoenicurus ochruros*), European Robin (*Erithacus rubecula*), Fieldfare (*T. pilaris*), Common Blackbird (*T. merula*), Song Thrush, Marsh Tit (*Poecile palustris*), Coal Tit (*Periparus ater*), Great Tit (*Parus major*), Common Chaffinch (*Fringilla coelebs*), European Siskin (*Spinus spinus*), and European Goldfinch (*Carduelis carduelis*).

Of these, 21 species were also identified through acoustic recordings, confirming a high level of reliability in detecting dominant and vocally active species. However, five species – Great Spotted Woodpecker, Woodlark, Blackcap, Wood Warbler, and Common Blackbird – were not detected acoustically. This may be due to low vocal activity during the recording periods, overlapping signals with closely related species, or interference from background noise. Conversely, 35 species recorded acoustically were not confirmed through visual observations, likely due to their secretive behavior or nocturnal activity.

This comparison highlights the complementary nature of acoustic and traditional field methods and underscores the importance of integrating both approaches for a comprehensive assessment of avian diversity.

Dominant and common bird species in the composition of avifauna

The most frequently identified species on the audio recordings were Coal Tit – 141 (Figure 4), European Siskin – 117 (Figure 5), Common Chaffinch – 104 (Figure 6), Common Chiffchaff – 102, Tree Pipit – 80, and Goldcrest (*Regulus regulus*) – 50 identifications

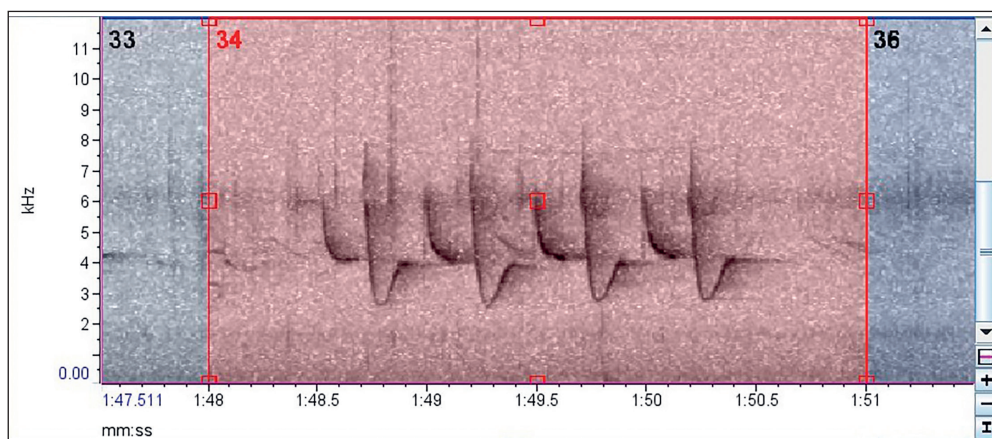


Figure 4. Sonogram of the Coal Tit (*Periparus ater*) song, recorded on 28 April 2023 in the Selyatyn ERD
 4. ábra A fenyvescinege (*Periparus ater*) énekének szonogramja, 2023. április 28-án rögzítve a Selyatyn ERD területén

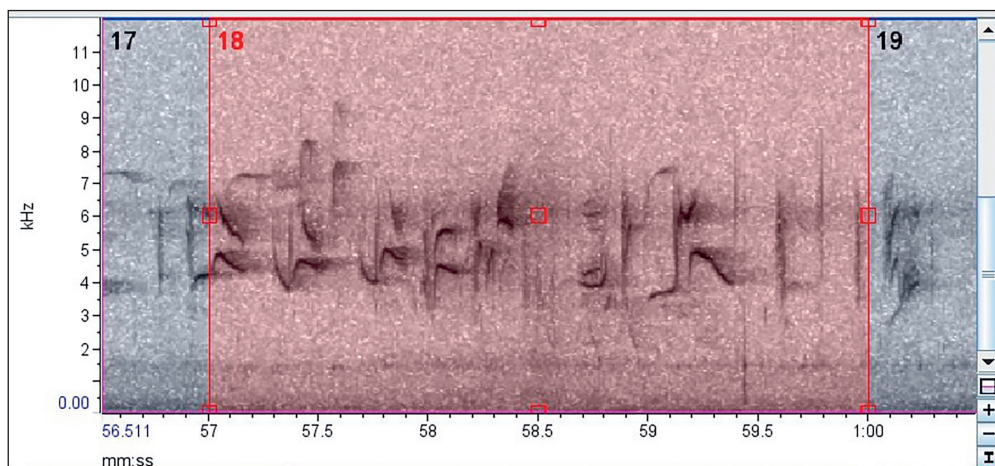


Figure 5. Sonogram of the European Siskin (*Spinus spinus*) song, recorded on 28 April 2023 in the Selyatyn ERD

5. ábra A csíz (*Spinus spinus*) énekének szonogramja, 2023. április 28-án rögzítve a Szeljatyn ERD területén

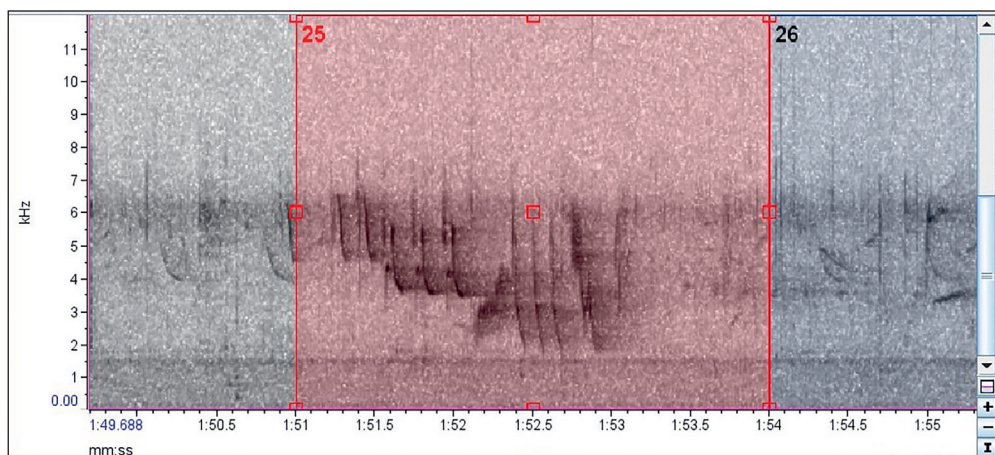


Figure 6. Sonogram of the Chaffinch (*Fringilla coelebs*) song, recorded on 28 April 2023 in the Selyatyn ERD

6. ábra Az erdei pinty (*Fringilla coelebs*) énekének szonogramja, 2023. április 28-án rögzítve a Szeljatyn ERD területén

(Figure 7). It can be concluded that these species form a dominant species assemblage within the biotopes of the Bukovynian Carpathians.

The subdominant group by the number of identifications includes Bullfinch (*Pyrrhula pyrrhula*) – 24, Great Tit – 22, European Robin – 19, Green Woodpecker (*Picus viridis*) – 16, and Common Teal – 11, Grey Wagtail (*Motacilla cinerea*) – 11, and Common Redstart – 11.

The remaining species have a small number of identifications, less than 10.

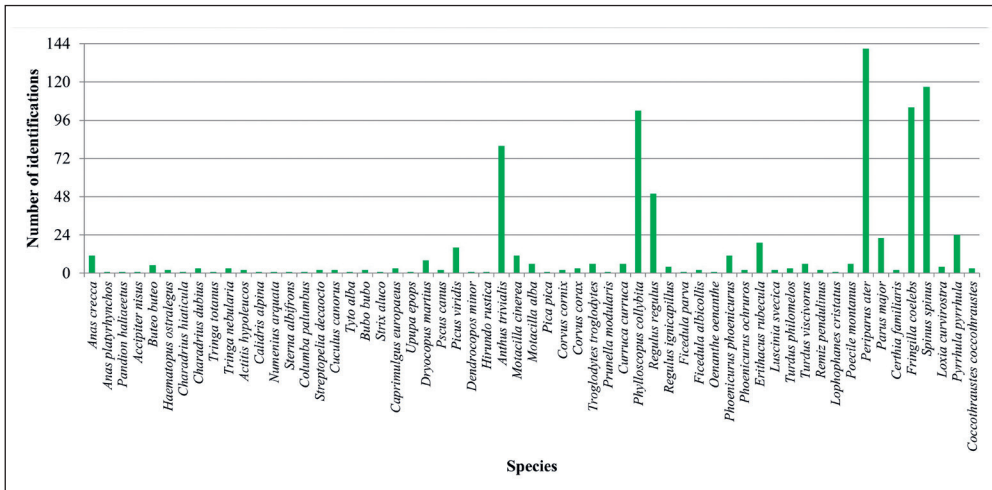


Figure 7. The number of identifications of individual bird species in audio files (misidentified and potentially misidentified species were not included in the analysis)

7. ábra Az egyes madárfajok azonosításainak száma a hangfájlokban (a tévesen vagy valószínűleg tévesen azonosított fajok nem szerepeltek az elemzésben)

In all the studied biotopes, Tree Pipit, Common Chiffchaff, and Common Chaffinch were identified, making these species common ones across all the studied locations in the Bukovynian Carpathians.

Analysis of identification reliability

The highest average values of identification reliability in the sound files were observed for Hawfinch (*Coccothraustes coccothraustes*) – 0.8270 ± 0.066 ; location III, Common Chiffchaff (0.8023 ± 0.237 ; III), Grey Wagtail (0.7591 ± 0.277 ; IV), Eurasian Wren (0.6992 ± 0.291 ; III), White Wagtail (*Motacilla alba*) (0.5929 ± 0.269 ; IV), Goldcrest (0.5865 ± 0.335 ; V), European Siskin (0.5309 , SD not applicable; V), and Coal Tit (0.5142 , SD not applicable; V), which also indicates the accuracy of their identification (Figure 8).

Through the analysis of sonograms, it has been proven that the tools are capable of accurately identifying the origin of sound files, even at very low average identification confidence levels. For example, with an average identification confidence of 0.1165 in the Selyatyn ERD, Eurasian Treecreeper (*Certhia familiaris*) was correctly identified (Figure 9).

Rare species of birds

The rare species identified ($n=58$) include 54 bird species listed in the European Red List of Birds (BirdLife International 2021) (Figure 10) and 21 species under the protection of the EU Birds Directive (Figure 11).

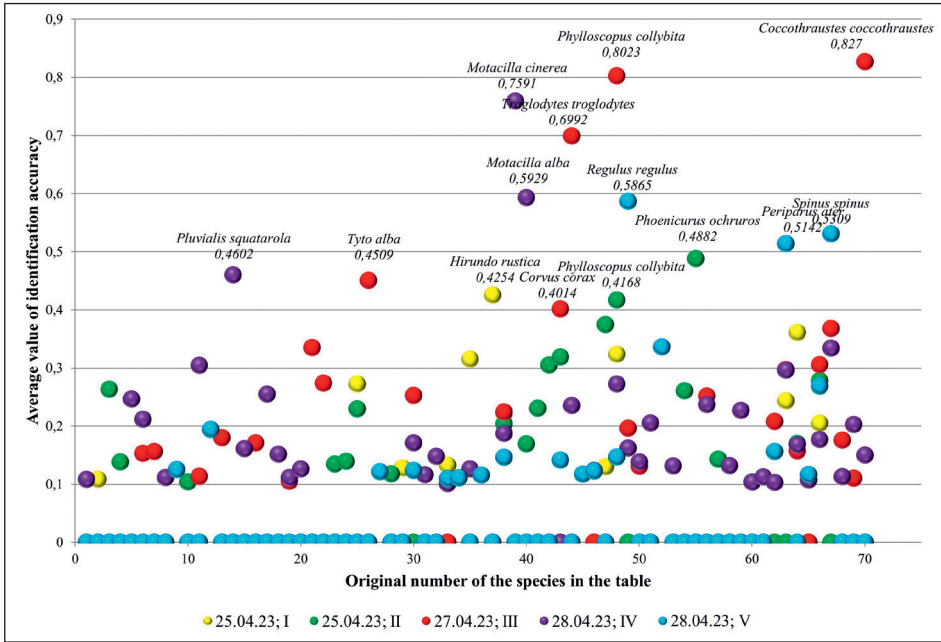


Figure 8. Accuracy of species identification on sound files. Note: The bubble chart illustrates the average confidence values of vocalization recognition for various bird species based on repeated detections in the recordings. High values indicate greater certainty in correct identification, which is important for assessing the quality of automated acoustic monitoring

8. ábra A fajazonosítás pontossága a hangfájlok alapján. Megjegyzés: A buborékdíagram az egyes madárfajok vokalizációinak ismételt észlelése alapján számított átlagos felismerési biztonsági értékeket mutatja be. A magas értékek nagyobb bizonyosságot jeleznek a helyes azonosításban, ami fontos az automatizált akusztikus megfigyelés minőségének értékeléséhez

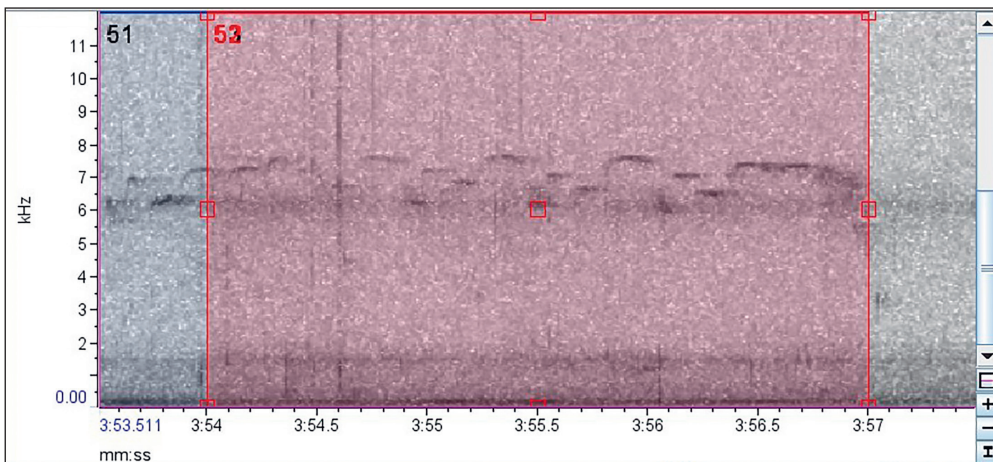


Figure 9. Sonogram of the Eurasian Treecreeper (*Certhia familiaris*) song, recorded on 28 April 2023 in the Selyatyn ERD

9. ábra A hegyi fakusz (*Certhia familiaris*) énekének szonogramja, 2023. április 28-án rögzítve a Szeljatyn ERD területén

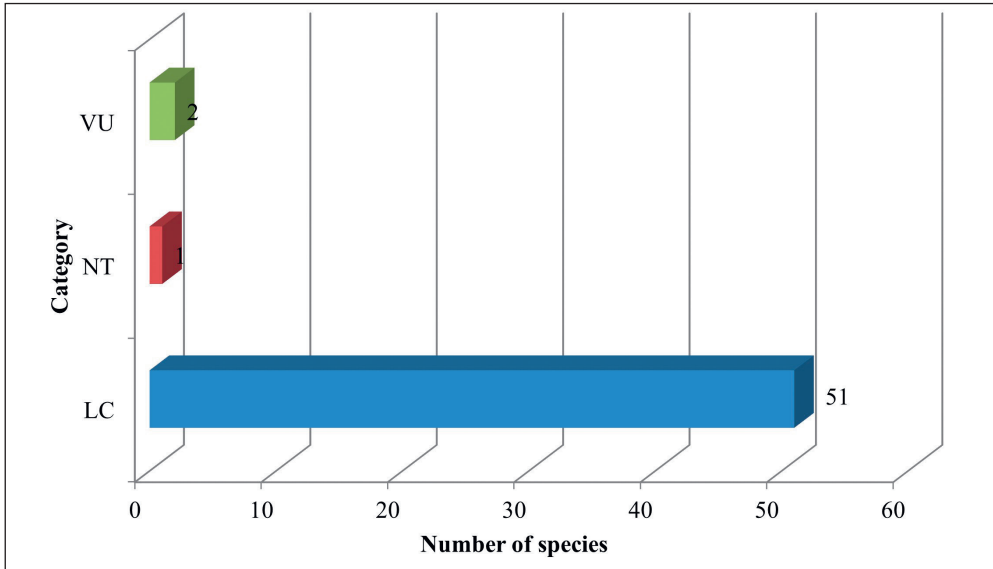


Figure 10. Species affiliation in the avifauna of the Bukovynian Carpathians to the European Red List of Birds (LC – Least Concern; NT – Near Threatened; VU – Vulnerable), verified through acoustic monitoring results

10. ábra A bukovinai Kárpátok madárfaunájának fajok szerinti besorolása a Madarak Európai Vörös Listája alapján (LC – nem veszélyeztetett; NT – mérsékelten veszélyeztetett; VU – sebezhető), akusztikus megfigyelés eredményei alapján ellenőrizve

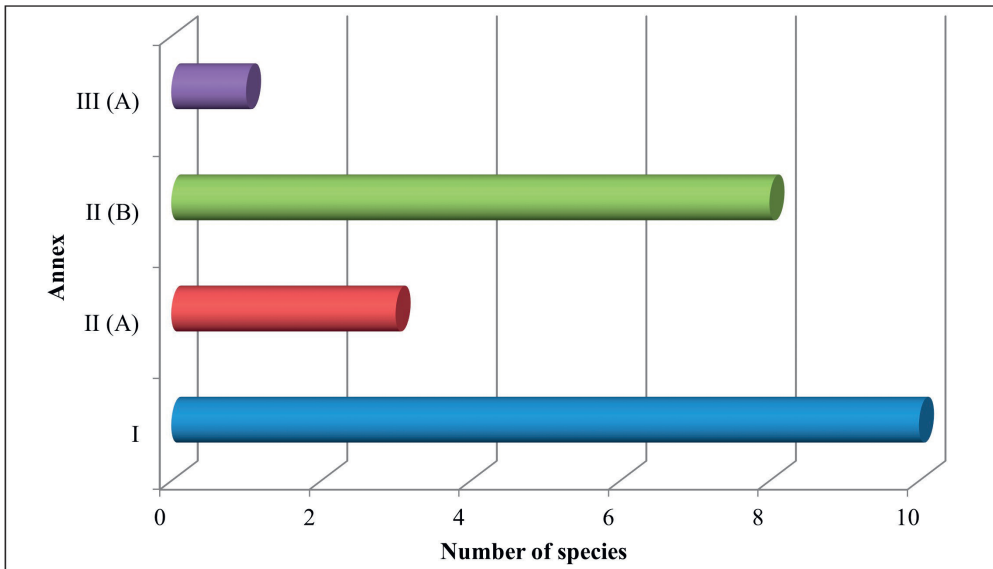


Figure 11. Species belonging to the avifauna of the Bukovynian Carpathians to the EU Birds Directive, verified by results of acoustic monitoring

11. ábra A bukovinai Kárpátok madárfaunájának fajok szerinti besorolása az EU Madárvédelmi Irányelve szerint, akusztikus megfigyelés eredményei alapján ellenőrizve

Assessment of avian community similarity

The analysis of avifauna species composition similarity revealed that the locations along the Sarata River and near the Perkalab ERD are the most similar in this respect, with 18 bird species common to these areas (Common Teal, Common Buzzard, Common Sandpiper (*Actitis hypoleucos*), European Nightjar (*Caprimulgus europaeus*), Tree Pipit, Eurasian Wren, Common Chiffchaff, Goldcrest, Common Firecrest (*R. ignicapillus*), European Robin, Willow Tit (*Poecile montanus*), Coal Tit, Great tit, Common Chaffinch, European Siskin, Red Crossbill (*Loxia curvirostra*), Bullfinch, Hawfinch), as also confirmed by the high values of the Jaccard and Sørensen–Czekanowski indices (0.43 and 0.60, respectively) (*Table 2*).

The calculated values of the Stugren–Rădulescu, Jaccard, and Sørensen–Czekanowski indices indicated that the lowest degree of avifauna species diversity similarity was recorded for the location at a private estate with a small photovoltaic power station in Putyla township and along the Sarata River (0.74; 0.13 and 0.23, respectively), as well as for the location at a private estate with a small photovoltaic power station in Putyla township and near the Perkalab ERD, as evidenced by the calculated values of the Stugren–Rădulescu, Jaccard, and Sørensen–Czekanowski indices (0.79; 0.13 and 0.23, respectively) (*Table 2*).

Table 2. Similarity of avifaunal species composition across different locations
2. táblázat A madárfauna fajdiverzitásának hasonlósága különböző helyszíneken

A pair of locations	Number of shared species	Similarity index		
		Jaccard	Sørensen–Czekanowski	Stugren–Rădulescu
I – II	6	0.26	0.41	0.50
I – III	5	0.16	0.39	0.68
I – IV	7	0.18	0.30	0.64
I – V	5	0.24	0.39	0.52
II – III	5	0.13	0.23	0.74
II – IV	6	0.13	0.23	0.79
II – V	4	0.14	0.24	0.72
III – IV	18	0.43	0.60	0.20
III – V	9	0.29	0.45	0.44
IV – V	10	0.25	0.40	0.50

Note: Incorrectly identified and presumably misidentified species were not included in the analysis
Megjegyzés: A tévesen és valószínűleg tévesen azonosított fajok nem szerepeltek az elemzésben

Analysis of species richness based on identification results

The lowest species richness of avifauna was recorded at the site in the Selyatyn ERD (DMe = 0.97) (*Table 3*).

In terms of species richness, the location near the rented administrative building of the National Park «Cheremoskyi» in the Putyla township is similar to the site in a private estate with a small photovoltaic solar power plant, both of which are characterised by average index values (DMe = 1.56 and 1.64, respectively). Within the private estate with a small

Table 3. Species richness of avifauna at different locations
3. táblázat A madárfauna fajgazdagsága különböző helyszíneken

Location	N	S	DMe
I	50	11	1.56
II	121	18	1.64
III	119	25	2.29
IV	312	35	1.98
V	241	15	0.97

Note: Species that were misidentified and likely misidentified were not included in the analysis. S – number of correctly identified species; N – total number of identified sound signals; DMe – Menhinick Species Richness Index
Megjegyzés: A tévesen és valószínűleg tévesen azonosított fajok nem szerepeltek az elemzésben. S – helyesen azonosított fajok száma; N – azonosított hangjelek teljes száma; DMe – Menhinick fajgazdagsági index

photovoltaic solar power plant, seven more bird species were recorded compared to the location near the rented administrative building of the National Park «Cheremosky» in Putyla township.

A high level of avifaunal species richness has been recorded for the location near the administrative building of the Perkalab ERD, with 35 species (DMe = 1.98), while the highest value is observed at the location along the Sarata River, with 25 species (DMe = 2.29) (Table 3).

Discussion

We found that the BirdNET-Analyzer tool is not sufficiently effective, as the accuracy of species identification does not exceed 70%. This value was obtained by comparing automated detections with manual annotations conducted by an experienced ornithologist on a randomly selected subset of the dataset. Similar performance levels (ranging from 60% to 80%) have been reported in other validation studies using BirdNET or comparable systems (Knight *et al.* 2017, Stowell *et al.* 2018, Kahl *et al.* 2021). These studies emphasize the importance of contextual tuning, sound quality, and species-specific detectability. To address these shortcomings, it is necessary to involve an ornithologist to listen to the audio files and compare the sonograms obtained from the recordings with the reference ones in the existing databases. Despite the significant imbalance in the dataset and the need for more precise bird detection, the results of such monitoring are very promising and demonstrate high potential for studying bird migration (Pamula *et al.* 2020), particularly during the night (van Doren *et al.* 2023). The indicators obtained from this monitoring allow for the assessment of arrival times for individual bird species (Bick *et al.* 2024).

When identifying bird sounds using the BirdNET-Analyzer tool, it is important to consider the number of repeated detections of a single species in the audio recording. A significant number of repeated identifications of one species in the recording indicates a high probability of correct species identification and allows for the establishment of dominant and common species in the studied habitat, demonstrating the spatial distribution of species (Maina *et al.* 2016) and assessing bird population density based on precise distance-based methods (Dawson

& Efford 2009). High average confidence scores of species identification (above 0.5 on a scale from 0 to 1) also suggest a relatively high probability that the identifications are correct. For more accurate isolation and classification of songs from continuous recordings, a species-specific approach must be applied (Hockman 2018).

Researchers can also assess the number of bird species that are heard in the recordings and use this information to determine species richness in the ecosystem (Maina 2015). The lowest bird species richness recorded at the Selyatyn ERD site ($DMe = 0.97$) may be related to specific weather conditions during the acoustic monitoring. In particular, at that time Mount Tomnatyk was still covered with snow about 20 cm thick (up to 0.5 m in some places), which caused a delay in the first wave of spring migration. As a result, the site was characterized mainly by resident and nomadic bird species, as well as the earliest migrants. This indicates a significant influence of weather conditions on the temporal structure of spring migration and the species composition of local bird communities.

Also the presence of species such as Great Crested Grebe, Mute Swan, Western Marsh Harrier, White-tailed Eagle, and Common Kingfisher in the study area is unexpected due to the altitudinal and habitat specificity of the Bukovynian Carpathians, their automated detections may indicate that mountain valleys and wetlands could serve as occasional stopover sites even for species typically associated with lowland habitats (Skilskyi *et al.* 2000, Skilskyi & Klitin 2001, Fesenko & Bokotei 2002). However, these records require cautious interpretation and further verification.

Bird communities in the Bukovynian Carpathians are closely associated with specific habitat types. Forest biotopes provide essential resources for the majority of species, whereas open ecosystems such as meadows and wetlands support distinct faunal assemblages, including waders, larks, and reed warblers. This pattern is clearly reflected in the results of similarity analysis. The highest similarity in avifaunal composition was observed between locations along the Sarata River and near the Perkalab ERD, with 18 shared species and corresponding Jaccard and Sørensen–Czekanowski indices of 0.43 and 0.60, respectively. These sites are characterized by relatively undisturbed riparian and forest-edge habitats. In contrast, the lowest similarity was recorded between the site near a private estate with a photovoltaic power station in Putyla township and both Sarata River and Perkalab ERD locations, with Jaccard indices as low as 0.13 and Sørensen–Czekanowski values of 0.23. These findings suggest a strong influence of anthropogenic disturbance and habitat modification on community structure. Interactions among species in these assemblages contribute to spatial and functional differentiation, with niche partitioning reducing interspecific competition. However, anthropogenic transformations-particularly habitat fragmentation, acoustic disturbance, and chemical pollution – are altering the composition and structure of bird communities. These stressors reduce habitat quality, disrupt acoustic communication, and promote the dominance of ecologically plastic species, while specialized and conservation-priority taxa tend to decline. Understanding these ecological processes is critical for developing targeted conservation strategies to maintain avian biodiversity under increasing anthropogenic pressure in mountain ecosystems.

A critical limitation of acoustic monitoring is that the time of day during which birds' songs are recorded may influence detection rates, as birds sing more actively in the evening

and less so during the day. This factor may have affected the results and should be considered in future studies.

Among the most vulnerable species identified by this study are the Eurasian Oystercatcher and the Common Redshank. To ensure survival and reproduction in their habitats, special habitat conservation measures are required for 10 bird species: the Osprey (*Pandion haliaetus*), the Eurasian Sparrowhawk (*Accipiter nisus*), the Little Tern (*Sternula albifrons*), the Eurasian Eagle-Owl (*Bubo bubo*), the European Nightjar, the Black Woodpecker (*Dryocopus martius*), the Grey-headed Woodpecker (*P. canus*), the Red-breasted Flycatcher (*Ficedula parva*), the Collared Flycatcher (*F. albicollis*), and the Bluethroat (Directive 2009, Ieronymidou *et al.* 2015).

Although this study utilized the advanced BirdNET-Analyzer software for automated vocalization recognition and processing of a limited set of audio recordings, further methodological improvements may require a comprehensive approach. In particular, it is recommended to implement additional vocalization classification systems based on confidence levels and to involve multiple experts for identification verification, which would enhance result reliability (Kahl *et al.* 2021). Moreover, improving analysis quality can be achieved through the application of digital pre-filtering of audio data and the use of windshields for microphones, reducing background noise levels and facilitating more accurate sound recognition. Thus, the application of the acoustic method allows obtaining high-quality data for assessing the status of populations of protected species and for planning further biodiversity conservation efforts in mountain ecosystems. Such an approach will increase the objectivity and precision of bird diversity assessments under conditions of anthropogenic pressure in mountain ecosystems.

An additional important limitation to consider is the variability in birdsong activity depending on the time of day. Although acoustic monitoring was conducted on the same calendar day at the studied sites, recordings took place at different times, which may have influenced the results. Birds tend to sing more actively during dawn and dusk, with lower vocal activity during midday hours. This temporal variation could affect the number and diversity of vocalizations detected, thereby influencing species richness estimates and monitoring outcomes.

To overcome the approximately 30% inaccuracy observed in BirdNET, it is recommended to apply a multi-tool approach by combining BirdNET with other acoustic analysis software, specifically Raven Pro, which provides detailed visual and manual spectrogram analysis. Using this complementary tool alongside expert validation helps reduce false positives and increases confidence in species identification.

Conclusions

Our research has established the presence of common and rare bird species in the inaccessible and remote mountainous landscapes of the Bukovynian Carpathians. Furthermore, these results will serve as a foundation for planning further studies, particularly for assessing bird population dynamics, identifying threats to their existence, and developing conservation strategies for rare species, as well as for preparing conservation programmes and gaining a better understanding of the biology and ecology of individual species.

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