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Bird collision risk at the interface of solar and wind farms – a cumulative effect?

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Abstract: One of the most controversial issues concerning wind turbines and photovoltaic farms is their negative impact on bird populations. The basic problem is the cumulative effect whereby birds, attracted by the water-like appearance of photovoltaic panels, may collide with the rotating blades of wind turbines. The paper analysed bird populations during four periods of their activity. The density of bird species of high, medium and low collision risk (HCR, MCR, LCR) at six photovoltaic farms was determined, including buffers of 200 and 1,000 metres from the installations. The results show that the structure of the avifauna occurring within and in the immediate vicinity of photovoltaic farms is variable and depends on both the nature of the specific installation and the phenological period. No bird mortality was observed during the 2-year study period. However, the potential expansion of photovoltaic farms to include wind farms may have the effect of increasing collision hazards, particularly during spring and autumn migration periods, as significantly higher densities of HCR birds were found during these times than during other periods. The study also indicated that LCR birds were abundant during the breeding period and post-breeding dispersion. They were significantly more densely distributed within a buffer of 200 m than 1,000 m from the installation. This confirms the attractiveness of photovoltaic farms for this group of birds, which may influence the possibility of not only cumulative impacts, but also synergistic impacts when photovoltaic farms are extended with wind farms.

Keywords: avifauna, collision risk, renewable energy sources, solar panel, wind turbine

INTRODUCTION

The basic aim of the Polish energy policy (PEP) is energy security while ensuring the competitiveness of the economy, energy efficiency and reduction of the impact of the energy sector on the environment, with optimal use of its own energy resources (Ministry of Climate and Environment, 2021). One way to achieve the PEP assumptions is the reduction of the pressure of conventional energy and gradually increasing the share of Renewable Energy Sources (RES) (Ministry of Climate and Environment, 2021; EEA, 2024).

Renewable energy sources, such as solar and wind systems, are viewed as promising green energy alternatives. They help reduce reliance on fossil fuels and play a role in combating climate change (Chock *et al.*, 2021; Mammadov, Ganiyeva and Aliyeva, 2022; Østergaard *et al.*, 2022; Mohammad *et al.*, 2023; Sayed *et al.*, 2023). A fundamental question that has emerged is whether these systems pose a threat to bird populations (Smith and Dwyer, 2016; Kosciuch *et al.*, 2020).

One of the most commonly cited threats to birds is the possibility of colliding with photovoltaic panels by mistakenly taking them for a surface of water ("lake effect"). That is why one of the most common recommendations for the location of photovoltaic farms is to avoid installing solar panels near wetlands, rivers, or other bodies of water, as these are often very important and densely populated habitats for birds (Taylor *et al*., 2019; Kosciuch *et al*., 2021; Smallwood, 2022).

Habitat loss is not just the removal of nesting or feeding areas but includes edge effects and habitat isolation, contributing to environment fragmentation. Additionally, the potential negative impact of solar farms, especially on waterfowl, may be connected with the alternation of flight patterns and feeding (Anderson, Hopkins and Anderson, 2025). Warming temperatures, increased climate variability, and devastating wildfires may reinforce this problem. Habitat loss is an indirect cause of avian mortality (Walston *et al*., 2015). Many anthropogenic stressors lead to direct avian mortality. Loss, Will and Marra (2015) have determined that billions of birds per year are killed in the US from various anthropogenic sources.

When assessing the threat to birds, it is important to consider the combined impact of several factors such as the construction of wind farms in close proximity to operational photovoltaic installation, which has not yet been studied. Photovoltaic farms attract birds that use them as feeding, breeding or resting areas contributing to an increase in the number of individuals in the area (Jarčuška *et al*., 2024; Copping *et al*., 2025). Increased density of individuals may result in more collisions with closely located wind turbines (Smallwood, 2007; Chock *et al*., 2021; Nilsson *et al*., 2023; Gómez-Catasús *et al*., 2024).

Another factor to be taken into consideration in assessing the risk of increased mortality of avifauna is the growing trend towards cable pooling, i.e., sharing the connection infrastructure of RES installations. This is an economically viable solution for farms that rarely reach full production capacity simultaneously (Mertens, 2022; Adamczewski *et al*., 2023; Włoch and Lazarek-Janowska, 2024). However, it may pose an additional threat to birds – a cumulative effect resulting from too close proximity of wind and PV farms. A cumulative impact is a change in the environment caused by the impact of an activity, in combination with other past, present or real future activities (Obwieszczenie, 2024).

This study aims to assess the possible cumulative impact of renewable energy sources on avifauna due to the proximity of wind and photovoltaic installations. It was assumed that in the case of the extension of the photovoltaic farm with wind turbines, there may be an increase in collision risks for avifauna due to the location of both installations in agricultural areas, i.e., potential breeding and feeding grounds.

MATERIALS AND METHODS

STUDY SITES

Field studies were carried out at six existing photovoltaic (PV) farms in Poland: Kolno (3.5 ha) 53.41N, 21.9E, Karpicka (11.3 ha) 52.14N, 16.13E, Ręczyn (40.8 ha) 51.04N, 14.97E, Witnica (113.3 ha) 52.67N, 14.89E, Grabik–Żary (137.0 ha) 51.66N, 15.11E, and Zwartowo (297.3 ha) 54.70N, 17.81E (Fig. 1).

The investigations were carried out in two zones, i.e., PV farm itself with a buffer of 200 m (B200) and a zone 200–1,000 m away from the farm (B1000). The extent of the zones were determined based on the land use structure on the studied sites (Tab. 1), taking into account the behavioural preferences (plant coverage, presence of potential nesting sites, abundance of food etc.) of the avifauna (Svensson *et al*., 2009). The analysed areas were characterised by the predominance of arable land (from

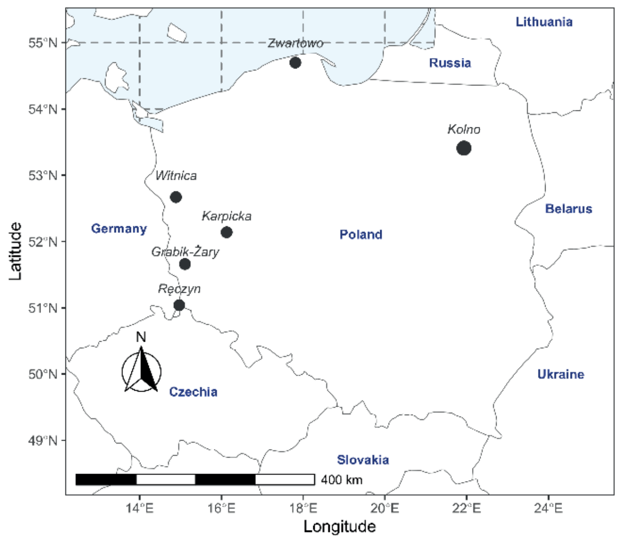

Fig. 1. Location of the farms on a map of Poland; source: own elaboration

Table 1. Land use structure of the study sites

Study site	Buffer area (B200 + B1000) without the farm (ha)	Agricultural land	Forests and woodlands	Built-up areas	Surface water bodies
		(%)			
Kolno	494.4	87.08	11.06	1.86	–
Grabik–Żary	940.6	51.25	34.68	14.07	–
Karpicka	533.6	65.07	1.12	33.81	–
Ręczyn	765.2	76.94	12.44	7.12	3.50
Witnica	865.9	89.25	2.12	8.63	–
Zwartowo	1,223.6	88.43	8.51	3.06	–

Explanations: B200 = 200 metres buffer area, B1000 = 1000 metres buffer area.
Source: own elaboration.

51.25 to 89.25%) concerning other land uses. Detailed maps of the study areas are included in Figures S1–S6.

The structure of land use around the photovoltaic farms varies. Kolno, Witnica, and Zwartowo are dominated by agricultural land (87–89%) with minimal forest and built-up areas. These homogeneous landscapes likely support mainly farmland species. Grabik–Żary has the most diverse surroundings: 51% farmland, 35% forests, and 14% built-up areas. This habitat variety likely supports a more diverse bird community. Karpicka is notable for its high share of built-up areas (34%) and low forest cover (1%). The mix of farmland and urban space may favour synanthropic species. **Ręczyn** offers the most balanced structure: 77% agriculture, 12% forest, 7% built-up areas, and 3.5% water bodies – the only site with surface water, which can attract more species during migration. Generally, sites with greater habitat heterogeneity, like Grabik–Żary and Ręczyn, likely support higher bird diversity. In contrast, more uniform, farmland-dominated areas may favour a narrower range of species adapted to open landscapes.

RESEARCH METHODS

The authors had permission to access the entire RES project area. The study was conducted during 2022 and 2023 in four periods of bird activity: the spring migration period (SM, March–April), the breeding period (BP, May–June), the post-breeding dispersion period (PBD, August–September) and autumn migration period (AM, October–November). The observations were carried out during one day – from dawn to dusk, by searching successive transects, 100–200 m apart, depending on the terrain and the visibility conditions, to inspect the entire investigated area (including the 1,000 m buffer). Binoculars of 10×50 and 11×40 were used, and pictures of birds with a 600 mm telephoto lens were taken. The recorded images aided in proper identification, particularly of raptor species and small Passeriformes at relatively high observation distances. During the observations attention was paid to the possible presence of dead birds on the ground (but none were found). The search for dead birds was also carried out in both buffer zones due to the possibility that an injured individual may have been able to fly some distance after a possible collision.

The identified bird species were divided into three groups (Tab. 2) based on the potential risk of collisions with wind turbines – high collision risk (HCR), medium collision risk (MCR), and low or incidental collision risk (LCR). The affiliation of a species to a particular group was established based on the experiences indicated in reviewed thematic literature (Barrios and Rodríguez, 2004; Hötker, 2006; Band, Madders and Whitfield, 2007; Bevanger, Berntsen and Clausen, 2010; Illner, 2011; Everaert, 2014; Kagan *et. al.*, 2014; Dürr, 2020; Chock *et al.*, 2021; Gómez-Catasús *et al.*, 2024) and the authors' own observations.

The observed species were classified according to their breeding status. The most likely breeding status of each species found was assessed using the simplified methodology of Sikora (ed.) (2007): LA – definitely breeding: a nest with eggs or chicks was found, non-flying young were observed, LB – possibly breeding: a pair was observed in a biotope convenient for nesting during the breeding season, sub-adults were observed, WL – found on the plot during the breeding season but not fulfilling any of the LA and LB criteria, P – migrant/non-breeder, WP – using the study area (resting, foraging). The paper uses the original designations from the literature cited. The density of the species of peculiar breeding status was presented in per cents in relation to the sum of the density of all avifauna in peculiar localisation buffer, assuming the observation periods.

The bird density (BD) of individual species in the buffers was calculated by dividing the number of identified individuals in a buffer by its area (Collier *et al.*, 1973). The BD value was expressed in individuals per ha (ind.·ha^{-1}). During the observed periods, the BD values of avifauna species within each collision risk group were summed for each location and buffer. The percentage density of bird groups (HCR, MDG, and LCR) was calculated by taking the ratio of the density of birds in each risk group to the total bird density in the research area across different periods of bird activity (SM, BP, PBD, AM). The calculated values were presented in the form of radar plots, compared three groups of birds (HCR, MCR, LCR) in terms of the BD value of each group at different locations.

The nonparametric Wilcoxon (Bauer, 1972) test assessed the diversity of bird groups in buffers (200 m and 1,000 m). Probability values lower than the assumed significance level of a = 0.05 indicate significant differences between the studied populations of bird groups (HCR, MCR, and LCR) in the separated buffers. The data were illustrated using boxplots that considered the diversity of the studied populations of bird groups

Table 2. Classification of bird species according to risk of collision with wind farm turbines

Collision risk	Bird species
HCR	*Phalocrocorax carbo*, *Ardea cinerea*, *Egretta alba*, *Ciconia ciconia*, *Ciconia nigra*, *Anser anser*, *Anser alfibrons*, *Anser fabalis*, *Anser sp.*, *Haliaetus albicilla*, *Pandion haliaetus*, *Buteo buteo*, *Buteo lagopus*, *Milvus milvus*, *Circus aeruginosus*, *Circus cyaneus*, *Circus pygargus*, *Falco tinnunculus*, *Grus grus*, *Apus apus*, *Hirundo rustica*, *Delichon urbica*, *Sturnus vulgaris*
MCR	*Cygnus olor*, *Anas platyrhynchos*, *Bucephala clangula*, *Accipiter gentilis*, *Accipiter nisus*, *Falco subbuteo*, *Vannelus vannelus*, *Larus ridibundus*, *Larus argentatus*, *Columba palumbus*, *Alauda arvensis*, *Corvus corax*, *Corvus corone*, *Corvus frugilegus*, *Pica pica*, *Turdus philomelos*, *Fringilla coelebs*
LCR	*Perdix perdix*, *Phasianus colchicus*, *Coturnix coturnix*, *Crex crex*, *Chlidonias niger*, *Sterna hirundo*, *Streptopelia decaocto*, *Cuculus canorus*, *Upupa epops*, *Garrulus glandarius*, *Parus major*, *Parus cearuleus*, *Turdus merula*, *Turdus pilaris*, *Oenanthe oenanthe*, *Saxicola rubetra*, *Phoenicurus ochruros*, *Erithacus rubecula*, *Sylvia communis*, *Sylvia curruca*, *Motacilla alba*, *Motacilla flava*, *Lanius collurio*, *Lanius excubitor*, *Carduelis carduelis*, *Carduelis cannabina*, *Emberiza citrinella*, *Emberiza calandra*, *Passer domesticus*, *Passer montanus*

Explanations: HCR = high collision risk, MCR = medium collision risk, LCR = low or incidental collision risk.
Source: own elaboration.

on the studied objects during four observation periods. Boxplots marked with two different colours have been used to distinguish the two buffers (200 and 1,000 m). Asterisks plotted in box plots indicate the probability values of the diversity of the studied bird populations (Wickham, 2016; R Foundation, 2023).

RESULTS

A total of 70 bird species were found in the six study plots. The highest number – 63 species – was observed on the largest photovoltaic farm – Zwartowo, 62 species were found on Ręczyn, 61 – Karpicka, 57 – Witnica, 53 – Kolno and 49 – Grabik–Żary. In the spring and autumn migration periods, the number of species in each location varied between 22 and 40 with an average value of 30. During the breeding period and post-breeding dispersion, the number of species was higher on average by 38.4% than during the SM and AM periods, regardless of the location of the farm and its buffer. The differences in the abundance of species observed in the surveyed buffers between the terms were small, in the BP and PBD terms of the order of 1%, and in the SM and AM ones of 8–13%, in favour of the B200 buffer.

In the spring migration period, the highest density of birds included in the HCR group was found in all plots, and it was highest in the plot in Karpicka (Fig. 2). In the breeding and post-breeding dispersion periods, the highest BD value was found in the Karpicka plot and also in Kolno, but the highest number of birds was from the LCR group. In the autumn migration period, the highest BD value belonging to the HCR group was again found in most plots (except for the Kolno plot), with the highest values in the Ręczyn and Karpicka plots. In the Kolno plot, the highest density of birds belonging to the LCR group was found. Overall, in the Ręczyn plot in the HCR group, the highest density values were found in as many as two observation periods (SM and AM), suggesting that conditions at this location are particularly favourable for birds of this group.

The densities of birds at different plots (Grabik–Żary, Karpicka, Kolno, Ręczyn, Witnica, Zwartowo) for three categories (HCR, MCR, LCR) in four observation periods are shown in Figure 3. In the spring migration period in the HCR bird group, there were no significant differences in density between buffers in most of the investigated sites. The significant differences were found ($p < 0.001$ and $p < 0.01$) only in the Karpicka and Ręczyn farms, where in the 200 m buffer a higher density of birds was observed. The MCR group of birds was found to have higher densities in most plots on the 200 m buffer compared to the 1,000 m buffer, with the most significant differences ($p < 0.001$) seen in the Karpicka plot. In Grabik–Żary, Ręczyn, and Witnica, the differences were significant at the $p < 0.01$ level and in Kolno at the $p < 0.05$ level. In the LCR bird group, higher densities were found on the 200 m buffer than on the 1,000 m buffer at all sites. The most significant differences ($p < 0.001$) were found at Karpicka and Ręczyn. At Grabik–Żary and Zwartowo, the differences were significant at the $p < 0.01$ level, and at Kolno and Witnica at the $p < 0.05$ level. Overall, during the whole observation period, higher bird densities were found in the 200 m buffer than in the 1000 m buffer, and the most significant differences were in the MCR and LCR bird groups, especially at Karpicka and Ręczyn. In the HCR bird group, differences were less pronounced and were not statistically significant in several locations.

In the breeding period (Fig. 4), the HCR group of birds showed no significant differences in their density on both buffers on the Grabik–Żary, Karpicka, and Zwartowo plots. Differences

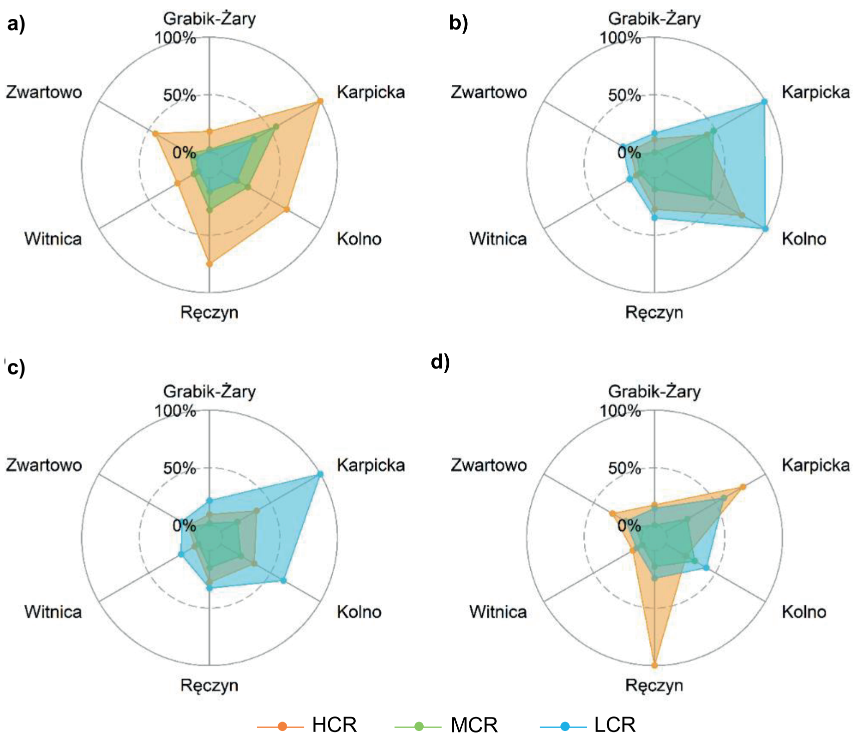

Fig. 2. Percentage density of bird groups (HCR, MCR, and LCR) depending on the object and measurement period: a) spring migration – SM; b) breeding – BP; c) post-breeding dispersion – PBD; d) autumn migration – AM; HCR, MCR, and LCR as in Tab. 1; source: own study

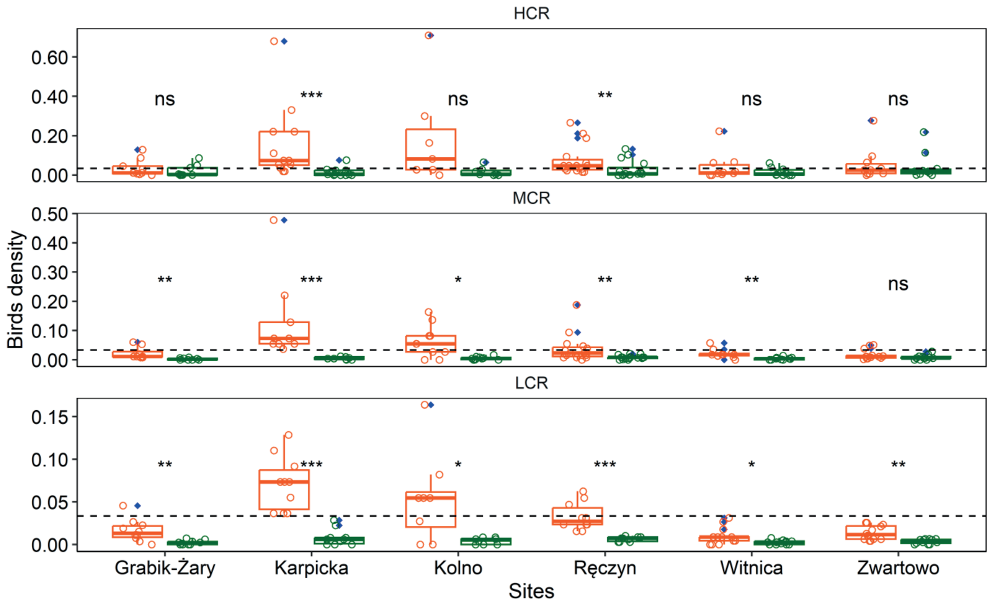

Fig. 3. Birds density (ind.·ha^{-1}) during a spring migration period at particular study sites: 200 m buffer (red), 1,000 m buffer (green); blue – the outliers; ns – no differences between the tested buffers, * significant difference at $p \leq 0.05$, ** significant difference at $p \leq 0.01$, *** significant difference at $p \leq 0.001$, **** significant difference at $p \leq 0.0001$; HCR, MCR, and LCR as in Tab. 1; source: own study

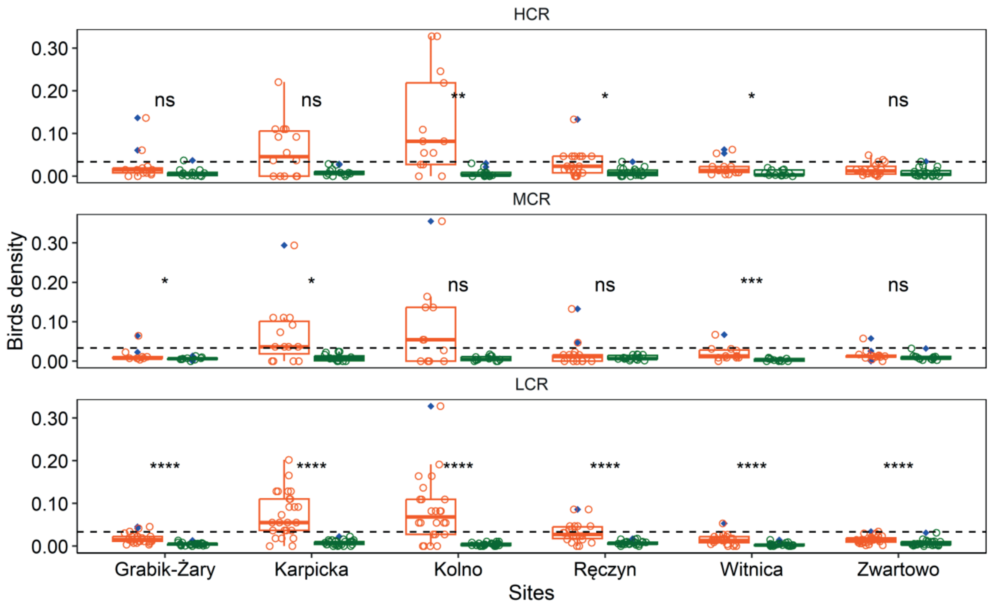

Fig. 4. Birds density (ind.·ha^{-1}) during a breeding period at particular study sites: 200 m buffer (red), 1,000 m buffer (green); blue – the outliers; ns – no differences between the tested buffers, * significant difference at $p \leq 0.05$, ** significant difference at $p \leq 0.01$, *** significant difference at $p \leq 0.001$, **** significant difference at $p \leq 0.0001$; HCR, MCR, and LCR as in Tab. 1; source: own study

were significant in the Kolno, Witnica and Ręczyn plots ($p < 0.01$, $p < 0.05$, and $p < 0.05$, respectively). In all these plots, the density of birds from this group was higher on the 200 m buffer than on the 1,000 m buffer. The density of birds included in the MCR group differed significantly ($p < 0.05$) in the Grabik–Żary and Karpicka plots. In the Witnica plot, differences in the density of birds from this group between buffers were also significant ($p < 0.001$). In all these plots, the higher density of birds was in the 200 m buffer. No significant differences were found in the Kolno, Ręczyn, and Zwartowo plots. In the group of birds classified as LCR, a significantly higher density of birds from this group was found on the 200 m buffer in all plots ($p < 0.0001$). Overall, in this group of birds (LCR), the most significant differences between buffers were found, while in the HCR group the differences between the buffers were the least significant. The most distinctive plots were Karpicka, Witnica, and Grabik–Żary, where differences between bird groups were most significant.

In the post-breeding dispersion period (Fig. 5), in the HCR group of birds, there were no significant differences in their density between the 200 and 1,000 m buffer on the plots Grabik–Żary, Witnica, and Zwartowo. In the plots Karpicka, Ręczyn, and Kolno, there were significantly more birds from this group in the 200 m buffer than in the 1,000 m buffer ($p < 0.001$ and 0.01, respectively). In the MCR bird group, no significant differences

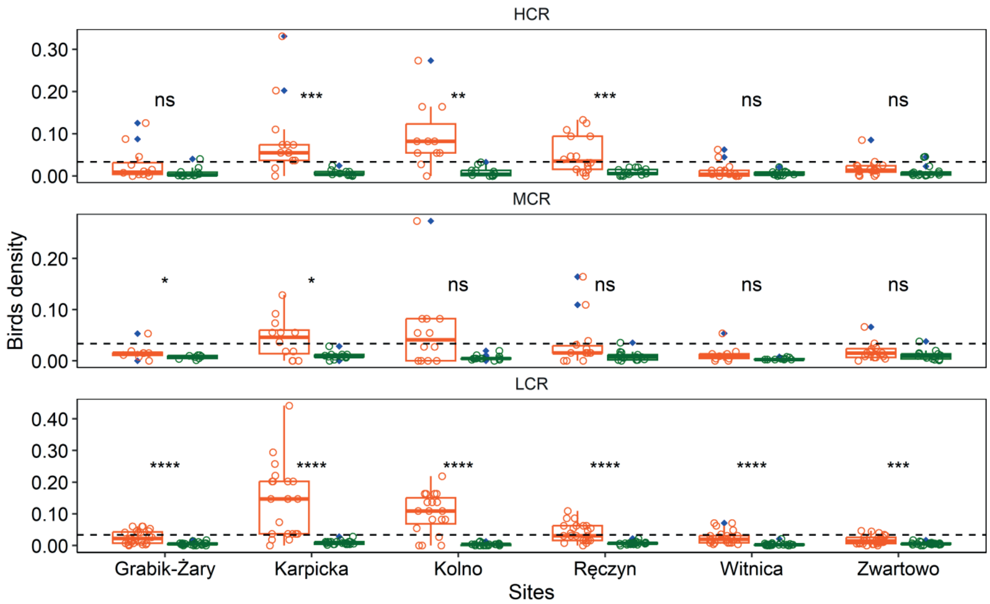

Fig. 5. Birds density (ind.·ha^{-1}) during a post-breeding dispersion period at particular study sites: 200 m buffer (red), 1,000 m buffer (green); blue – the outliers; ns – no differences between the tested buffers, * significant difference at $p \leq 0.05$, ** significant difference at $p \leq 0.01$, *** significant difference at $p \leq 0.001$, **** significant difference at $p \leq 0.0001$; HCR, MCR, and LCR as in Tab. 1; source: own study

were found between buffers in density in most plots (Kolno, Ręczyn, Witnica, and Zwartowo). Such differences were found in the plots of Grabik–Żary and Karpicka ($p < 0.05$). In the LCR bird group, significant differences in density were found between buffers in all plots.

In the autumn migration period (Fig. 6), irrespective of the location, the HCR group of birds showed no significant differences in their density between buffers. In the MCR group of birds, no significant differences in density were found in the Grabik–Żary, Karpicka, Ręczyn, and Zwartowo plots. A significantly higher density of birds from this group in the 200 m buffer compared to the 1,000 m buffer was found on the Kolno and Witnica ($p < 0.05$) plots. The most significant differences in bird density by buffer were found in the LCR group, as all plots had higher bird densities in the 200 m buffer compared to the 1,000 m buffer. In the Grabik-Żary plot, the significance of differences was already found at $p < 0.0001$. In the Karpicka and Kolno plots, the significance of differences was found at $p < 0.001$ and Kolno, and in the other plots at $p < 0.01$. Overall, in this observation period, the most significant effect of the buffer on bird density was observed in the LCR bird group, while the effect was more minor in HCR and MCR.

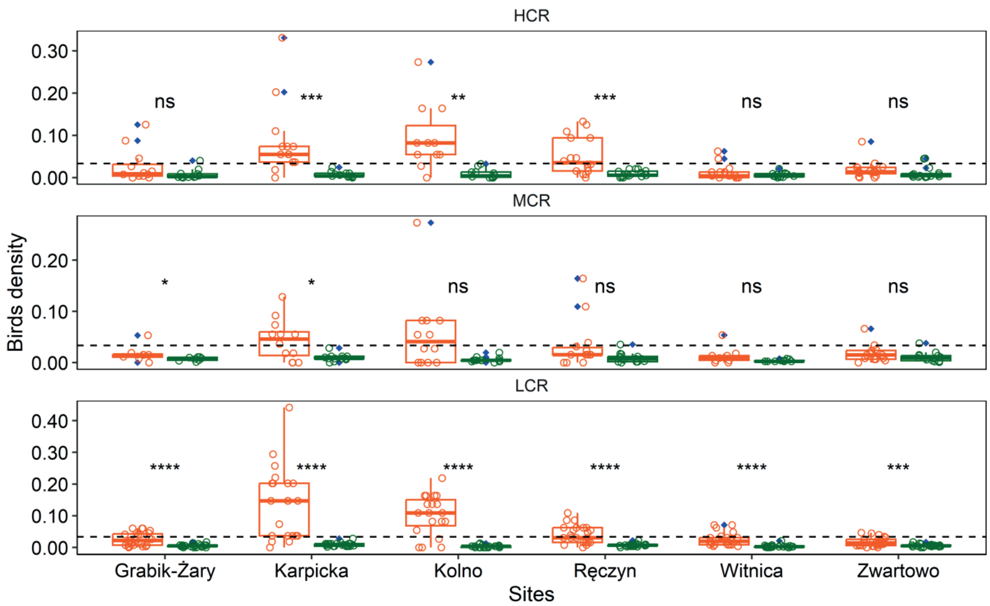

Fig. 6. Birds density (ind.·ha^{-1}) during an autumn migration period at particular study sites: 200 m buffer (red), 1,000 m buffer (green); blue – the outliers; ns – no differences between the tested buffers, * significant difference at $p \leq 0.05$, ** significant difference at $p \leq 0.01$, *** significant difference at $p \leq 0.001$, **** significant difference at $p \leq 0.0001$; HCR, MCR, and LCR as in Tab. 1; source: own study

The structure of the birds of various breeding status at the surveyed sites in the range of two investigated distances (200 and 1,000 meters) is presented in Table 3. In all observation periods, species from groups WP and WL (in total), i.e., non-breeding or probably non-breeding, dominate within both buffers. During the breeding season and the breeding dispersal, the proportion of species from groups LA and LB increased in comparison with the SM period. The proportion of passerine or migrating species is variable regardless of the observation season and the installation analysed.

In the HCR group, species with WP and WL breeding status dominated among the observed birds in all analysed plots, regardless of the buffer. In the WP group, raptors such as kestrel (*Falco tinnunculus*), common buzzard (*Buteo buteo*) and marsh harrier (*Circus aeruginosus*) accounted for the largest number of species, while in the WL group, passerine species (including grey goose – *Anser anser* and grey heron – *Ardea cinerea*) were observed. In all plots in the MCR group birds belonging to the WP group were observed, among others raven (*Corvus corax*), grey crow (*Corvus corone*), magpie (*Pica pica*), and from those belonging to the WL group common finch (*Fringilla coelebs*). Blackbird (*Turdus merula*) was the only species from LCR group of the WP breeding status observed in all plots.

DISCUSSION

The study carried out at 6 sites (2 years of observations over 4 periods of bird activity) confirms the conclusions of Kosciuch *et al.* (2020) that the number of bird deaths attributed to solar panels is often overestimated. No dead birds were found in the locations of the installation and on the buffer surfaces (200 m and 1,000 m away).

A phenomenon called the "lake effect" is most often cited as the cause of collisions. Migrating waterfowl and shorebirds may perceive the reflective surfaces of the PV panels as bodies of water

Table 3. Structure of breeding status at the surveyed sites at 200 m (B200) and 1,000 m (B1000) distance from the installation

Breeding status	B200						B1000					
	R	Ko	G–Z	Ka	W	Z	R	Ko	G–Z	Ka	W	Z
Spring migration period												
P	12.2	9.2	23.7	16.0	12.6	8.2	19.7	27.1	37.4	34.0	21.0	15.6
WP	44.7	52.9	39.5	40.3	56.3	31.7	38.9	21.9	33.2	28.1	17.0	34.0
LA	11.1	14.9	12.4	8.3	10.2	10.7	6.9	10.4	5.3	6.5	7.4	5.1
LB	4.6	6.9	14.7	6.8	7.8	8.0	1.4	2.1	1.6	12.4	6.8	2.7
WL	27.5	16.1	9.6	28.6	13.2	41.3	33.2	38.5	22.5	19.0	47.7	42.6
Breeding period												
P	6.2	10.2	11.5	8.4	11.4	15.6	16.2	29.5	21.5	23.0	12.9	20.8
WP	33.8	44.0	40.1	40.6	38.9	38.8	38.5	36.9	37.4	36.3	42.9	40.5
LA	23.6	19.9	19.8	21.3	24.4	18.9	10.7	11.5	12.3	16.4	17.8	11.2
LB	26.7	19.3	23.8	23.8	17.6	16.8	22.0	18.0	16.0	11.5	12.3	11.6
WL	9.7	6.6	4.8	5.9	7.8	9.8	12.6	4.1	12.8	12.8	14.1	15.8
Post-breeding dispersion period												
P	4.2	8.2	6.8	4.4	9.1	13.3	13.3	28.3	21.4	12.6	14.7	20.6
WP	31.2	35.8	34.7	36.7	28.4	32.2	52.0	46.9	35.9	44.2	32.7	43.6
LA	24.9	25.4	29.9	33.9	39.6	25.2	10.0	7.1	15.8	20.6	25.3	10.4
LB	17.9	28.4	23.5	19.8	21.3	19.1	17.0	15.0	20.5	16.1	13.3	11.4
WL	21.8	2.2	5.1	5.2	1.5	10.2	7.7	2.7	6.4	6.5	14.0	13.9
Autumn migration period												
P	20.9	12.5	11.1	10.3	9.6	15.7	30.7	24.3	40.2	29.3	27.3	25.1
WP	24.6	37.5	37.3	45.7	34.2	41.3	21.6	21.4	18.0	37.1	20.5	24.8
LA	13.7	33.3	35.7	21.6	26	19.9	6.7	7.1	9.8	6.4	6.8	16.2
LB	2.4	12.5	4.8	6.0	5.5	3.8	3.3	0.0	0.0	0.0	0.0	1.8
WL	38.4	4.2	11.1	16.4	24.7	19.2	37.7	47.1	32.0	27.1	45.5	32.1

Explanations: B200 = 200 m buffer, B1000 = 1,000 m buffer, R = Ręczyn, Ko = Kolno, G–Z = Grabik–Żary, Ka = Karpicka, W = Witnica, Z = Zwartowo, P = passerine or migrating, WP = using the study area (resting, foraging), LA = definitely breeding, LB = possibly breeding, WL = found on the plot during the breeding season but not fulfilling any of the LA and LB criteria.
Source: own study.

and collide with these structures treating them as a landing places (Kagan *et al.*, 2014). For these reasons, PV farm locations are not recommended near wetlands and open water. The analysed areas are typical agricultural areas, where only in one location (Ręczyn) water bodies were present. The occurrence of open water in the vicinity of this farm most probably resulted in an increased number of bird species (61 species). It should be noted that the highest density of birds in the area occurred in autumn periods, which may indicate temporary resting or even wintering of migratory birds.

The land-use structure plays a crucial role in evaluating the risks to bird populations, not only at photovoltaic farms but also at wind farms. Mandatory monitoring of bird populations before and after the implementation of RES systems helps to more accurately estimate the risk of mortality of these animals, especially near free migration corridors. The reason for this is the danger of collision with a rotating or even stationary wind turbine rotor. The Ręczyn installations analysed in this study, but also Grabik–Żary, Karpicka, Witnica, and Kolno are located within or in the vicinity of ecological corridors of pan-European importance (Jędrzejewski *et al.*, 2011), and for these reasons, the avifauna of Europe may be more exposed to cumulative impacts. This may necessitate detailed monitoring during spring and autumn migration periods in these areas.

Considering the location of the close location of two types of RES installations may not only cause cumulative but also synergistic effects. Potentiating impacts may arise from the presence of a number of animal species that are food sources for birds of prey (generally HCR species) at wind farms. Predator-prey encounters or territory defence, in which the pursuer or pursued is at risk of collision with components of the technical infrastructure, are indicated by the studies of Hager and Craig (2014), Kahle, Flannery and Dumbacher (2016), and Smallwood (2022). The results of our study indicate that the potential expansion of PV farms with wind farms may influence increased collision risks, particularly during spring and autumn migration periods, where the occurrence of the HCR bird group was significantly higher than during other periods. This may mean increased mortality of birds of this group during these periods of the year. During autumn migration, *Accipiter nisus* and *Falco tinnunculus* observed in the study area behave in a way that makes them more vulnerable to collisions (although they were not observed), which is in line with research results presented in the literature (Hötker, 2006; Illner, 2011; Dürr, 2020).

During the post-migration period, when birds search for food and penetrate the area with greater intensity, the most vulnerable are species of the genus *Circus* sp., commonly found in both buffers of the analysed PV farms. Other birds of prey from the HCR group, such as *Haliaeetus albicilla*, *Milvus milvus* and *Pandion haliaetus* have been observed sporadically in the study area and are therefore less likely to be found as collision victims. However, it should be emphasised that there can be significant discrepancies in estimating the effects of collisions between birds and wind turbines. This is because the number of factors influencing these values is complex and difficult to determine precisely. According to Hötker (2006), the number of collision victims can range from 0 victims/turbine/year to 64 victims/turbine/year.

Industrial areas, resulting from the combination of RES installations, can sometimes improve the biodiversity of the fauna of these areas (Nordberg and Schwarzkopf, 2023; Tölgyesi *et al.*, 2023; Boscarino-Gaetano, Vernes and Nordberg, 2024). The structural elements of PV farms, as well as the landscaping of the plots with isolation greenery, enrich the landscape structure and provide habitat and breeding opportunities for various invertebrate and vertebrate species, which are attractive food for predators and omnivores (Chock *et al.*, 2021; Chozas *et al.*, 2022; Nordberg and Schwarzkopf, 2023). This poses an additional threat to birds, as they may not only be exposed to the lake effect, but to collisions with nearby wind turbines. Studies have indicated that LCR birds are abundant during the breeding period and post-breeding dispersion one. They were also shown to be significantly denser in a 200 m buffer than in a 1,000 m buffer, confirming the attractiveness of PV farms to this group of birds. A key issue is, therefore, the proper management of the development site to preserve small areas of shrubs, hedgerows, etc. – the potential habitats for insects that provide food for birds.

The results of the study show that the structure of the avifauna occurring within and in the immediate vicinity of photovoltaic farms is variable and depends on both the nature of the specific installation and the phenological period. There is a consistently high proportion of non-breeding species that use the farm site as a feeding or resting area. This demonstrates the continued interest of a certain group of birds in this type of land use. During the breeding and nesting dispersal period, there is greater activity and density of species that are definitely or probably nesting on the installation. According to Golawski, Mitrus and Jankowiak (2025), that phenomenon considers such species as the corn bunting (*Emberiza calandra*) and whinchat (*Saxicola rubetra*). This decreases – albeit slightly – during the post-breeding season, but this is mainly because some species simply fly away, while a significant proportion of those that consistently visit problem areas are wintering ones.

CONCLUSIONS

1. The structure of the avifauna occurring within and in the immediate vicinity of photovoltaic farms is variable and depends on both the nature of the specific installation and the phenological period.
2. The potential expansion of photovoltaic farms to include wind farms may have the effect of increasing collision hazards, particularly during spring and autumn migration periods, as significantly higher densities of High Collision Risk birds were found during these times than during other periods.
3. The birds of Low Collision Risk were abundant in the range of photovoltaic farms during the breeding period and post-breeding dispersion and significantly more densely distributed within a buffer of 200 m than 1,000 m from the installation.
4. The attractiveness of photovoltaic farms for this group of birds, may influence the possibility of not only cumulative impacts, but also synergistic impacts when photovoltaic farms are extended with wind farms.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at: https://www.jwld.pl/files/Supplementary_material_66_Oglecki.pdf.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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