



Bird community assembly in utility-scale solar farms of agricultural landscapes

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ARTICLE INFO

Keywords:

Ecovoltaics
Grassland birds
Landscape composition
Photovoltaics
Renewable energy
Urbanization

ABSTRACT

Bird communities are facing heavy declines, especially in agricultural landscapes. An exponentially spreading landscape feature, photovoltaic solar farms, may offer an opportunity for their conservation. Compared to croplands and other disturbed areas, solar farms may provide stable food and nesting sources, but also pose challenges due to intensive vegetation management and the presence of artificial structures. We know little about how bird communities respond to these novel habitat characteristics, preventing the formulation of evidence-based guidelines to benefit birds in solar farms. Here, we aimed to unravel drivers of bird community patterns in solar farms embedded in transformed, agricultural landscapes. Using data from 32 farms and surrounding landscapes, we found that birds in the farms form distinct communities compared to the surrounding landscape, and the bigger the farm, the more distinct the community. Indicator species of solar farms include urban and open-habitat species, while forest species only spill over to the farms from adjacent woody habitats. Although some open-habitat species regularly occur in solar farms, those that require a clean skyline avoid the farms. In addition, if better-quality grasslands are available around, open-habitat birds do not enter in higher numbers but tend to lower their preference on the farms. Birds showed seasonal variation in solar farm use; they were more common during the breeding season than in the fall. These findings highlight the potential (e.g., for open-habitat bird conservation) and the limitations (e.g. unfavourable off-season conditions) of solar farms, which we could strategically exploit and should navigate with targeted interventions, respectively.

1. Introduction

Global energy consumption is expected to double by the mid-21st century (Kober et al., 2020), while there is growing demand for renewable solutions to slow down climate change (Papadis and Tsatsaronis, 2020). This challenge spurred renewable energy developments worldwide, and the utilization of solar energy has become the fastest-growing option (Van de Ven et al., 2021, Nijssen et al., 2023). Compared to other energy sources, solar irradiation has a low energy density, necessitating large land allocations when photovoltaic panels

are deployed on the ground (1.6–3.5 ha MW⁻¹, depending on climatic conditions) (Hernandez et al., 2014, Ong et al., 2013, Blaydes et al., 2021), making solar energy utilization an emerging land-use type (Späth, 2018; Hermoso et al., 2023). For example, the USA has set aside 8900 km² potential area for future solar developments in eleven western states (BLM (Bureau of Land Management), 2024), while European economies, such as the UK or Poland, have also pledged themselves to similar levels of greening, including an up to tenfold increase in the cumulative area of utility-scale solar farms by 2030 (UK Government, 2023, <https://www.smart-grids.pl>, <https://www.teraz-srodowisko.pl>).

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<https://doi.org/10.1016/j.biocon.2026.112025>

Received 26 December 2025; Received in revised form 20 July 2026; Accepted 23 July 2026

Available online 28 July 2026

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The exponential spread of solar farms can lead to conflicts with other land-based activities, such as agriculture or nature conservation (including restoration). Agricultural production can be continued in solar farms if scaffolds and panels are adjusted to fit the movement of agricultural machinery and appropriate crop types are selected to match the altered site conditions (Dinesh and Pearce, 2016). As an analogue to this ‘agrivoltaic’ solution, ‘ecovoltaic’ solar developments combine biodiversity conservation and components of nature restoration with solar energy generation (Sturchio and Knapp, 2023; Tölgyesi et al., 2023). However, solar farms have unique habitat features (solar panels, scaffolds, fences, and other accessories) and vegetation management requirements (e.g. to avoid panel shading) that have consequences on wildlife. Therefore, careful, evidence-based guidelines are needed on how to optimize for biodiversity (e.g., to provide nesting sites or provide food sources for birds) and best assist nature recovery in solar farms to make them ecovoltaic.

To construct and maintain ecovoltaic solar farms, we first need to understand how wildlife interacts with solar facilities. Solar farms are known to increase habitat fragmentation as the artificial structures are avoided by some animals, and the fences represent significant barriers to the movements of large animals, such as mammals (Levin et al., 2023). Water-associated animals (e.g. water birds and polarotactic insects) can mistake solar arrays for water, leading to collisions (Walston Jr et al., 2016; Visser et al., 2019) and reproductive failures (Horváth et al., 2010). However, the most substantial concern for wildlife is habitat loss, as major solar developments in many regions of the world often occur in natural areas, such as grasslands (Hernandez et al., 2015; Tsafack et al., 2022; Young et al., 2025). A particularly vulnerable group of species in such areas is open-habitat specialist birds (often referred to as ‘grassland birds’), which have already undergone massive declines globally due to agricultural expansion and land-use intensification (Brennan and Kuvlesky Jr, 2005; Douglas et al., 2023). Overall, the impact of such solar developments is likely to be negative on grassland birds by decreasing habitat quality or supporting synanthropic, often invasive bird species (DeVault et al., 2014; Visser et al., 2019; Young et al., 2025).

The effects of solar developments on birds are not necessarily negative in agricultural landscapes, particularly if the farms are constructed in the place of croplands, mining sites, and other degraded brownfields. This is the case in much of Europe and other regions of the globe with a large human footprint index, where remote natural areas are scarce and, if present, are no-go zones for solar developments (Golowski et al., 2025). In agricultural landscapes, we can expect a mixture of negative and positive effects on bird communities. Compared to croplands with regular soil and vegetation disturbance, low food diversity, and limited nesting opportunities, solar farms can offer more favourable conditions, but the artificial structures or some grassland management options, such as maintaining a short turf, are not necessarily perceived as attractive habitat features (Jarčuška et al., 2024; Copping et al., 2025). Optimizing for the above positive effects can potentially yield considerable improvements for bird communities. Such targeted improvements have been initiated for other organisms, such as vascular plants and pollinators (Blaydes et al., 2021; Lambert et al., 2022; Meyer et al., 2023), but, for birds, no evidence-based guidelines can be developed as long as we do not have a more in-depth understanding of their community-level interaction with solar farm habitats. To this end, we aimed to unravel community assembly patterns of birds in solar farms located in agricultural landscapes of Central Europe. Specifically, we hypothesized that 1) that solar farms can maintain distinct bird communities compared to the surrounding landscape, and the level of compositional distinctness is determined by local to landscape level ecological drivers (incl. farm size, season, management intensity, soil type, and landscape composition), and 2) these ecological drivers also affect the diversity, abundance, and composition of bird communities within the solar farms.

2. Material and methods

2.1. Study area

The study was carried out in the Great Hungarian Plain of Hungary, Central Europe. The region has a subcontinental climate with an increasing Mediterranean influence. Its mean annual precipitation and temperature range between 500 and 600 mm and 11–12 °C, respectively (Erdős et al., 2024), and it is located 80–140 m above sea level. Native vegetation is primarily forest-steppe, which is a mosaic transition between temperate broadleaf forests of Western Europe and the arid steppes of Eastern Europe and Middle Asia (Erdős et al., 2018). However, most of the natural ecosystems of the region have been transformed into cropland, tree plantations, or urbanized areas (Biró et al., 2013, 2018). As a recent trend since the late 2010s, utility-scale solar farms have appeared as a novel land-use type, and their number is still increasing rapidly. Most solar farms have been built on former arable land, and their vegetation is managed solely to serve the purposes of energy production, mostly leading to low-nature-value grassland vegetation among the panels. Ecovoltaic principles, where supporting biodiversity is intentionally considered (see Tölgyesi et al., 2023; Sturchio and Knapp, 2023), have not become a regular strategy yet.

2.2. Data collection

We selected 32 solar farms in the region, differing from each other in terms of size, soil type, and management intensity (Fig. 1). All variables had two levels. Regarding size, we had small (1–1.5 ha) and large (4–10 ha) farms; intermediate sizes are rare in the entire region due to technological reasons. We classified soils into either coarse-grained sand or clayey-loamy, cohesive soils, with a strong effect on the species composition and structure of the vegetation. Sandy farms are arid and have bare patches, while cohesive soils usually host a continuous-canopy sward. Managers either applied intensive methods to suppress vegetation, including spraying herbicides and frequent mowing (up to 3–4 times a year), or followed a more moderate management with no spraying and less frequent mowing (2–3 times a year), and sometimes grazing. Information about the management was directly obtained from the solar farm owners. We also considered the composition of the landscape in 1000-m zones around the farms (henceforth “surrounding landscape”). We used the CORINE Land Cover (CLC) dataset (European Environment Agency (EEA), 2018) and reclassified the original CLC categories using high-resolution (3 m) four-band PlanetScope satellite imagery provided by Planet Labs (Planet Team, 2025). Categories included ‘cropland’ (arable fields, orchards and vineyards), ‘forest’ (forested and shrubby habitat patches outside urban areas), ‘grassland’, and ‘urban area’ (inhabited areas, roads, strongly disturbed areas such as quarries and sandpits). Images corresponding to the sampling periods were selected to ensure temporal consistency with biological data. We processed all satellite images and derived data with ArcGIS Pro (ESRI (Environmental Systems Resource Institute), 2024).

We surveyed every solar farm once in summer (in June) for resident birds after the end of the spring migration, and once in fall (in October) during migration. Half of the parks were surveyed in 2023 and the other half in 2024. After arriving to the solar farms, we allowed a few-minute settling period for the birds before starting the survey. During the surveys, we slowly walked for 20 min along the perimeter of the farms and recorded every bird – heard or seen – that was inside (e.g. perched on solar structures, feeding on the ground, etc.) or actively used the airspace of the farm (hovering kestrels, hunting swallows, etc.). The allocated time was enough to compile a complete checklist for both small and large farms. A spatially more balanced sampling effort could have been achieved by sampling only a fraction of the large farms that equalled the size of small farms but that would have pushed a solar farm part to the surroundings of the sampled part of the large parks, which would have always been absent in the surroundings of small farms. We

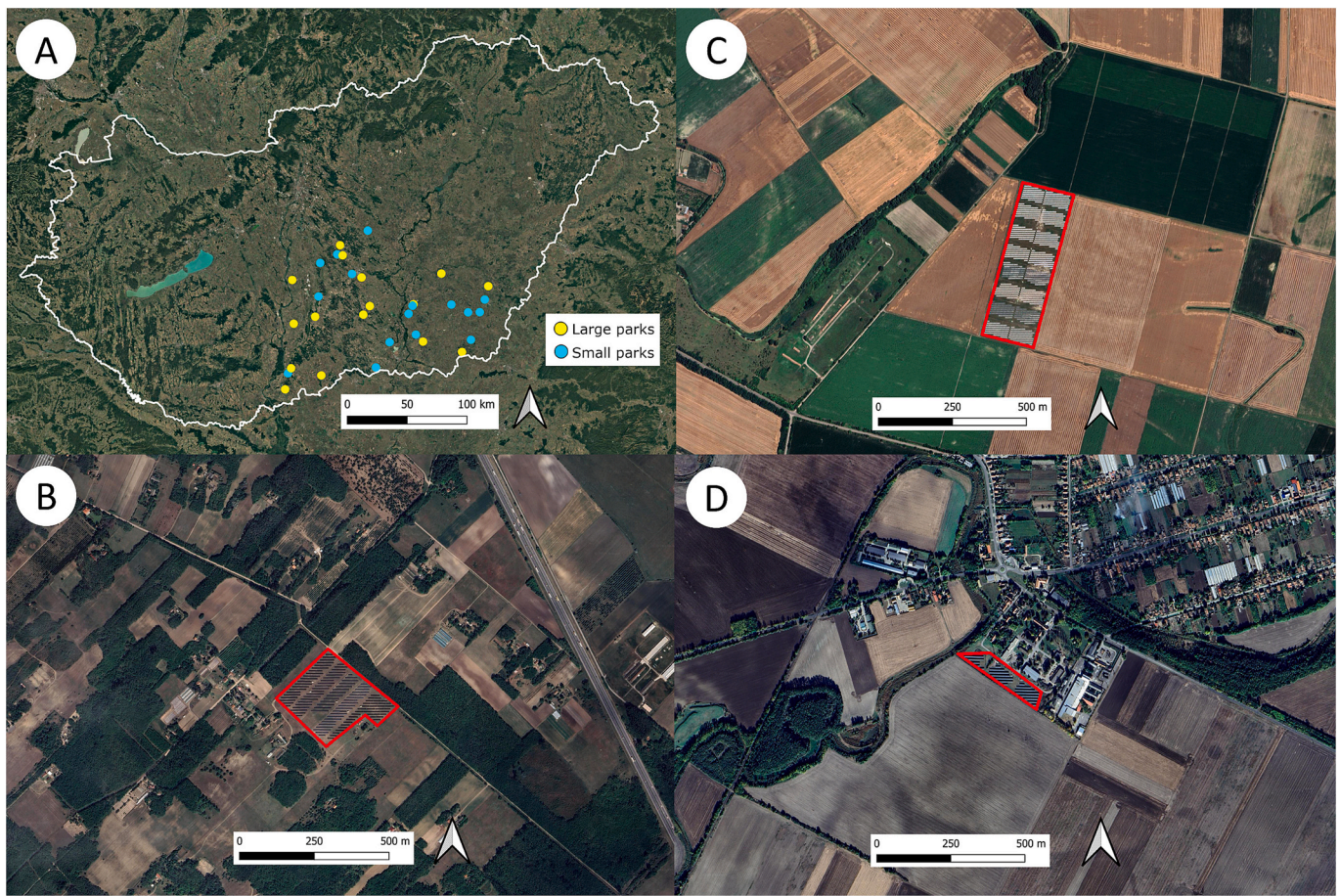


Fig. 1. Distribution of the studied 32 solar farms in the Great Hungarian Plain, Central Europe (A); a large solar farm near Kalocsa in a predominantly agricultural landscape with a small share of grassland (B), a large solar farm with higher forest cover in its surroundings near Jászszentlászló (C), and a small solar farm in an urbanized environment near Mezőkovácsháza (D).

considered this more difficult to handle during the interpretation of the results than a simple difference in the size of the sampling sites. We also recorded every bird – heard or seen – in an approximately 150 m wide section of the surrounding landscape around the farm (henceforth “surrounding buffer”). Since forested habitats were comprised by semi-arid tree plantations and small spontaneous patches of woody species, it was possible to detect most birds both in open and forested parts of the buffer with equal reliability, although some silent foraging individuals might have remained elusive in all habitat types. Flybys (e.g. migrating birds) without interaction with the farm below or its buffer zone were noted but excluded from the analysis. Birds that we flushed during the survey and changed position (to the buffer from the farm or to the farm from the buffer) were counted only in their former position. Birds that crossed the border of the solar farms on their own were recorded to both the solar farm and its buffer. Birds that left one of the locations to the direction of the other but without landing or interacting with it in any active way were recorded only in the first location. Surveys were conducted within four hours after sunrise (approx. From 5 a.m. to 9 a.m. in summer and from 7 a.m. to 11 a.m. in October). All surveys were done by the first author; therefore, data quality was not affected by inter-observer differences.

2.3. Comparing solar farms to surrounding buffer habitats

All data processing and analysis were performed in R 4.2.2. (R Core Team, 2022). Raw species richness and abundance data are of limited usability for solar farm vs. surrounding buffer comparisons because buffer sizes showed high variation due to the different shapes and sizes

of the farms; therefore, we analysed only compositional and proportional data. First, we tested whether the bird community composition of solar farms differed from the surroundings with permutational multivariate analysis of variance (PERMANOVA). For this, we used the ‘adonis2’ function of the *vegan* package (Oksanen et al., 2024); the distance measure was Bray-Curtis dissimilarity, locality was set as strata, and we applied a permutation test with 5000 permutations. We also compared multivariate dispersion between solar farms and the surrounding buffers using the ‘betadisper’ and ‘permutest’ functions of the *vegan* package (Bray-Curtis dissimilarity, 5000 permutations, and locality used as strata). We visualized compositional patterns with non-metric multidimensional scaling (NMDS), with Bray-Curtis dissimilarity on log-transformed bird counts, using the ‘metaMDS’ function of the *vegan* package. We applied data transformation because some counts were rather large compared to the rest, but the ecological importance of this was comparatively low, as the high scores occurred due to the flocking behaviour of some species (e.g., Common Starling).

After describing the main compositional patterns, we separated the compositional difference of sample pairs (between each solar farm and its surrounding buffer; no cross-locality distances were considered) into its two components, turnover and nestedness, using the ‘beta.pair’ function of the *betapart* package (Jaccard distance, Baselga et al., 2023). We compared the two components with a paired Wilcoxon signed-rank test to reveal any difference in their importance. High turnover can indicate that each sample type (solar farm or surrounding buffer) has its own species, while a high nestedness indicates that one of the samples is just a subset of the other, more diverse one, e.g. if only a subset of the birds enter solar farms from the surroundings. Since the turnover

component was higher, we prepared a linear mixed-effects model to understand what determines its value. We used management intensity, soil type, landscape composition (i.e. the share of cropland, grassland, forest, and urban area in the surrounding landscape), park size, and season as fixed factors and locality as the random effect. We prepared the model with the 'lmer' function of the *lme4* package (Bates et al., 2015). We checked the predictors for multicollinearity with the 'vif' function of the *car* package (Fox and Weisberg, 2019), and calculated pairwise correlations among them using the built-in 'cor.test' function. We found high variance inflation factor for the proportion of arable land, forest, grassland, and urban areas in the landscape buffer. We checked the actual correlation pattern between these variables with the built-in 'cor.test' function and found that arable land correlated negatively with the others, while the others did not have a significant correlation with each other (Table S1). We thus dropped arable land from the model, and after this, all VIF values remained below 2. We tested the individual predictors for significance using the 'Anova' function of the *car* package. Since the retained, non-correlated landscape composition predictors are proportional, significant effects of their increasing proportion is to be interpreted together with decreasing arable land cover proportions. We calculated the marginal R^2 values with the 'r.squaredGLMM' function of the *MuMIn* package (Bartoni, 2025). We checked the residual distribution with QQ-plot and found no significant deviation (Fig. S1). We tested the model for outliers with the 'check_outliers' function of the *performance* package (Lüdecke et al., 2021), and found no outliers.

We also made an indicator species analysis using the 'multipatt' function of the *indicspecies* package (De Cáceres and Legendre, 2009) to identify species significantly associated with solar farms and the surrounding buffer. The analysis calculates indicator values following the IndVal approach of Dufrene and Legendre (1997). It combines two components describing how characteristic a species is to a group of samples: specificity (how restricted a species is to a group) and fidelity (how consistently the species occurs within that group). A high indicator value therefore means that a species occurs mainly in one group and is present in most samples of that group. Statistical significance of species-group associations was assessed using a permutation test.

We categorized species according to their habitat preferences into open-habitat, forest, urban, and wetland birds using Mullarney et al. (2023) and our own expertise on regional conditions (Table S2). Open-habitat birds were those inhabiting grasslands but also occurring on arable land, while all species that prefer denser woody vegetation from closed-canopy forests to shrubby thickets were included in the category of forest species. Double preferences were allowed for species that regularly use two habitat types. We did not use fuzzy classification; a species with double affiliation contributed to each category with the same weight as single-affiliation species. We calculated the proportion of each species group (species richness and abundance) in all farms, both inside and outside, and compared the proportion of open-habitat, forest, and urban birds inside and outside using paired *t*-tests. Wetland birds were scarce; therefore, we excluded them from this analysis.

2.4. Effects of ecological drivers on solar farm birds

After the comparison of the bird fauna inside and outside the farms, we took a closer look at the inside fauna. We tested the effect of management intensity (high and low), soil type (sandy and cohesive), farm size (small and large), and season (summer and fall) using PERMANOVA the same way as above (Bray-Curtis dissimilarity, locality as strata, 5000 permutations, 'adonis2' function). For significant drivers, we checked for indicator species by calculating indicator values, similar to the inside vs. outside analysis. We visualized the compositional patterns of the bird communities using NMDS (Bray-Curtis dissimilarity, 'metaMDS' function).

To assess bird diversity patterns in the farms, we prepared generalized linear mixed-effects models for the species richness and linear

mixed-effects models for the log-transformed abundance of the bird communities, with management intensity, soil type, the share of cropland, grassland, forest, and urban area, farm size and season as the fixed effects, and locality as a random effect. We used Poisson error term for species richness and Gaussian for abundance. The Poisson model was tested for overdispersion with the 'testDispersion' function of the *DHARMA* package (Hartig, 2026). We checked both models for outliers with the 'testOutliers' function of the *performance* package (Lüdecke et al., 2021), and found no outliers. We tested the Poisson model for zero inflation with the 'testZeroInflation' function of the same package, and found no zero inflation. Residual diagnostics for the Gaussian model was implemented by assessing the QQ-plot, while for the Poisson model we used the 'simulateResiduals' function of the *performance* package and plotted the output. No severe deviation was detected in any of the models (Fig. S2–3). We calculated marginal R^2 values with the 'r.squaredGLMM' function of the *MuMIn* package (Bartoni, 2025).

The average species richness and abundance in the surrounding landscapes tended to be somewhat lower in fall (11.6 and 13.0, respectively) than in summer (13.9 and 13.4, respectively). Therefore, we made an additional analysis that controlled for this difference by standardizing species richness and abundance with their average season-specific values in the surrounding landscape, and tested the effect of season on these adjusted scores using linear mixed-effects models.

Finally, we prepared generalized linear mixed-effects models for the species richness (Poisson error term) and linear mixed-effects models for the abundance (Gaussian error term) of the three main groups of birds according to habitat preference (forest, open, and urban habitats) and tested the effect of management intensity, soil type, landscape composition (i.e. the share of cropland, grassland, forest, and urban area in the surrounding landscape), farm size, and season following the same approach and diagnostics protocol as for the other mixed-effects models. The models for urban and open habitat bird species richness showed significant overdispersion ($p < 0.05$); therefore we proceeded with negative binomial models for these variables, implemented with the 'glmer.nb' function of the *vegan* package (Oksanen et al., 2024). We found a slight deviation in the QQ-plots of urban species but we did not consider it critical; the other models did not show any deviation from the assumptions (Fig. S2–3).

3. Results

3.1. Solar farm vs. surrounding landscape

Despite the moderate sampling effort (single visits in 32 solar farms), we detected a total of 3607 bird individuals (683 inside and 2914 outside) of 87 bird species (47 inside and 81 outside; Fig. 2, Table S2). Inside and outside species composition differed significantly (PERMANOVA, $F = 13.61$, $p < 0.001$). Beta dispersion was also significant ($F = 13.38$, $p = 0.001$), but the significant PERMANOVA did not seem an artifact of this as the NMDS scatterplot (Fig. 3), although the stress factor was slightly high (0.20), indicated a clear separation of the two groups (inside and outside). The ellipses were also different in size, reflecting the different multivariate dispersions. Therefore, the justified compositional difference allowed us to proceed with dissimilarity partitioning, and found that the turnover component of the Jaccard distance was significantly larger than the nestedness ($V = 1046.5$, $p = 0.009$), thus, birds in solar farms are not just a subset of the overall surrounding landscape but have some species that have preference on them, while some others apparently avoid them.

Species with a preference for solar farms included Black Redstart (*Phoenicurus ochruros*) ($p < 0.001$), White Wagtail (*Motacilla alba*) ($p = 0.009$), Red-backed Shrike (*Lanius collurio*) ($p = 0.016$), and House Martin (*Delichon urbicum*) ($p = 0.046$) according to the indicator species analysis. The surrounding landscape had a total of 28 significant indicator species (Table S3), which avoid solar farms if occurring in the area. Most of these species (18) are associated, at least partly, with woody

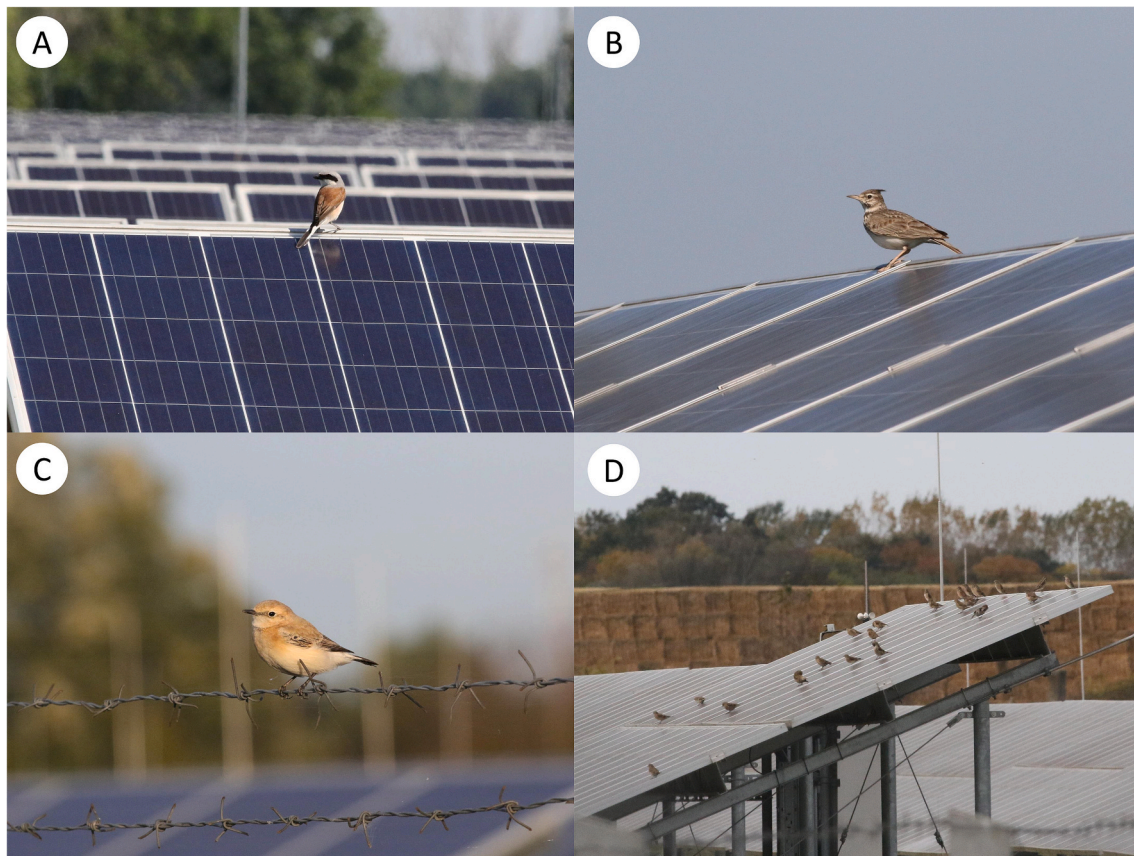


Fig. 2. Red-backed Shrikes (*Lanius collurio*) (A) and Crested Larks (*Galerida cristata*) (B) frequently use solar panels as observation and singing posts in the studied solar farms. The first observation of Western Black-eared Wheatear (*Oenanthe hispanica*) for Hungary was found in a solar farm during this study (C). Some birds, such as Common Linnets (*Linaria cannabina*) not only feed in solar farms but also use the panels to warm themselves up during cold spells (D). Photos by [blinded]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

habitats, but some grassland specialists, such as Skylark (*Alauda arvensis*), were also among them.

According to the linear mixed-effects model on turnover, higher scores were associated with larger farms and summer season (Table 1). The other tested variables had no effect on turnover; the overall marginal R^2 was 0.21.

The proportions of the richness and abundance score of the species groups differed greatly between the solar farms and their surroundings (Table 2). Forest bird species were proportionately more frequent in the surrounding landscape than inside the farms, while the proportion of both open-habitat and urban bird species was higher in the solar farms than in the surrounding landscape. The proportion of the abundance of forest birds was also lower, whereas that of urban birds was higher in the farms compared to the surroundings. We found no difference in the proportion of the abundance of open-habitat birds between inside and outside communities.

3.2. Community patterns within solar farms

The bird species composition of solar farms was affected by the size of the farms (PERMANOVA, $F = 2.10$, $p = 0.019$) and season ($F = 9.20$, $p < 0.001$), but management type and soil had no significant effect ($F = 1.51$, $p = 0.103$ and $F = 1.54$, $p = 0.094$, respectively). Summer and fall data separated clearly, but the distinction according to size was less pronounced in the NMDS scatterplot (Fig. 4). Significant indicator species for large farms included Common Starling (*Sturnus vulgaris*) ($p = 0.009$), Crested Lark (*Galerida cristata*) ($p = 0.012$), and White Wagtail (*Motacilla alba*) ($p = 0.026$). Small farms had no indicator species. Regarding season, we found six indicator species for the summer season

and two for the fall season (Table 3).

According to the generalized linear and linear mixed-effects models both total species richness and abundance in the solar farms were affected by farm size and season, and marginally negatively by the cover of grassland in the landscape buffer, while the other predictors had no detectable effect (Figs. 5 and 6, Table S4). Larger farms, summer season, and potentially less grassland around the farms contributed to higher species richness and abundance scores. According to the models on the species richness and abundance scores standardized with the season-specific availability of birds in the landscape, we still found that the solar farms had fewer species ($\chi^2 = 69.71$, $p < 0.001$) and lower abundance ($\chi^2 = 65.25$, $p < 0.001$) in fall than in summer.

The species richness of forest specialist birds was higher with a larger forest cover and urban area (and thus potentially with lower arable cover due to the multicollinearity) in the landscape buffer, and was also higher in summer than in fall (Figs. 5 and 6, Table S4). Management, soil type, grassland cover in the landscape buffer, and, interestingly, farm size had no detectable effect. Effect patterns were similar for the abundance of forest species, although forest cover had only a marginally significant effect, and larger solar farms had marginally higher abundance scores. Concerning the species richness and abundance score of open-habitat birds, farm size and season had significant effects (higher scores in large farms and in summer). Higher grassland cover in the surroundings was associated with marginally lower open-habitat bird abundance. Urban birds were significantly affected by farm size and season, both in terms of species richness and abundance, with higher scores in large parks and in summer; the other predictors had no significant effects.

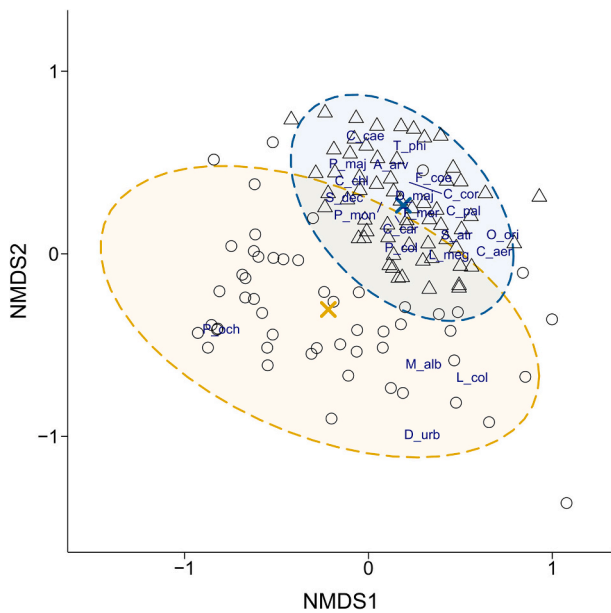


Fig. 3. NMDS scatterplot of bird communities of solar farms (circles) and 150-m wide surrounding landscape buffers (triangles) with their 95% ellipses and centroids in the middle. Only indicator species with a $p < 0.001$ are shown. Stress: 0.20. A_arv: *Alauda arvensis*, C_car: *Carduelis carduelis*, C_aer: *Circus aeruginosus*, C_pal: *Columba palumbus*, C_cor: *Corvus cornix*, C_cae: *Cyanistes caeruleus*, D_urb: *Delichon urbicum*, D_maj: *Dendrocopus major*, F_coe: *Fringilla coelebs*, L_col: *Lanius collurio*, L_meg: *Luscinia megarhynchos*, M_alb: *Motacilla alba*, O_ori: *Oriolus oriolus*, P_maj: *Parus major*, P_mon: *Passer montanus*, P_och: *Phoenicurus ochruros*, S_dec: *Streptopelia decaocto*, S_atr: *Sylvia atricapilla*, T_mer: *Turdus merula*, T_phi: *Turdus philomelos*.

Table 1

Test results of the linear mixed-effects model on the turnover-related component of Jaccard dissimilarity between the bird fauna of solar farms and their surrounding landscape. Significant predictors ($p < 0.05$) are indicated with boldface.

Variable	Chi ²	p
Management	0.02	0.883
Soil type	0.72	0.789
Surrounding forest cover	0.05	0.820
Surrounding grassland cover	0.04	0.833
Surrounding urban area	1.21	0.270
Farm size	4.25	0.039
Season	6.78	0.009

Table 2

Proportions (mean $\pm$ SEM) of the species richness and abundance of birds specific to certain habitats and the statistical test results of the comparisons between solar farms and their surroundings calculated using paired t -tests. The sum of proportions exceeds 1 both in the solar farms and in the surroundings for both species number and abundance because double habitat preferences were allowed. Significant differences are marked with boldface.

Species richness	Solar farm	Surroundings	t	p
Forest species	0.25 $\pm$ 0.02	0.52 $\pm$ 0.04	6.74	<0.001
Open-habitat species	0.46 $\pm$ 0.04	0.36 $\pm$ 0.02	-2.17	0.032
Urban species	0.55 $\pm$ 0.04	0.37 $\pm$ 0.02	-4.47	<0.001
Abundance				
Forest species	0.22 $\pm$ 0.04	0.48 $\pm$ 0.02	6.30	<0.001
Open-habitat species	0.50 $\pm$ 0.04	0.50 $\pm$ 0.03	0.09	0.926
Urban species	0.60 $\pm$ 0.04	0.44 $\pm$ 0.02	3.69	<0.001

4. Discussion

4.1. Solar farms vs. surrounding landscape

The exponential global spread of photovoltaic solar farms is a relatively recent phenomenon; therefore, we know little about how bird communities interact with them, potentially rendering the realization of ecovoltic concepts rather ad hoc for this group of organisms. Here, we contribute to our knowledge on the opportunities and limitations ecovoltic developers may encounter by providing a detailed assessment of bird community patterns in solar farms in a central European region.

We found that bird communities associated with solar farms are rather distinct from the surrounding landscape, as some species avoid the parks, while others are attracted to them, which is more pronounced in large farms and summer. The lower distinctness of small farms may be related to the territory sizes of bird species recorded. Red-backed Shrikes usually have a territory size of around 1.5 ha (Golawski and Mitrus, 2018), which is the maximum size of the small farms, whereas the European Stonechat, another common species in our dataset, may need up to 4 ha (Hueting and Santucci, 2024), forcing them to use both the farms and the surroundings in the case of small farms. The lower turnover in the fall season may be related to the fact that birds are often less habitat specific during migration (Chernetsov, 2006).

Species that avoided solar farms generally had a preference for woody vegetation. This is not surprising, as the panels and their frames, even though they may distantly resemble shrubby conditions (due to shading and emergent structures with vertical components), probably do not provide the necessary food resources. Although these emergent structures do not attract forest birds, some grassland birds, such as Skylarks, also avoid solar farms as the resulting habitat is probably not open enough. So, solar farms are neither recognized as a shrubby-woody habitat, nor as pure grassland by the bird communities. The latter deficiency was apparent in some other studies, where Skylark (Jarčuška et al., 2024; Golawski et al., 2025), as well as ecologically similar species in North America (e.g. Horned Lark and Grasshopper Sparrow; Walston et al., 2025) and South Africa (e.g. Eastern Clapper Lark; Visser et al., 2019) also avoided solar farms. In contrast, open-habitat birds that need observation points for sit-and-wait foraging (e.g. Red-backed Shrikes) and singing (e.g. Crested Larks) can take advantage of the structures that are provided by the solar farms but are scarcer in managed grasslands. This species group is also overrepresented in the solar farms of other regions (e.g. Young et al., 2025), so this may be a general pattern. However, it is unclear if solar farms are indeed favourable for them or they are just attracted by the availability of perches without getting access to more food resources, and thus falling into an ecological trap. Ecological traps are widespread for birds, particularly in anthropogenic, transformed landscapes (Battin, 2004; Zuniga-Palacios et al., 2021); therefore, this potential concern requires special attention before solar farms are deemed as a novel tool for the conservation of open-habitat birds. Future research should evaluate food availability and consumption rates as well as breeding success compared to high-quality grassland habitats.

Despite the mixed response of open-habitat birds, bird communities recognize solar farms more as grassland than shrub- or woodland, as open-habitat species are generally attracted to the solar farms, while birds of woody habitats tend to stay away, as indicated also by their proportional distributions (see also Zaplata and Dullau, 2022 for German solar farms). The third group, urban birds, was also attracted to the farms. Species that frequent artificial structures (Black Redstart and White Wagtail) or typically nest in anthropogenic environments (House Martin) were among the indicator species of the studied solar farms. Such species, even if anthropogenic habitats are scarce in the landscape, can find the farms relatively quickly after their construction (Young et al., 2025), and are major contributors to the higher species richness and abundance of birds inside the farms compared to outside plots (Jarčuška et al., 2024; Copping et al., 2025). This calls attention to the

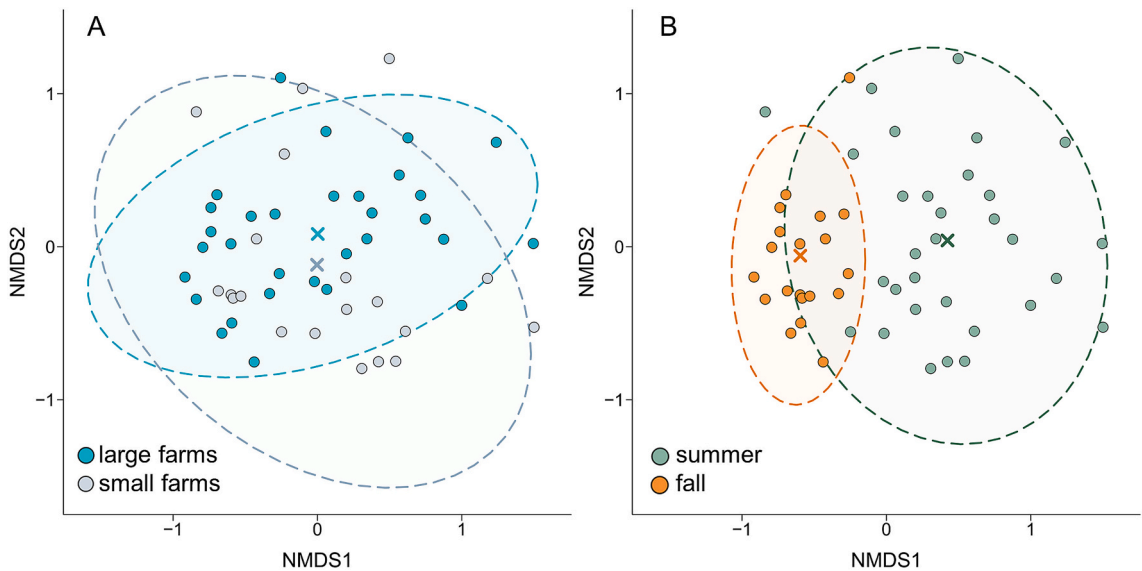


Fig. 4. NMDS scatterplot of solar farm bird communities with the indication of different farm sizes (A) and seasons (B). Ellipses indicate 95% predictions for each category level and centroids are shown in the middle. Stress: 0.16.

Table 3
Significant indicator species of solar farms for the summer and fall seasons as calculated with indicator value analysis.

Summer	
Species	p
Barn Swallow (<i>Hirundo rustica</i>)	<0.001
Red-backed Shrike (<i>Lanius collurio</i>)	0.001
White Wagtail (<i>Motacilla alba</i>)	0.001
Common Starling (<i>Sturnus vulgaris</i>)	0.007
Tree Sparrow (<i>Passer montanus</i>)	0.048
Stonechat (<i>Saxicola rubicola</i>)	0.050
Fall	
Species	p
Black Redstart (<i>Phoenicurus ochruros</i>)	<0.001
Meadow Pipit (<i>Anthus pratensis</i>)	0.010

need for some caution when interpreting such comparisons, as high local species richness and abundance may actually be part of a larger-scale homogenization of biodiversity (Valera et al., 2024), as often shown for urbanization processes (McKinney, 2006). In addition, some of the locally solar-farm-specific urban birds can be alien invasive species (e.g. Eurasian Collared Dove in the USA (Young et al., 2025) and House Sparrow in South Africa (Visser et al., 2019), which may not only use the solar farms locally, but also as potential stepping stones and sources to colonize surrounding areas.

4.2. Community patterns within solar farms

The analysis focusing only on the solar farm data revealed further nuances of bird community assembly. The composition was affected by size, and large parks had several indicators, while small ones did not have any, corroborating the conclusion we drew from the evaluation of turnover, which had a higher share in large farms. The effect of season is not surprising as the breeding period is characterized by summer visitors, while wintering and passage migrant species contribute to the fall communities in the region, including solar farms. Indicator species for both seasons had similar traits; there were ground-foragers taking advantage of the grassy vegetation cover (Common Starling and Tree

Sparrow in summer, and Meadow Pipit in fall) and sit-and-wait hunters perching on the infrastructure (Red-backed Shrike in summer and Black Redstart in fall). Barn Swallow, as an aerial hunter, was also an indicator of summer farms, however, since flying insects are mostly absent in colder months, no such species was found among fall indicators. Thus, it seems that various resources are utilized in the structured habitat offered by the farms in both seasons, as also found by some other solar farm studies (Jarčuška et al., 2024; Diekmann et al., 2025) and in more general investigations of habitat heterogeneity–diversity relationships (Báldi, 2008). However, a more detailed resource utilization and niche analysis could reveal further patterns.

We found no effect for management intensity and soil type. Intensive management usually renders grassy vegetation more species-poor as well as structurally and functionally less diverse, leading to lower abundance of arthropod food resources for birds (Bonari et al., 2017; Klein et al., 2020). Maybe the two levels of our management intensity did not differ enough. The intensive one was probably comparable to Walston et al.'s (2025) intensive homogeneous solar farm sward, but our extensive ones were still far from seeded and carefully managed grasslands of ecovoltaic parks (Lambert et al., 2022, 2023). Similarly, we expected some effects of soil type, as the sparser vegetation and bare sandy patches, together with the different plant species composition of sand soils compared to finer-textured soils (Biró et al., 2007, Biró et al., 2008), could affect the bird communities as well, but no such effect was detectable with our sampling effort. Maybe the commonly occurring sparse vegetation under the panels (Armstrong et al., 2016) or other structural components of solar farms override any management-level and soil type differences, in terms of habitat compatibility of species with the applied sampling intensity.

Regarding species richness and abundance, results on farm size have to be interpreted with caution; significant difference with higher scores for large parks should be considered as the expected result due to the larger surveyed area of large parks. It is, thus, not surprising that larger farms had larger total species richness and abundance. The scores were also higher in summer than in fall, and this was unrelated to the overall density of birds in the surrounding landscapes, so we can conclude that solar farms are more attractive for birds during the breeding season, consistent with the findings of Walston et al. (2025). In the fall, when the vegetation in our parks was mostly in a post-mowing phase, the short vegetation may have offered fewer food sources due to both lower arthropod availability and the relative lack of seeds, as many plants

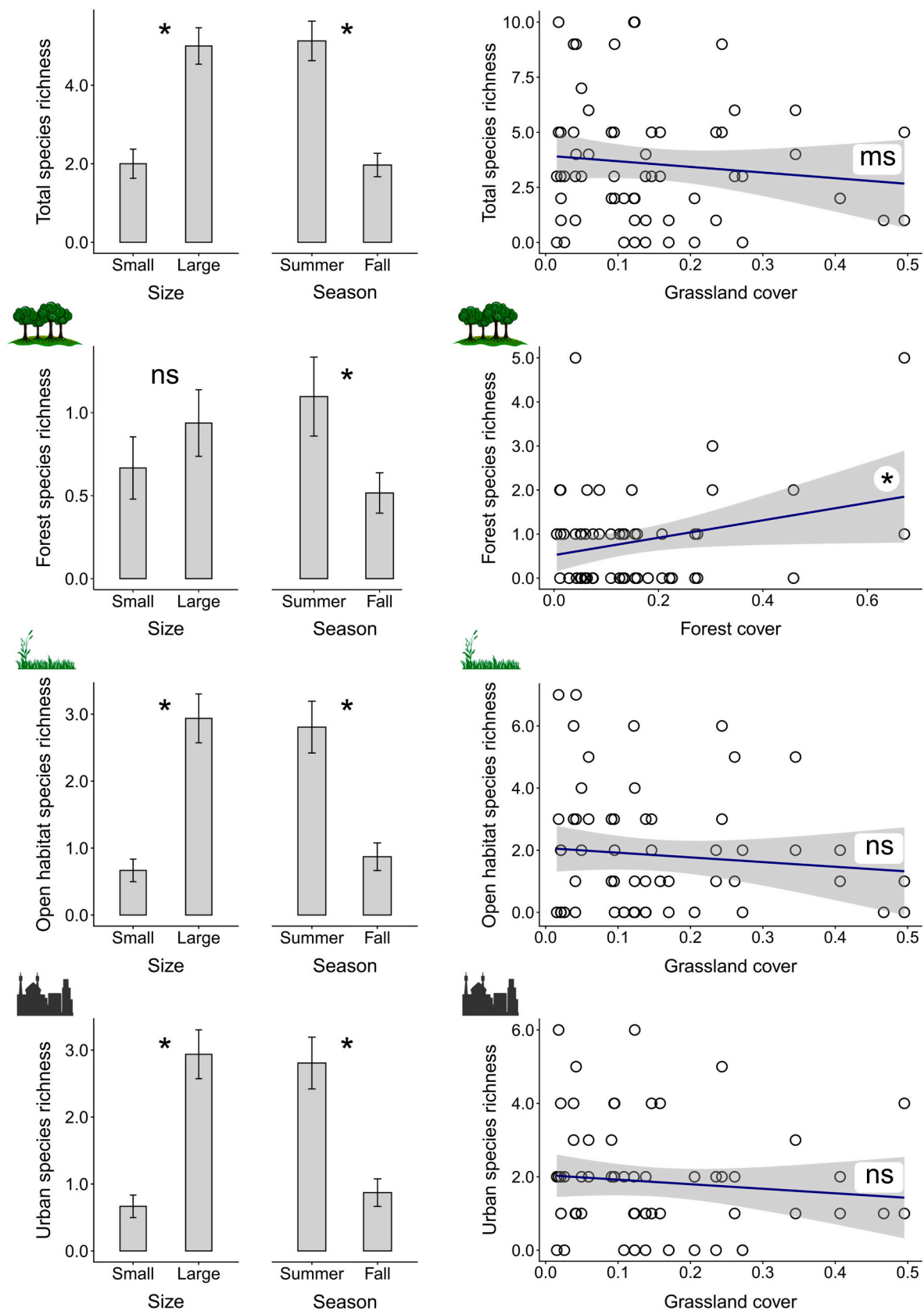


Fig. 5. Bird species richness relations in small and large solar farms, in summer and fall surveys, and according to forest and grassland cover in the landscape buffer, where applicable. *: significant difference or trend, ms: marginally significant ($0.1 > p > 0.05$), ns: non-significant.

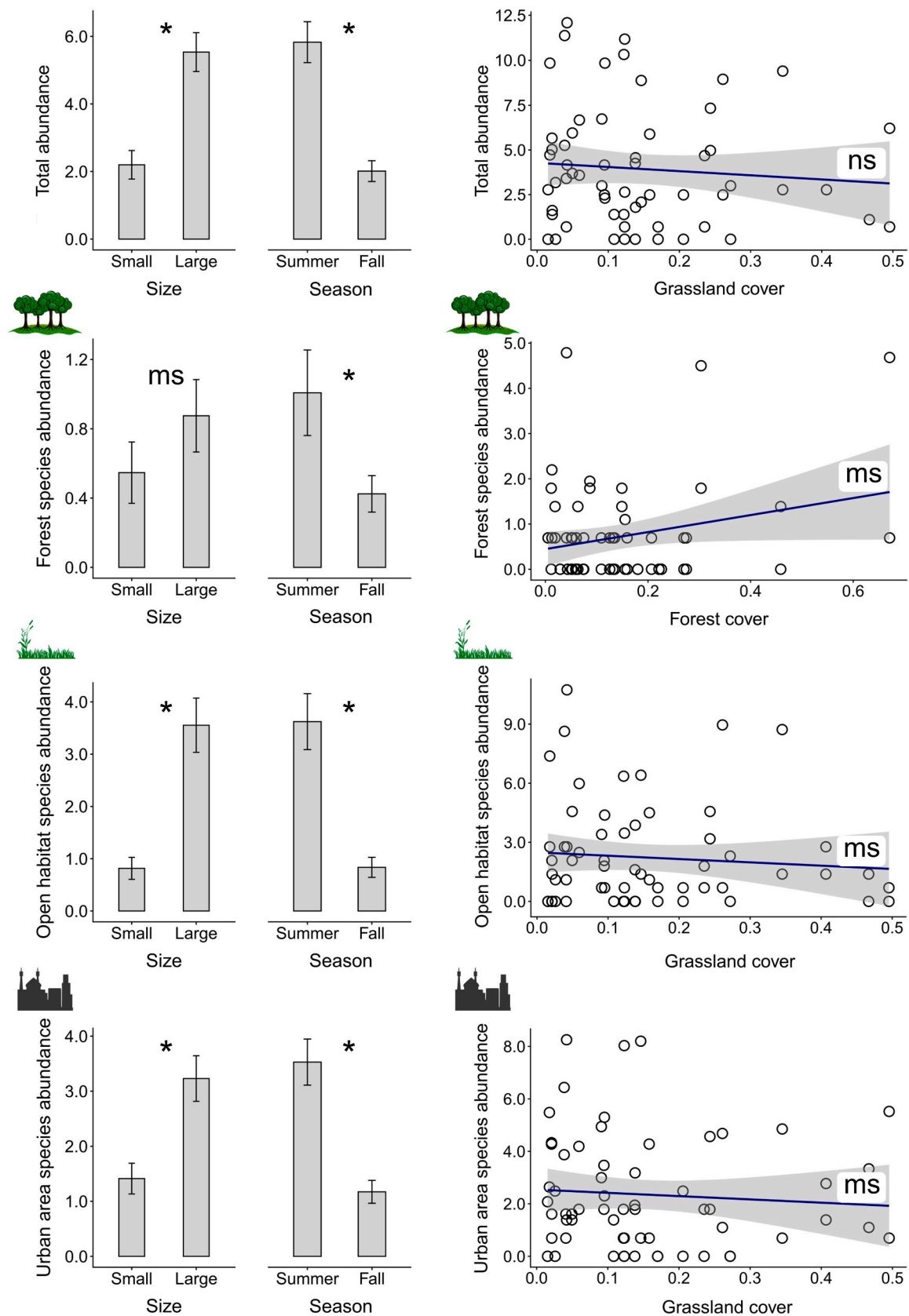


Fig. 6. Bird abundance relations in small and large solar farms, in summer and fall surveys, and according to forest and grassland cover in the landscape buffer, where applicable. *: significant difference or trend, ms: marginally significant ($0.1 > p > 0.05$).

cannot reach a seed-bearing phenological stage due to the mowing. The marginally negative effect of grassland cover in the landscape buffer on total species richness and abundance is explained by the individual responses of the main species groups (forest, open-habitat and urban specialist birds), as discussed below.

Forest species showed an interesting pattern in that forest cover in the landscape buffer had a positive effect (which may also be reinforced by the shifts in arable cover, which negatively correlates with forest cover), but larger parks did not have more forest species than smaller ones. This may be an indication of a spillover effect from surrounding woody patches, which has a certain distance range from the forest edges (Rand et al., 2006), apparently not wide enough to provide large farms with more species than small farms. The significant effect of season can be explained by the fact that most forest birds we detected are insectivorous summer visitors, and the positive effect of urban area cover is probably due to the relatively high density of trees in our urban areas, which can also attract forest birds to the landscape (Machar et al., 2021).

Compared to forest birds, the majority of open-habitat species did not avoid solar farms, reflected in the lack of deviation from the expected positive effect of farm size. Nevertheless, the quality of solar farms as grassland was lower than that of the surrounding semi-natural grasslands, because a higher grassland cover in the surroundings did not increase but tended to decrease open-habitat bird abundance. So, they opted for the semi-natural grasslands if those were available, but if not, they accepted the solar farms as surrogate habitats. Shifts in arable land cover may also have contributed to the detected patterns.

The marginally negative response of urban birds to increasing grassland may be related to species with double urban-open preferences, which may react similarly to grassland cover in the landscape buffer as the open-habitat-specialist species group (see above). However, the probably most meaningful pattern for urban species was the lack of significance of urban area cover in the landscape buffer. So, these birds did not spill over to the farms from surrounding urban areas (unlike forest birds from woody habitats), and did not prefer surrounding urban habitat patches more than the solar farms (unlike open-habitat birds the grasslands), but probably considered them as prime habitats (see also Visser et al., 2019), corroborating the findings and associated concerns outlined above in the solar farm vs. surrounding landscape comparisons.

4.3. Recommendations for active ecovoltaic improvements for birds

1. Forest birds tend to avoid conventional solar farms; therefore, specific interventions are needed if ecovoltaic developers intend to support them. The introduction of some woody patches in places where solar panels are absent or along northern or southern edges (in the northern and southern hemispheres, respectively), as well as some shorter hedges elsewhere, may benefit forest birds in terms of food and breeding site availability, as shown for farmland areas in general (Batáry et al., 2012). Installing nest boxes can also improve breeding success (Dulisz et al., 2022).
2. Conventional solar farms provide habitat for open-habitat birds but seem suboptimal for some species. Improved foraging possibilities (through more structured and compositionally diverse vegetation that supports arthropod food sources) and breeding success (by avoiding mowing during the breeding season to protect ground-nesting species) would probably have favourable effects (Shaffer and DeLong, 2019).
3. Arthropod abundances in the solar farms should be boosted as much as possible to reduce the potential mismatch between the density of perches and food sources, thus avoiding ecological traps for sit-and-wait type insectivorous species. However, substantial research is needed in this respect.
4. Conventional solar farms are lower-quality habitats for birds in the fall, which could be improved by appropriate management (Shaffer and DeLong, 2019). Higher vegetation with seed-bearing shoots should be left into the fall to favour both insectivorous and

granivorous birds, as long as excessive shading does not occur on the panels.

5. Solar farms are suitable habitats for urban birds, potentially including invasive ones; therefore, landscapes with predominantly natural habitats harbouring sensitive species should be reconsidered for solar developments, even if the actual construction would be on a degraded patch.
6. If the concern about unfavourable species is imminent in a region, smaller parks are to be favoured, as they are less likely to develop distinct species composition featuring excessive amounts of urban species.

CRedit authorship contribution statement

Csaba Tölgyesi: Writing – original draft, Visualization, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kata Frei:** Writing – original draft, Visualization, Formal analysis. **Zoltán Batori:** Writing – original draft. **Dorottya Hajnal:** Writing – original draft. **Tomás Hamrik:** Writing – original draft, Data curation. **Péter Török:** Writing – original draft. **Róbert Gallé:** Writing – original draft, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The study was realized as part of the NKFIH FK 142926 grant. C. T. and Z. B. were also supported by the NKFIH K 146137 and NKFIH FK 142428 grants, respectively. P.T. was supported by KKP 144068 during manuscript preparation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biocon.2026.112025>.

Data availability

Data will be made available on request.

References

- Armstrong, A., Ostle, N.J., Whitaker, J., 2016. Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environ. Res. Lett.* 11 (7), 074016.
- Báldi, A., 2008. Habitat heterogeneity overrides the species–area relationship. *J. Biogeogr.* 35 (4), 675–681.
- Bartoń, K., 2025. MuMin: Multi-Model Inference. R Package Version 1.48.11. <https://CRAN.R-project.org/package=MumIn>.
- Baselga, A., Orme, D., Villeger, S., De Bortoli, J., Leprieux, F., Logez, M., Martinez-Santalla, S., Martin-Devasa, R., Gomez-Rodriguez, C., Crujeiras, R., 2023. betapart: Partitioning Beta Diversity into Turnover and Nestedness Components. R package version 1.6. <https://CRAN.R-project.org/package=betapart>.
- Batáry, P., Kovács-Hostyánszki, A., Fischer, C., Tscharnkte, T., Holzschuh, A., 2012. Contrasting effect of isolation of hedges from forests on farmland vs. woodland birds. *Community Ecol.* 13 (2), 155–161.
- Bates, D., Maechler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. *J. Stat. Softw.* 67 (1), 1–48.
- Battin, J., 2004. When good animals love bad habitats: ecological traps and the conservation of animal populations. *Conserv. Biol.* 18 (6), 1482–1491.
- Bíró, M., Révész, A., Molnár, Z., Horváth, F., 2007. Regional habitat pattern of the Danube-Tisza Interfluvium in Hungary, I: the landscape structure and habitat pattern; the fen and alkali vegetation. *Acta Bot. Hungar.* 49 (3–4), 267–303.
- Bíró, M., Czúcz, B., Horváth, F., Révész, A., Csátsári, B., Molnár, Z., 2013. Drivers of grassland loss in Hungary during the post-socialist transformation (1987–1999). *Landsc. Ecol.* 28 (5), 789–803.
- Bíró, M., Böloni, J., Molnár, Z., 2018. Use of long-term data to evaluate loss and endangerment status of Natura 2000 habitats and effects of protected areas. *Conserv. Biol.* 32 (3), 660–671.

- Blaydes, H., Potts, S.G., Whyatt, J.D., Armstrong, A., 2021. Opportunities to enhance pollinator biodiversity in solar parks. *Renew. Sust. Energ. Rev.* 145, 111065.
- BLM (Bureau of Land Management), 2024. Utility-scale solar energy development PEIS/RMPA. <https://eplanning.blm.gov/eplanning-ui/project/2022371/510>. (Accessed September 2024).
- Bonari, G., Fajmon, K., Malenovsky, I., Zelený, D., Holuša, J., Jongepierová, I., Kočárek, P., Konvička, O., Uričar, J., Chytrý, M., 2017. Management of semi-natural grasslands benefiting both plant and insect diversity: the importance of heterogeneity and tradition. *Agric. Ecosyst. Environ.* 246, 243–252.
- Brennan, L.A., Kuvlesky Jr., W.P., 2005. North American grassland birds: an unfolding conservation crisis? *J. Wildl. Manag.* 69 (1), 1–13.
- Chernetsov, N., 2006. Habitat selection by nocturnal passerine migrants en route: mechanisms and results. *J. Ornithol.* 147 (2), 185–191.
- Copping, J.P., Waite, C.E., Balmford, A., Bradbury, R.B., Field, R.H., Morris, I., Finch, T., 2025. Solar farm management influences breeding bird responses in an arable-dominated landscape. *Bird Study* 1–6.
- De Cáceres, M., Legendre, P., 2009. Associations between species and groups of sites: indices and statistical inference. *Ecology* 90, 3566–3574.
- DeVault, T.L., Seamans, T.W., Schmidt, J.A., Belant, J.L., Blackwell, B.F., Mooers, N., Tyson, L.A., Van Pelt, L., 2014. Bird use of solar photovoltaic installations at US airports: implications for aviation safety. *Landsc. Urban Plan.* 122, 122–128.
- Diekmann, L., Zitzmann, F., Schaarschmidt, F., Reich, M., 2025. Habitat use of birds on a high-mounted agrivoltaic trial plot. *Ecol. Evol.* 15 (8), e71864.
- Dinesh, H., Pearce, J.M., 2016. The potential of agrivoltaic systems. *Renew. Sust. Energ. Rev.* 54, 299–308.
- Douglas, D.J., Waldinger, J., Buckmire, Z., Gibb, K., Medina, J.P., Sutcliffe, L., Beckmann, C., Collar, N.J., Jansen, R., Kamp, J., Little, I., Sheldon, R., Yanosky, A., Koper, N., 2023. A global review identifies agriculture as the main threat to declining grassland birds. *Ibis* 165 (4), 1107–1128.
- Dufrène, M., Legendre, P., 1997. Species assemblages and indicator species: the need for a flexible asymmetrical approach. *Ecol. Monogr.* 67 (3), 345–366.
- Dulisz, B., Stawicka, A.M., Knozowski, P., Diserens, T.A., Nowakowski, J.J., 2022. Effectiveness of using nest boxes as a form of bird protection after building modernization. *Biodivers. Conserv.* 31 (1), 277–294.
- Erdős, L., Ambarlı, D., Anenkhonov, O.A., Bátor, Z., Cserhalmi, D., Kiss, M., Kröel-Dulay, G., Liu, H., Magnes, M., Molnár, Z., Naqinezhad, A., Semenishchenkov, Y.A., Tölgyesi, C., Török, P., 2018. The edge of two worlds: a new review and synthesis on Eurasian forest-steppes. *Appl. Veg. Sci.* 21 (3), 345–362.
- Erdős, L., Ónodi, G., Tölgyesi, C., Kröel-Dulay, G., Bátor, Z., Aradi, E., Török, T., Ho, K. V., Puspitasari, I., Körmöcz, L., 2024. Forest encroachment in Eastern European forest-steppes at a decadal time scale. *J. Plant Ecol.* 17 (5), rtæ086.
- ESRI (Environmental Systems Resource Institute), 2024. ArcGIS Pro 3.3.1. ESRI, Redlands, California. URL: <https://www.esri.com/en-us/home>.
- European Environment Agency (EEA), 2018. CORINE Land Cover 2018 (CLC2018). Copernicus Land Monitoring Service. <https://land.copernicus.eu/>.
- Fox, J., Weisberg, S., 2019. An {R} Companion to Applied Regression, Third Edition. Sage, Thousand Oaks CA. URL: <https://socialsciences.mcmaster.ca/jfox/Books/Companion/>.
- Golawski, A., Mitrus, C., 2018. Weather conditions influence egg volume repeatability in clutches of the red-backed shrike *Lanius collurio*. *Zool. Stud.* 57, e2.
- Golawski, A., Mitrus, C., Jankowiak, Ł., 2025. Increased bird diversity around small-scale solar energy plants in agricultural landscape. *Agric. Ecosyst. Environ.* 379, 109361.
- Hartig, F., 2026. DHARMA: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models. R Package Version 0.5.0. <https://CRAN.R-project.org/package=eDHARMA>.
- Hermoso, V., Bota, G., Brotons, L., Morán-Ordóñez, A., 2023. Addressing the challenge of photovoltaic growth: integrating multiple objectives towards sustainable green energy development. *Land Use Policy* 128, 106592.
- Hernandez, R.R., Hoffacker, M.K., Field, C.B., 2014. Land-use efficiency of big solar. *Environ. Sci. Technol.* 48 (2), 1315–1323.
- Hernandez, R.R., Hoffacker, M.K., Murphy-Mariscal, M.L., Wu, G.C., Allen, M.F., 2015. Solar energy development impacts on land cover change and protected areas. *Proc. Natl. Acad. Sci.* 112 (44), 13579–13584.
- Horváth, G., Blahó, M., Egri, Á., Kriska, G., Seres, I., Robertson, B., 2010. Reducing the maladaptive attractiveness of solar panels to polarotactic insects. *Conserv. Biol.* 24 (6), 1644–1653.
- Huetting, S., Santucci, B., 2024. Ecological requirements, distribution, and population density of the European stonechat *Saxicola rubicola* in a high mountain area of the central Apennines, Italy. *Riv. Ital. Ornitol.* 94 (2).
- Jarcuska, B., Gálffyová, M., Schnürmacher, R., Baláz, M., Mišík, M., Repel, M., Fulín, M., Kerestúr, D., Lackovičová, Z., Mojžiš, M., Zámečník, M., Kaňuch, P., Kristín, A., 2024. Solar parks can enhance bird diversity in agricultural landscape. *J. Environ. Manag.* 351, 119902.
- Klein, N., Theux, C., Arlettaz, R., Jacot, A., Pradervand, J.N., 2020. Modeling the effects of grassland management intensity on biodiversity. *Ecol. Evol.* 10 (23), 13518–13529.
- Kober, T., Schiffer, H.W., Densing, M., Panos, E., 2020. Global energy perspectives to 2060–WEC's World Energy Scenarios 2019. *Energ. Strat. Rev.* 31, 100523.
- Lambert, Q., Gros, R., Bischoff, A., 2022. Ecological restoration of solar park plant communities and the effect of solar panels. *Ecol. Eng.* 182, 106722.
- Lambert, Q., Bischoff, A., Enea, M., Gros, R., 2023. Photovoltaic power stations: an opportunity to promote European semi-natural grasslands? *Front. Environ. Sci.* 11, 1137845.
- Levin, M.O., Kalies, E.L., Forester, E., Jackson, E.L.A., Levin, A.H., Markus, C., McKenzie, P.F., Meek, J.B., Hernandez, R.R., 2023. Solar energy-driven land-cover change could alter landscapes critical to animal movement in the continental United States. *Environ. Sci. Technol.* 57 (31), 11499–11509.
- Liudecke, D., Ben-Shachar, M.S., Patil, I., Waggoner, P., Makowski, D., 2021. performance: an R package for assessment, comparison and testing of statistical models. *J. Open Source Softw.* 6 (60).
- Maehar, I., Poprach, K., Praus, L., Úradník, L., 2021. Floodplain forests and urban parks—a brief comparison of bird diversity. *J. Landscape Ecol.* 14 (3), 1–11.
- McKinney, M.L., 2006. Urbanization as a major cause of biotic homogenization. *Biol. Conserv.* 127 (3), 247–260.
- Meyer, M.H., Dullau, S., Scholz, P., Meyer, M.A., Tischew, S., 2023. Bee-friendly native seed mixtures for the greening of solar parks. *Land* 12 (6), 1265.
- Mullarney, K., Svensson, L., Zetterström, D., 2023. Birds of Europe, Third Edition. Princeton University Press, Oxford, UK, p. 480.
- Nijssse, F.J.M.M., Mercure, J.-F., Ameli, N., Larosa, F., Kothari, S., Rickman, J., Vercoulen, P., Pollitt, H., 2023. The momentum of the solar energy transition. *Nat. Commun.* 14 (1), 6542.
- Oksanen, J., Simpson, G., Blanchet, F., Kindt, R., Legendre, P., Minchin, P., O'Hara, R., Solymos, P., Stevens, M., Szoecs, E., Wagner, H., Barbour, M., Bedward, M., Bolker, B., Borcard, D., Carvalho, G., Chirico, M., De Cáceres, M., Durand, S., Evangelista, H., FitzJohn, R., Friendly, M., Furneaux, B., Hannigan, G., Hill, M., Lahti, L., McGlinn, D., Ouellette, M., Ribeiro Cunha, E., Smith, T., Stier, A., Ter Braak, C., Weedon, J., 2024. vegan: Community Ecology Package. R package version 2.6-8. URL: <https://CRAN.R-project.org/package=vegan>.
- Ong, S., Campbell, C., Denholm, P., Margolis, R., Heath, G., 2013. Land-use Requirements for Solar Power Plants in the United States (no. NREL/TP-6A20-56290). National Renewable Energy Laboratory (NREL), Golden, CO (United States).
- Papadis, E., Tsatsaronis, G., 2020. Challenges in the decarbonization of the energy sector. *Energy* 205, 118025.
- Planet Team, 2025. Planet Application Program Interface: In Space for Life on Earth. San Francisco, CA. URL: <https://api.planet.com>.
- R Core Team, 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. URL: <https://www.R-project.org/>.
- Rand, T.A., Tylanakis, J.M., Tschamrtke, T., 2006. Spillover edge effects: the dispersal of agriculturally subsidized insect natural enemies into adjacent natural habitats. *Ecol. Lett.* 9 (5), 603–614.
- Shaffer, J.A., DeLong, J.P., 2019. The Effects of Management Practices on Grassland Birds: An Introduction to North American Grasslands and the Practices Used to Manage Grasslands and Grassland Birds (Professional Paper 1842-A). U.S. Geological Survey. <https://doi.org/10.3133/pp1842A>.
- Späth, L., 2018. Large-scale photovoltaics? Yes please, but not like this! Insights on different perspectives underlying the trade-off between land use and renewable electricity development. *Energy Policy* 122, 429–437.
- Sturchio, M.A., Knapp, A.K., 2023. Ecovoltai principles for a more sustainable, ecologically informed solar energy future. *Nat. Ecol. Evol.* 7 (11), 1746–1749.
- Tölgyesi, C., Bátor, Z., Pascarella, J., Erdős, L., Török, P., Batáry, P., Birkhofer, K., Scherer, L., Michalko, R., Košulić, O., Zaller, J.G., Gallé, R., 2023. Ecovoltai: framework and future research directions to reconcile land-based solar power development with ecosystem conservation. *Biol. Conserv.* 285, 110242.
- Tsafack, N., Fang, W., Wang, X., Xie, Y., Wang, X., Fattorini, S., 2022. Influence of grazing and solar panel installation on tenebrionid beetles (Coleoptera Tenebrionidae) of a central Asian steppe. *J. Environ. Manag.* 320, 115791.
- UK Government, 2023. Powering Up Britain. Department for Energy Security and Net Zero.
- Valera, F., Sálek, M., Bolonio, L., Václav, R., 2024. Comment on “Solar parks can enhance bird diversity in agricultural landscape” by Jarcuska et al. *J. Environ. Manag.* 366, 121781.
- Van de Ven, D.J., Capellan-Peréz, I., Arto, I., Cazcarro, I., De Castro, C., Patel, P., Gonzalez-Eguino, M., 2021. The potential land requirements and related land use change emissions of solar energy. *Sci. Rep.* 11 (1), 2907.
- Visser, E., Perold, V., Ralston-Paton, S., Cardenal, A.C., Ryan, P.G., 2019. Assessing the impacts of a utility-scale photovoltaic solar energy facility on birds in the Northern Cape, South Africa. *Renew. Energy* 133, 1285–1294.
- Walston Jr., L.J., Rollins, K.E., LaGory, K.E., Smith, K.P., Meyers, S.A., 2016. A preliminary assessment of avian mortality at utility-scale solar energy facilities in the United States. *Renew. Energy* 92, 405–414.
- Walston, L.J., Hartmann, H.M., Fox, L., Stanger, M.E., Steele, S.E., Narváez, N.R., Szoldatits, K.E., Hogstrom, I., Macknick, J., 2025. Ecovoltai solar energy development can promote grassland bird communities. *J. Appl. Ecol.* 62 (12), 3341–3354.
- Young, A.C., Meliopoulos, D., Desmond, M.J., Daniel, D., Abadi, F., 2025. Impacts of solar energy development on breeding birds in desert grasslands in south Central New Mexico. *Environ. Manag.* 75 (4), 883–895.
- Zaplata, M.K., Dullau, S., 2022. Applying ecological succession theory to birds in solar parks: an approach to address protection and planning. *Land* 11 (5), 718.
- Zuniga-Palacios, J., Zuria, I., Castellanos, I., Lara, C., Sanchez-Rojas, G., 2021. What do we know (and need to know) about the role of urban habitats as ecological traps? Systematic review and meta-analysis. *Sci. Total Environ.* 780, 146559.