The diversity and behaviour of farmland birds on solar parks in the UK

Benjamin Secker

Lancaster University

Lancaster Environment Centre

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Abstract

Ground-mounted solar photovoltaic parks are the largest renewable terrestrial land use in the UK, and as such are an emerging anthropogenic habitat. Despite birds being a well-studied and ubiquitous taxon, relatively little is known about how avian diversity and behaviour are impacted by solar parks. This study begins to address these unknowns by using an existing dataset of 28 solar parks across the UK to model the relationship between solar park age, size, sward height, predator abundance and grazing management regimes, on all bird and farmland species richness, and skylark presence and abundance. This study also reports evidence of the first systematic searches for nesting skylarks on solar parks in the UK, using thermal imaging technology, and focal watches to quantitatively assess skylark behaviour on solar parks. The results reveal that all bird and farmland bird species richness increase with age of solar parks, but that grazing was negatively associated with all bird species richness and abundance and presence of skylarks. Nest searches indicated that no skylarks were nesting at the sites in this study but do indicate solar parks may potentially provide valuable foraging resources compared to the surrounding agricultural landscape, with evidence that skylarks were taking food offsite to nestlings or recently fledged young on adjacent land. The solar parks included in this study were primarily designed and managed for electricity generation, with some biodiversity improvement measures. This indicates that those designed with a greater focus on wildlife would have a greater positive impact on birds in an increasingly depleted agricultural landscape. Indeed, one site managed with a focus on biodiversity had multiple pairs of corn buntings nesting successfully over a period of three years. Major improvements in pre- and post-construction monitoring data are now required to understand the short- and longer-term effects of the development and management of solar parks on birds.

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Introduction

Over recent decades, the rising global demand on land for food, housing, and industry to sustain an increasing population has come into conflict with the equally important need to conserve the Earth's ecosystems and species, and to mitigate climate change (Lambin and Meyfroidt, 2011; Sharmina et al., 2016; Stehfest et al., 2019). Investment in the renewable energy sector is set to increase exponentially in the coming decades to reduce domestic reliance on fossil fuels, and to produce cleaner energy for the future. The International Energy Agency (IEA) predicts that approximately 6000TWh of solar photovoltaic (PV) power will be generated globally by 2050 to supply society's needs, around 16% of the total energy generated (IEA, 2014). Currently, solar photovoltaic energy is the most abundant onshore renewable land use in the UK (Jones et al., 2014). The UK government has previously suggested renewables will have a "crucial role" to play in reducing the reliance on fossil fuels in the coming decades (Gov UK, 2013), with Solar Energy UK projecting solar parks will constitute around 70,000 Ha of UK land by 2035, equivalent to around 0.3% of total land cover (Solar Energy UK, 2023b). For context, arable fields are currently estimated to constitute around 6,000,000 Ha, with total used agricultural area at around 17,000,000 Ha. If the projected area of ground-mounted solar were used to grow wheat, it would account for just 4% of the UK's annual wheat yield (Carbon Brief, 2022). Despite this relatively minimal reduction in agricultural output, there will inevitably be further developmental pressures as the area of land used for solar power generation increases.

Whilst the investment in renewable energy sources is seen by many as a positive, the use of large tracts of land for solar photovoltaic energy facilities (hereafter "solar parks") will increase competition for land resources as food production and energy demand rise, with potentially significant consequences for biodiversity. A large proportion of solar energy capacity consists of ground-mounted solar parks, resulting in more significant impacts on land use change compared with other renewable resources (Armstrong et al., 2014). In the UK and Europe, where solar parks are typically constructed on agricultural land, grasslands, or pasture, there is evidence that solar parks have associated environmental costs both during and post-construction (De Marco et al., 2014; Hastik et al., 2015; Randle-Boggis et al., 2020). These costs include visual pollution (del CarmenTorres-Sibille et al., 2009), land-use change and habitat loss (Capellán-Pérez et al., 2017; Dhar et al., 2020; Tawalbeh et al., 2021), as well as impacts associated with the manufacturing and recycling process (Tawalbeh et al., 2021), yet relatively little is known about their impacts on wildlife. The most reliable evidence of wildlife activity within renewable energy facilities comes from wind farms, particularly for birds and bats (Smith and Dwyer, 2016). However, due to the contrasting structural composition of solar parks, and therefore different challenges regarding land use change, little of this work can be applied with confidence to solar parks.

Agricultural intensification in the post-war period is widely considered to be the main driver of terrestrial biodiversity loss in Europe (Robinson and Sutherland, 2002; Ekroos et al., 2016; Kehoe et al., 2017). The ecological improvement potential of solar parks is greatest in cropland, grassland, permanent wetlands, mixed forests, and barren terrains (Adeh et al., 2019), and therefore may present opportunities to enhance local biodiversity (Randle-Boggis et al., 2020). Generally, lower management intensity on solar parks compared to the surrounding landscape can enhance plant diversity, altering the vegetation species composition (Lambert et al., 2023), and consequent benefits have been recorded for a range of taxa. For example, increased floral abundance during the latter period of the growing season due to panel shading improves food resource availability throughout the summer season (Graham et al., 2021). Greater overall invertebrate diversity has also been recorded (Blaydes et al., 2021), leading to suggestions that solar parks may support a greater diversity and abundance of bird species compared to the generally species-poor agricultural landscapes surrounding solar parks (Jarčuška et al., 2024).

The decline in populations of farmland birds is one of the major issues facing conservationists in Europe today (Donald et al., 2001b). These declines have corresponded with changes in agricultural management practices, with a variety of factors acting in concert (Reif, 2013; Stanton et al., 2018; Rigal et al., 2023). These include the introduction of field drainage systems, the extensive use of fertilisers, the loss and degradation of hedgerows, and a general switch from spring to autumn sowing (Odderskaer et al., 1997; Gillings and Fuller, 1998; Brickle et al., 2000; Newton, 2004; King et al., 2008 Cornulier et al., 2011; Aebischer et al., 2015; Walker et al., 2018). Together, these changes have negatively impacted populations of farmland birds through diminished food supplies (Evans et al., 1997; Brickle et al., 2000), loss of nesting habitat (Wilson et al. 1997; Chamberlain et al. 1999), and direct mortality of birds with machinery (Crick et al. 1994; Green 1995). Several targeted agricultural conservation schemes have had some success, for example interventions to change the timing and patterns of mowing reduced chick mortality in corncrake *Crex crex*, leading to a population increase (Wotton et al., 2015), and nest box schemes for tree sparrows *Passer montanus* have helped boost productivity and reduce their declines (McHugh et al., 2017). However, successes are generally limited to individual species, so there is still an urgent need for more work to help conserve declining farmland species.

In the 1980s, agricultural efficiency increased significantly because of subsidies and technological developments, and as a result over-production became an issue (Buckingham et al., 1999). The introduction of the ‘set-aside scheme’ as part of a reform of the common agricultural policy (CAP) meant subsidies were allocated to farmers for leaving a proportion of their land fallow, resulting in the conversion of over 600,000 Ha of UK farmland which had been in arable production (Evans et al,. 1997). Several studies have indicated that areas of set-aside on farmland can provide refugia for breeding farmland birds on arable and mixed farms (Draycott et al., 1997; Vickery et al., 2002; Firbank et al., 2003), but the withdrawal of some of these schemes over recent years has meant that less space has been allocated for wildlife in farmland areas. Therefore, the development of solar parks may be one way of retaining beneficial habitat for farmland birds, through careful stewardship to promote food availability and nesting habitat. On the other hand, the construction of large-scale solar parks may present new challenges to farmland species, and wider biodiversity. For example, installation of solar parks during the construction phase involves the complete removal of vegetation (Lovich and Ennen, 2011; Devault et al., 2014). The destruction associated with this is what has caused much of the concern to date (Lovich and Ennen, 2011), particularly when those species with restricted ranges and specific habitat requirements are displaced (Visser et al., 2019). Birds have also been shown to be injured or killed in collisions with solar panels and their associated infrastructure (Walston et al., 2016; Visser et al., 2019). This may occur as they are attracted by solar panels, which reflect polarised light in a similar way to water bodies, yet there are few studies to support or refute this (Kagan et al., 2014; Visser et al., 2019).

Unfortunately, the limited work on birds and solar parks completed to date in the UK has generally comprised of ecological appraisals by consultancy firms (Parker and McQueen 2013; Montag et al., 2016; Solar Energy UK, 2023a), with little in the way of focused research, and as a result, little is known about how birds are affected by and interact with solar park infrastructure. In this study, I present one of the first analyses of avian species richness, as well as the abundance and presence of skylarks *Alauda arvensis*, at solar parks in the UK. I also use systematic nest searches using thermal imaging, focal watches, and previous data from volunteers to investigate the breeding and behaviour of two declining ground-nesting bird species, skylarks and corn buntings *Emberiza calandra*, on these sites. It is hoped that the results of this study will contribute to the implementation of informed management of current operational solar parks and will thereby help to improve conditions for birds on solar parks in the UK.

Chapter 1

Investigating variation in bird species richness and abundance across UK solar parks

Introduction

Solar photovoltaic technology led the worldwide expansion in renewable energy growth in 2022, when it surpassed wind energy generation for the first time (IEA, 2023b). Therefore, there is an urgent and growing need to understand its impacts on biodiversity. Construction of solar parks involves destruction of vegetation and changes in the composition of soil structure, with grading compaction and erosion changing the physical and chemical properties of soil, thereby reducing its quality (Lambert et al., 2022). Post-construction, solar panels can also change humidity, temperature, and solar radiation beneath the panels, altering microclimate and vegetation growth (Armstrong et al., 2016; Tanner et al., 2020). These changes have consequences for vegetation structure and composition, thereby altering habitat, and can have wide-ranging impacts on wildlife (Harte and Jassby, 1978), including significant ground disturbance, and both direct (e.g. mortality) and indirect (e.g. habitat loss, degradation, modification) effects on species and their habitat (Kuvlesky et al., 2007). For example, Cypher et al. (2021) found that home range size of San Joaquin kit foxes *Vulpes macrotis mutica* was significantly increased on solar energy facilities, likely due to reduced prey numbers after construction. On the other hand, a wide range of positive changes have also been demonstrated when solar park management regimes are tailored for biodiversity. For example, Blaydes et al. (2022) suggest twice as many bumblebees can forage and nest inside solar parks managed as wildflower meadows, compared to those with only wildflower margins. However, studies on the impact of solar parks on biodiversity are still relatively rare, and more research is needed to determine the effects of both construction and post-construction management of solar parks, especially for birds.

The majority of studies on solar parks and birds that have been completed to date are limited to the south-western United States and South Africa, in arid desert climates (e.g. deVault et al., 2014; Jeal et al., 2019; Visser et al., 2019; Kosciuch et al., 2021; Gerringer et al., 2022), and may therefore have limited relevance to those in temperate climates, such as in the UK and Europe. The limited research in temperate areas mainly consists of ecological monitoring reports and reviews from the UK and Germany (Peschel, 2010; Parker and McQueen, 2013; Montag et al*.,* 2016; Peschel et al., 2019), and to date there has only been one peer-reviewed study in the primary literature in Europe using a repeatable and standardised sampling protocol to assess bird diversity on solar parks (Jarčuška et al., 2024). These studies have generally found positive trends, with all reporting increased species richness on solar parks compared to the surrounding landscape, and some suggest increased abundance, and the potential for nesting site provision. However, in the UK there has been no major study examining the impact of solar parks on birds, which is a particular issue given that most are constructed on farmland, and farmland birds are generally suffering from strong declines (Siriwardena et al., 1998; Woodward et al., 2018). Furthermore, the majority of existing work has generally compared bird species richness and abundance between solar parks and the surrounding landscape, typically using control sites located close to solar parks. Consequently, there is little to no evidence of the impact of differences in site characteristics and management practices between different solar parks on bird species richness and abundance, and the response of species to post-construction ecological effects.

The decline in farmland bird species in the UK has coincided with widespread changes in agricultural practices, mainly linked to increases in intensification (Donald et al., 2001b; Robinson and Sutherland, 2002, Aebischer et al., 2016). These include factors such as a switch from spring to autumn sowing, removal of hedgerows, and increase in fertiliser use (Odderskaer et al., 1997; Gillings and Fuller, 1998; Brickle & Harper, 2000; Newton, 2004; King et al., 2008; Cornulier et al., 2011). In the UK context, most solar parks are constructed on 'poor-quality' agricultural land (Palmer et al., 2019), as development of solar parks on brownfield sites and rooftops are generally limited to smaller scale projects and may not be compatible with the large-scale deployment needed to meet net-zero targets (Solar Energy UK, 2023b). However, whilst this 'poor-quality' land, traditionally referred to as 'set-aside', may be unprofitable from an agricultural perspective, these areas harbour the greatest biodiversity value compared to cropped fields and pasture (Henderson et al., 2000; van Buskirk & Willi, 2004; Kovács-Hostyánszki et al., 2011), and are key reproductive habitat for many farmland birds (Vickery et al., 2004; Redhead et al., 2018). Furthermore, detrimental effects to bird species resulting from the construction of solar parks in an agricultural setting may vary depending on the type of land on which they are constructed; farmland is variable in the extent of the declines seen across bird species, with different species declining in areas where cereals are predominantly grown, compared to areas of mainly pasture. Therefore, previous land use is likely to have an impact on the pre-construction species composition of a site, and may determine the post-construction impacts, which are likely to be variable between sites depending on context. One previous study (Shotton, 2019) found significantly greater bird species richness on solar parks compared to arable field control sites, with greater bird abundance towards the centre of the array. However, this study pooled abundance across all species, with no measure of community composition. Furthermore, the study did not address differences in bird communities between different solar parks or investigate the impact of different on-site management practices on bird species. Consequently, there is still work required to understand how site variation impacts birds, and how different species are affected.

Here, I focus on bird diversity using an existing dataset of 28 solar parks in the UK. Preliminary ecological appraisals of solar parks have recorded a relatively high prevalence of skylarks (Shotton, 2019; Solar Energy UK, 2023a), a declining, red-listed species in the British Trust for Ornithology (BTO) Birds of Conservation Concern (BoCC; Stanbury et al., 2021). This has led to a large amount of interest from within the renewable energy industry regarding how many are present on solar parks, and how they are using them. Using a generalised linear modelling approach, this study investigates the impact of solar park age, size, sward height, corvid abundance (as a proxy of general predator abundance), and grazing on all bird species richness, farmland bird species richness, skylark abundance and presence. It is hoped this will provide an insight into the factors affecting birds on solar parks in the UK, which will subsequently help to inform management regimes on operational sites to improve conditions for the birds there.

Methodology

Data collection

Data collected by Wychwood Biodiversity and Clarkson and Woods for Solar Energy UK, as part of a standardised protocol for monitoring biodiversity on solar parks (Carvalho et al., 2023; Solar Energy UK, 2023a), were provided to this study for analysis. These data were collected at a sample of 28 solar parks across the UK, the locations of which are to remain strictly confidential, although a summary of their national distribution and diversity of variables is outlined in Table 1.

Table 1. *Summary of the national distribution and diversity of variables of solar parks contained within the dataset.*

County	**Size (Ha)**	**Capacity (MW)**	**Age (years)**
Buckinghamshire	16.4	9.0	8
Cambridgeshire	33.9	31.8	8
Cambridgeshire	47.4	31.6	8
Cambridgeshire	13.2	5.3	10
Cumbria	8.1	4.4	7
Derbyshire	10.7	4.9	7
Devon	10.2	5.0	7
Devon	15.8	8.0	8
Devon	13.2	10.0	6
Devon	16.5	6.5	8
Dorset	18.4	12.1	8
Dorset	41.2	20.4	8
East Sussex	16.1	8.2	8
Essex	3.8	2.3	7
Essex	22.8	18.8	8
Essex	24.2	21.3	8
Fife	9.9	4.0	6
Hampshire	74.8	48.0	8
Kent	20.6	11.0	9
Kent	20.0	10.0	8
Leicestershire	26.8	13.9	8
Norfolk	8.3	5.0	7
Norfolk	98.0	49.9	8
Northamptonshire	8.6	4.9	6
Northamptonshire	7.8	6.8	6
Somerset	5.2	3.0	8
West Glamorgan	12.2	6.0	8
West Yorkshire	8.4	5.0	6
Mean	21.9	13.1	8.6
SD	21.2	12.8	1.0

The dataset included bird species richness and abundance, which were recorded using an adapted version of the BTO Breeding Bird Survey (BBS) methodology (Risely, 2011), and were recorded across two visits, one early in the breeding season, between April and May, and one later, between June and July. This was altered for application on solar parks, where a zig zag transect across the site was undertaken, recording birds seen within 50m either side of the transect, as opposed to traditional BBS methods which include walking a straight line transect. All bird species richness, farmland bird species richness, skylark abundance (measured as a count of the number of skylarks present on the solar park) and skylark presence, were extracted from the dataset as response variables to include in a series of generalised linear models. Bird species in this study were defined as those included in the standard BTO, JNCC, and RSPB classification for the UK Government (DEFRA, 2021; Table 2).

Table 2. *Species classified as farmland birds by the Department for Environment and Rural Affairs, together with their BoCC classification (DEFRA, 2021; Stanbury et al., 2021).*

Species	**Scientific name**	**BoCC status**
Corn bunting	*Emberiza calandra*	Red
Goldfinch	*Carduelis carduelis*	Green
Grey partridge	*Perdix perdix*	Red
Jackdaw	*Corvus monedula*	Green
Kestrel	*Falco tinnunculus*	Amber
Lapwing	*Vanellus vanellus*	Red
Linnet	*Carduelis cannabina*	Red
Reed bunting	*Emberiza schoeniclus*	Not assessed
Rook	*Corvus frugilegus*	Not assessed
Skylark	*Alauda arvensis*	Red
Starling	*Sturnus vulgaris*	Red
Stock dove	*Columba oenus*	Amber
Tree sparrow	*Passer montanus*	Red
Turtle dove	*Streptopelia turtur*	Red
Whitethroat	*Sylvia communis*	Amber
Woodpigeon	*Columba palumbus*	Amber
Yellow wagtail	*Motacilla flava*	Red
Yellowhammer	*Emberiza citronella*	Red

The following explanatory variables were also extracted from the dataset: site age, site size, sward height, corvid abundance and presence of grazing. The age of the site (in years) was defined as the time the site had come into operation up until the season when the ecological surveys took place (2022). Size of the site (in hectares) was provided by asset-holders prior to the survey. Sward height, which is known to be a key determinant of habitat selection in ground-nesting species such as skylark (Wakeham-Dawson et al, 1998; Chamberlain et al., 1999), was extracted from individual site surveys for each solar park within the dataset. A mean value was calculated from measurements taken across the site using 2x2m quadrats at fixed locations: five quadrats directly beneath the panels, five quadrats recorded in the open area between the panels, and five quadrats in the "enhanced" area (selected as the most diverse habitat within the solar park boundary; Solar Energy UK, 2023a). Corvid abundance was used as a proxy for predator abundance, which is the main cause of nest failure in many bird species, accounting for 80% of losses (Martin, 1993), of which corvids and mammals make up a significant portion (Weidinger, 2009). Specifically, corvids are well-documented to have an impact on ground-nesting farmland bird species, including skylarks (Morris and Gilroy, 2008). Corvid abundance was calculated by averaging the abundance of six species of corvid observed during BBS surveys (Table 3). Finally, general site management practices were noted in the dataset for each site, classified as either grazed, cut, or grazed and cut. This allowed presence of grazing (henceforth "grazing") to be analysed as a measure of the effect of different management practices.

Table 3. *Corvid species included in the measure of corvid abundance fitted in generalised linear models, used as a proxy of predator abundance.*

Species	**Scientific name**
Carrion crow	*Corvus corone*
Jackdaw	*Corvus monedula*
Jay	*Garrulus glandarius*
Magpie	*Pica pica*
Raven	*Corvus corax*
Rook	*Corvus frugilegus*

For some sites (n = 7), targeted bird surveys were not requested by the asset holder as part of the ecological monitoring work, but the surveying ecologist recorded a list of the bird species observed regardless. These data were suitable for inclusion in the analyses of species richness and skylark presence, but not skylark abundance, for which the standardised BBS-style approach is required. For analyses where these non-BBS data were included, only the first visit from those sites where BBS surveys were conducted were used. Corvid abundance was also omitted from the analyses where data from these sites were included, and so it was only included in the analysis of skylark abundance.

Statistical analyses

Generalised linear models were used to test whether skylark abundance (negative Binomial error structure), skylark presence (binomial error structure), species richness (Poisson error structure), and farmland bird species richness (Poisson error structure) were predicted by solar park age, size, sward height, corvid abundance, and grazing. A negative binomial model was found to have the best fit for skylark abundance data due to zero-inflation and overdispersion. All analyses were carried out in R (Version 4.3.3; R Core Team, 2018). Prior to analysis, all explanatory variables were centred and scaled to improve interpretation of the main effects (Schielzeth, 2010). Collinearity between predictor variables was checked using pairwise scatterplots, correlation coefficients and variance inflation factors (Zuur et al., 2010). All variables were included in the analysis as there was no collinearity between them ($r \leq 0.5$ in all cases) and variance inflation factors were small (<3). Solar park size was fitted as an offset for models assessing species richness due to wide variation in the size of solar parks included in the dataset (Table 1). The interactions between size and age, and between sward height and grazing were included; it was hypothesised that any effect of age may depend on the size of the site, and that sward height effects may be more apparent in the absence of grazing. The full model for each response variable was subjected to the 'dredge' function in the package ‘MuMIn’ (Barton, 2009) to rank all sub-models by Akaike’s Information Criterion, with the Hurvich and Tsai correction for small sample size. If $\Delta AICc \leq 2$ for more than one model, model averaging was performed using MuMIn to obtain estimates for plotting. Models were checked for overdispersion and validated by plotting the distribution of the residuals, the residuals versus the fitted values and the residuals versus each of the covariates (Zuur et al., 2009) using the R package DHARMa (Hartig, 2022). Preliminary analyses revealed that many skylarks were observed at one site that was disproportionately larger, at 98Ha, than the rest of the sites in the dataset which, excluding this site, averaged 19Ha. Whilst the model passed validation, the model was run without the outlier for comparative purposes.

Results

Species richness

Age of solar parks was an important predictor of species richness; a greater number of species were likely to be observed on older solar parks (Figure 1, Table 4). Two of the four best-fitting models also contained grazing, indicating that species richness was likely to be lower at sites where management practices included grazing (Figure 2, Table 4). Sward height and size were contained in one of the best-fitting models, as well as an interaction between age and size. However, these effects are likely to be marginal or perhaps not biologically meaningful due to the small effect size (Table 4). The sums of the weights of all models are presented in Table 5.

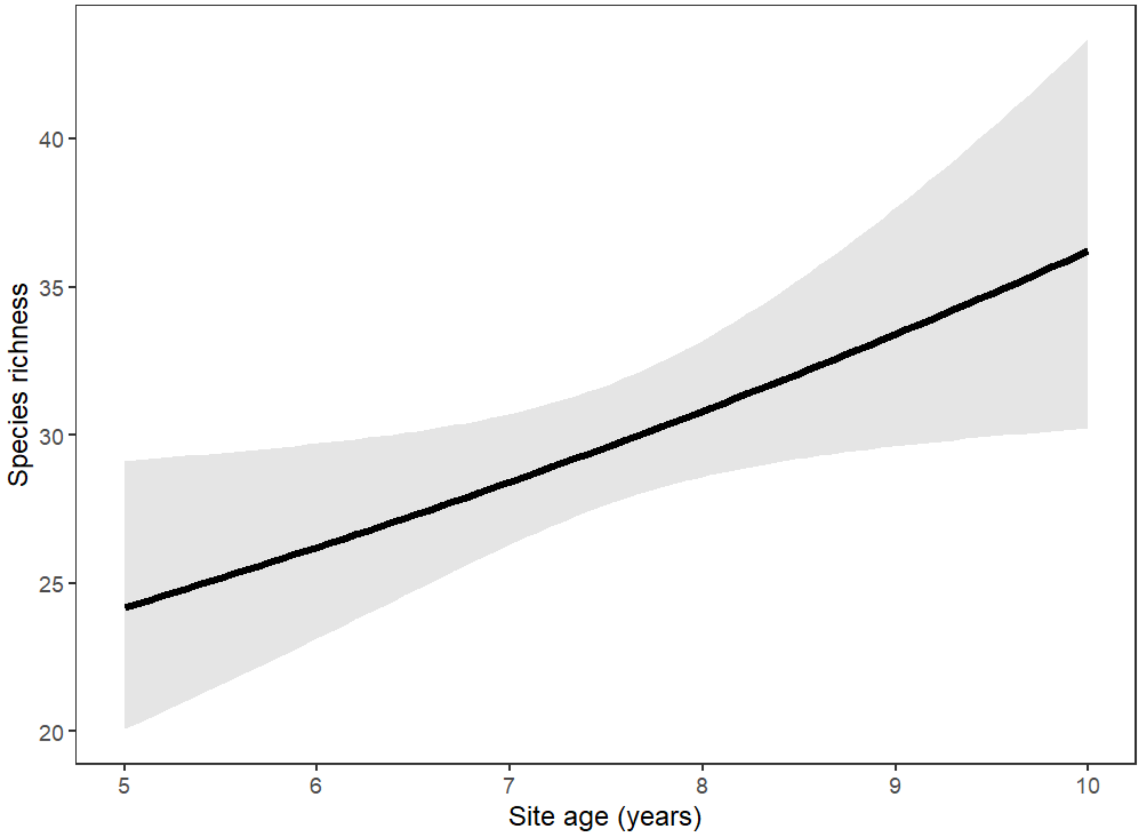

Figure 1. *The relationship between all bird species richness and solar park age. The line shows the predicted relationship from averaging of the best-fitting generalised linear models. The 95% confidence interval is shown in grey.*

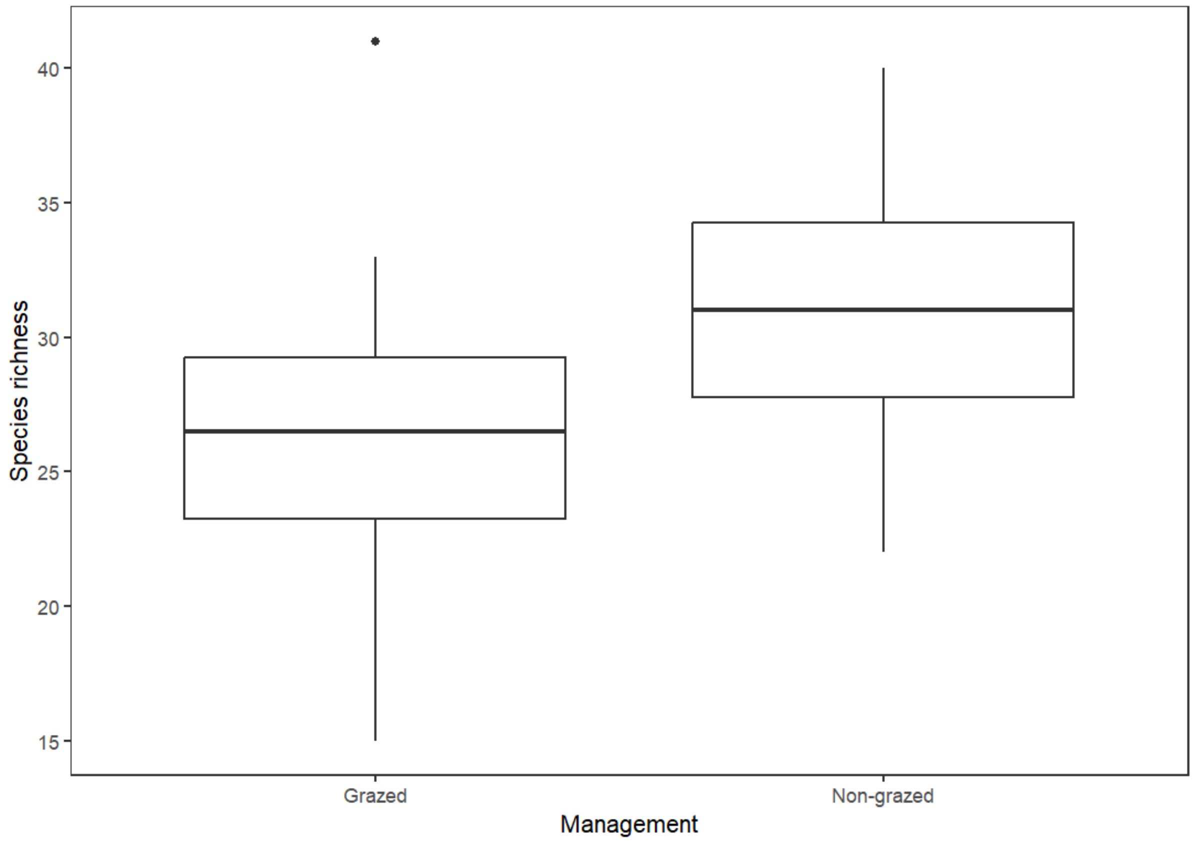

Figure 2. *The relationship between species richness and grazing management practices on solar parks. The mean species richness at grazed and non-grazed solar parks is shown. Error bars indicate the standard error.*

Table 4. *The best-fitting generalised linear models of the factors associated with species richness: glm(species richness ~ grazing + age + size + sward height + graze:sward + age:size). Models with a ΔAICc value within 2 of that of the best-fitting model are shown, and the null model is shown for comparison.*

Model	(Intercept)	Graze	Age	Size	Sward height	Graze x sward	Age x Size	df	loglik	AICc	Delta	Weight
1	2.821	+	0.08047					3	-86.688	180.4	0.00	0.198
2	2.782		0.08074					2	-88.163	180.8	0.43	0.160
3	2.745	+	0.07558		0.002329			4	-85.693	181.1	0.75	0.136
4	2.852		0.07075				0.0002383	3	-87.533	182.1	1.68	0.086
null	3.388							1	-90.897	183.9	3.57	0.033

Table 5. *Sum of variable weights across all models of bird species richness.*

Variable	**Sum of weights**	**N containing models**
Age	0.84	20
Age x Size	0.24	10
Grazing	0.6	18
Grazing x Sward	0.06	6
Sward	0.41	18
Size	<0.01	15

Farmland bird species richness

Age appeared to be an important predictor of farmland bird species; all the best-fitting models contained age, and the effect size was also larger than for all bird species richness (Figure 3, Table 6). Grazing was also included in the best-fitting model, as well as an interaction between age and size, although the effect size was small and therefore unlikely to be biologically significant (Table 6). The sums of the weights of all models are presented in Table 7.

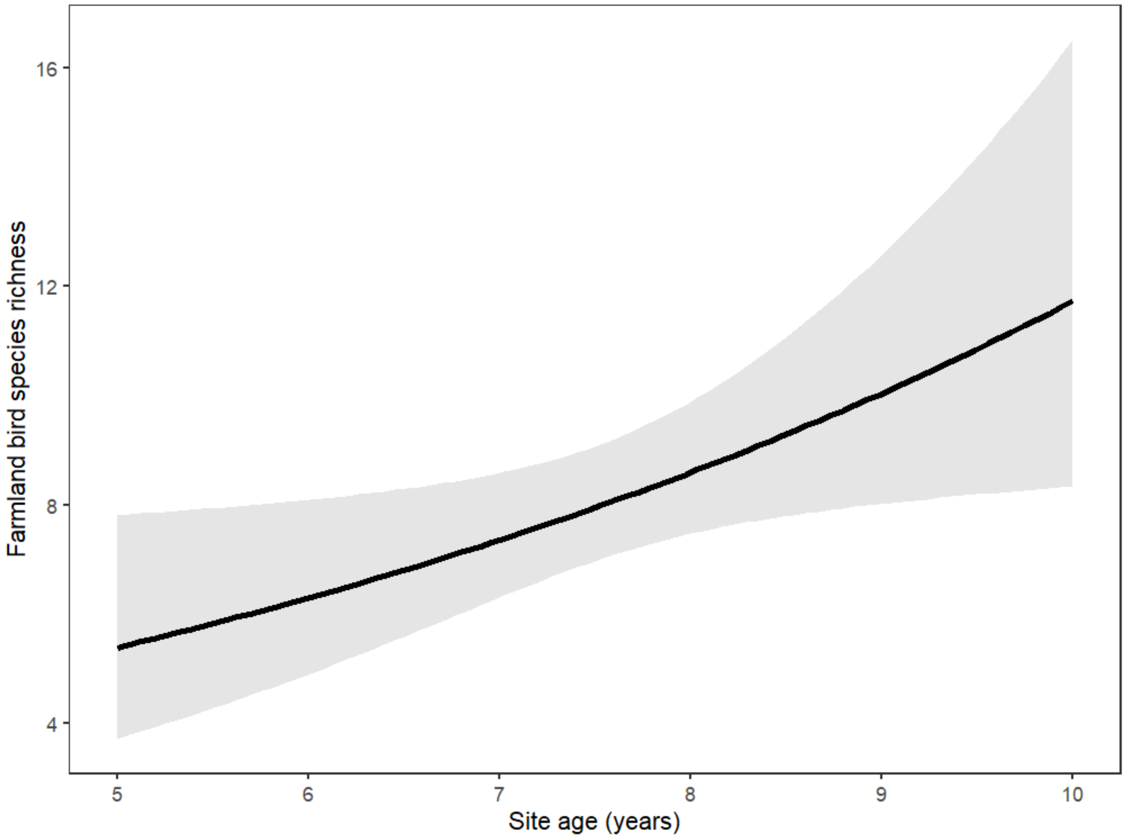

Figure 3. *The relationship between farmland bird species richness and solar park age. The line shows the predicted relationship from averaging of the best-fitting generalised linear models. The 95% confidence interval is shown in grey.*

Table 6 *The best-fitting generalised linear models of the factors associated with farmland species richness: glm(farmland species richness ~ grazing + age + size + sward height + graze:sward + age:size). Models with a ΔAICc value within 2 of that of the best-fitting model are shown, and the null model is shown for comparison.*

Model	(Intercept)	Graze	Age	Size	Sward	Graze x sward	Age x Size	df	loglik	AICc	Delta	Weight
1	0.9044		0.1558					2	-60.485	125.5	0.00	0.268
2	0.9789	+	0.1531					3	-59.583	126.2	0.71	0.188
3	1.0140		0.1314				0.0004107	3	-59.948	126.9	1.45	0.132
null	2.079							1	-63.184	128.5	3.07	0.058

Table 7. *Sum of variable weights across all models of farmland bird species richness.*

Variable	Sum of weights	N containing models
Age	0.85	20
Age x Size	0.25	10
Grazing	0.41	18
Grazing x Sward	0.03	6
Sward	0.24	18
Size	<0.01	15

Skylark abundance

Skylark abundance was predicted by size of solar parks; the best-fitting model included size, indicating more skylarks are likely to be observed at larger solar parks (Figure 4, Table 8). Presence of grazing management regimes was also included in the best-fitting model, indicating skylarks are less likely to be observed at grazed solar parks (Figure 5, Table 8). No other models with a ΔAICc value within 2 of that of the best-fitting model were present (Table 8). The sums of the weights of all models are presented in Table 9.

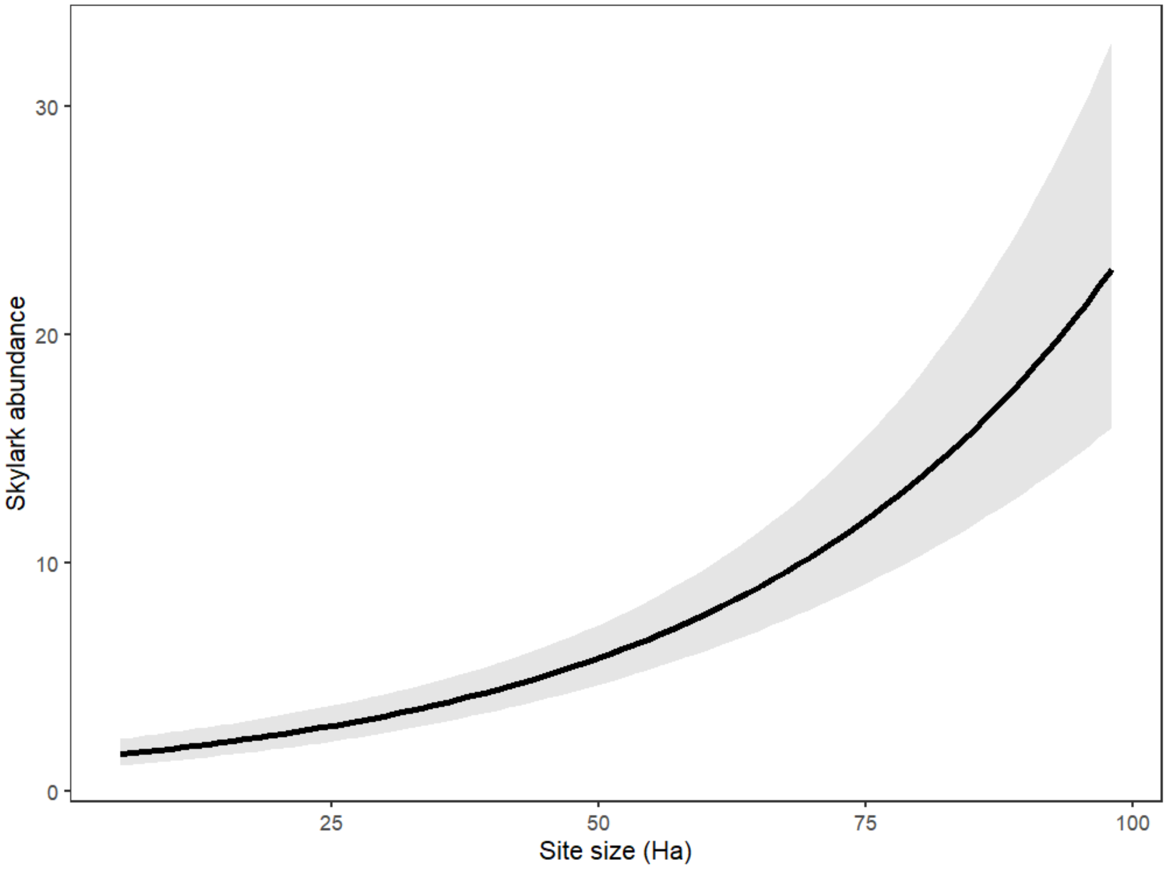

Figure 4. *The relationship between skylark abundance and solar park size. The line shows the predicted relationship from averaging of the best-fitting generalised linear models. The 95% confidence interval is shown in grey.*

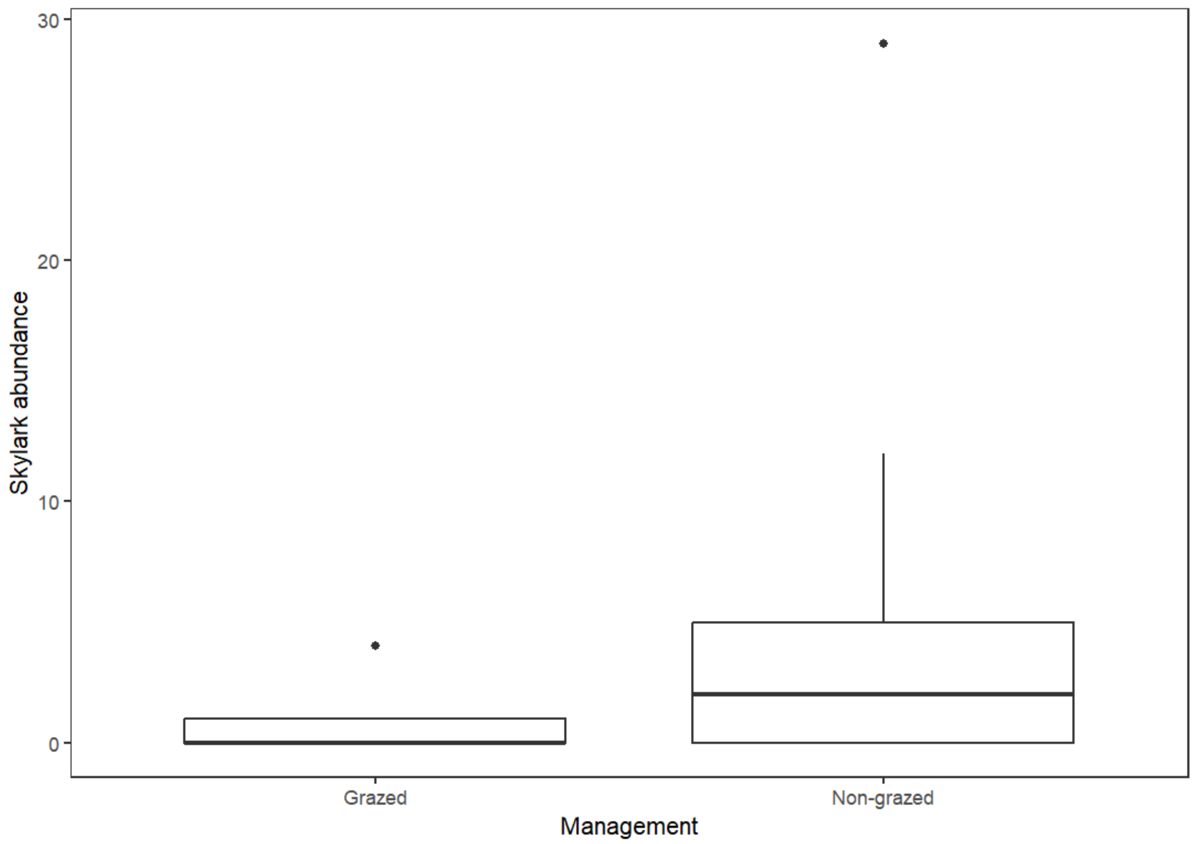

Figure 5. *The relationship between skylark abundance and grazing management practices on solar parks. The mean skylark abundance on grazed and non-grazed solar parks is outlined. Error bars represent standard error.*

Table 8. *The best-fitting generalised linear models of the factors associated with skylark abundance: glm(skylark abundance ~ grazing + age + corvid abundance + size + sward height). Models with a ΔAICc value within 2 of that of the best-fitting model are shown, and the null model is shown for comparison.*

Model	(Intercept)	Graze	Age	Corvid abund	Size	Sward height	df	loglik	AICc	Delta	Weight
1	-1.5430	-2.046			+		3	-41.730	90.9	0.00	0.325
null	1.3120						2	-46.621	97.9	7.04	0.010

Table 9. *Sum of variable weights across all models of skylark abundance.*

Variable	Sum of weights	N containing models
Age	0.85	20
Age x Size	0.25	10
Grazing	0.41	18
Grazing x Sward	0.03	6
Sward	0.24	18
Size	<0.01	15

Skylark presence

The best-fitting models of skylark presence indicated an effect of site size; all three of the best-fitting models contained this variable, with skylarks more likely to be present on larger sites (Figure 6, Table 10). Two of the best-fitting models also included grazing, suggesting skylarks were less likely to be present on sites where grazing management practices were used (Figure 8, Table 10). Sward height was also included in the third best-fitting model, suggesting a possible effect on skylark presence, but the effect size was very small and is unlikely to be biologically meaningful. As with skylark abundance, the model was re-run without the disproportionately large site. This version of the model returned very similar results to the first, indicating that size and grazing both appeared to impact the likelihood of skylarks being present (Table 11). Finally, sward height was again contained within one of the best-fitting models, indicating a possible effect, but the effect size remained small (Table 11).

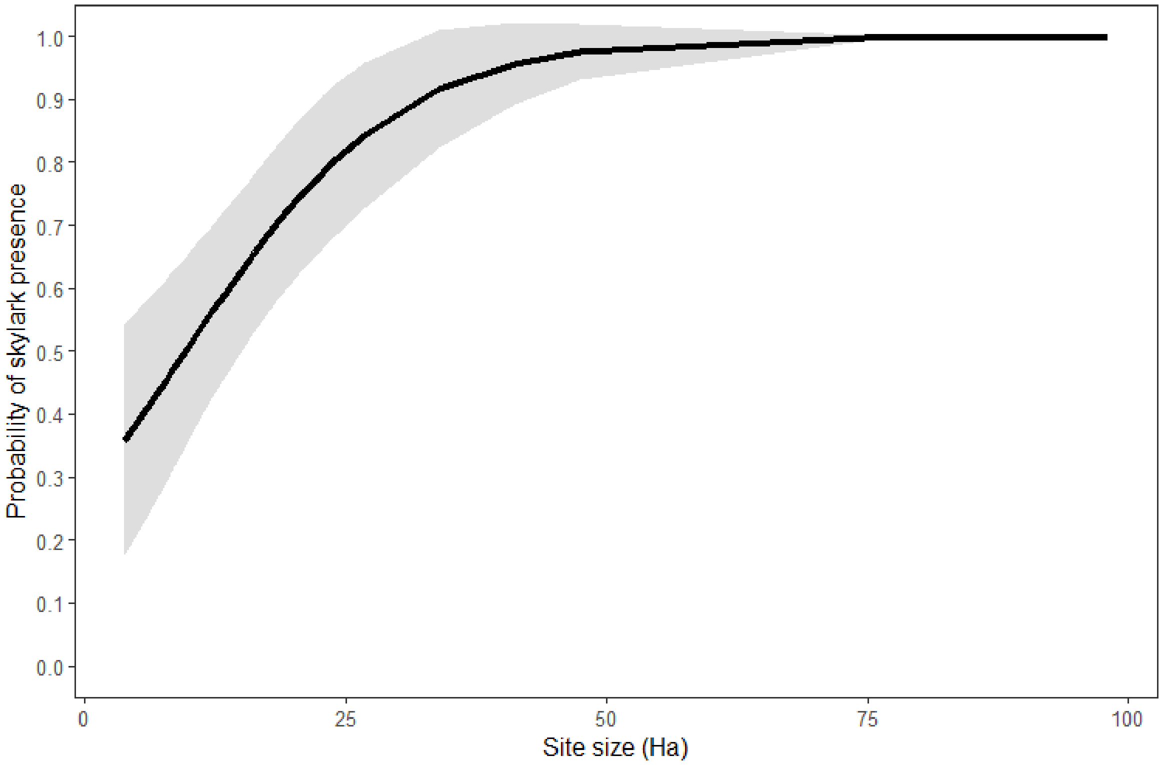

Figure 6. *The relationship between the probability of skylark presence and solar park size. The line shows the predicted relationship from averaging of the best-fitting generalised linear models. The 95% confidence interval is shown in grey.*

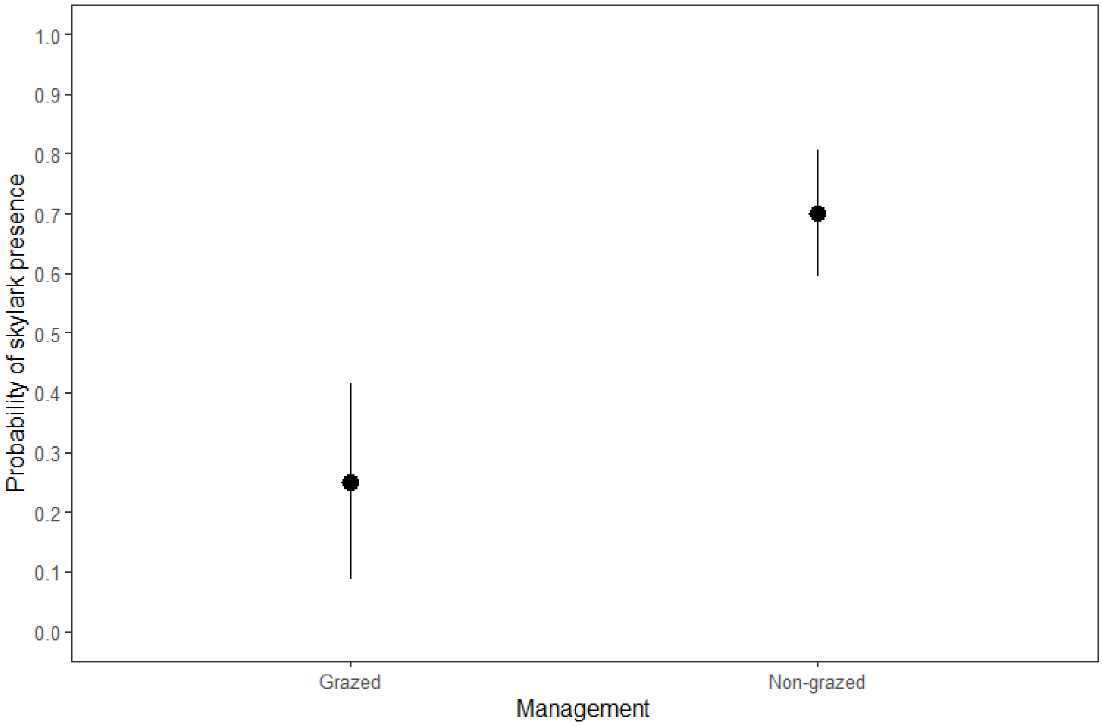

Figure 7. *The relationship between the probability of skylark presence and grazing in solar park management practices. The points illustrate the mean probability of skylarks being present on a solar park from averaging of the best-fitting linear model. Error bars represent standard error.*

Table 10. *The best-fitting generalised linear models of the factors associated with skylark presence, including the disproportionately large site: glm(skylark presence ~ age + size + sward height + grazing). Models with a ΔAICc value within 2 of that of the best-fitting model are shown, and the null model is shown for comparison.*

Model	(Intercept)	Graze	Age	Size	Sward height	df	loglik	AICc	Delta	Weight
1	1.3090	+		2.067		3	-13.934	34.9	0.00	0.285
2	0.7361			2.040		2	-15.857	36.2	1.32	0.147
3	1.4110	+		2.484	-0.5449	4	-13.341	36.4	1.55	0.131
null	0.2877					1	-19.121	40.4	5.53	0.018

Table 11. *The best-fitting generalised linear models of the factors associated with skylark presence, excluding the disproportionately large site: glm(skylark presence ~ age + size + sward height + grazing). Models with a ΔAICc value within 2 of that of the best-fitting model are shown, and the null model is shown for comparison.*

Model	(Intercept)	Graze	Age	Size	Sward height	df	loglik	AICc	Delta	Weight
1	1.3080	+		2.066		3	-13.934	34.9	0.00	0.264
2	0.7355			2.038		2	-15.856	36.2	1.30	0.138
3	1.4110	+		2.484	-0.5448	4	-13.341	36.5	1.59	0.119
null	0.2231					1	-18.548	39.3	4.34	0.030

Discussion

The potential for solar parks to be refugia for bird species within an increasingly ecologically depleted agricultural landscape has been the subject of much debate, yet there has been limited evidence to inform these discussions. The results of this study demonstrate that solar park age, grazing, and to a lesser extent sward height, may influence the bird species present on solar parks. They provide evidence demonstrating that whilst solar parks may represent an opportunity to promote biodiversity in agricultural landscapes, ensuring management regimes are tailored to support wildlife is of paramount importance if they are to become of significant conservation value for bird species, particularly those in a farmland context.

Site age was an important predictor of all bird and farmland bird species richness on solar parks. There are many potential drivers behind this result, but they are likely to be related to increases in structural diversity and habitat heterogeneity occurring over time. Habitat heterogeneity is positively associated with the complexity of agricultural landscapes (Benton et al., 2003; Gonthier et al., 2014; Landis, 2017; Estrada-Carmona et al., 2022), and the planting of wildflower meadows and lower intensity of management regimes on solar parks compared to surrounding cropland may provide preferential habitat for species in the surrounding intensively managed landscapes. Furthermore, previous studies have shown that anthropogenic disturbance can have negative effects on species diversity (Stanton et al., 2018; Matuoka et al., 2020), as well as reproductive output (Grüebler et al., 2015), depending on timing and habitat-specific disturbance characteristics. The construction of solar parks inevitably involves initial disturbance of habitat to install the arrays, with vegetation cover likely to be minimal immediately after construction, meaning only a small number of species that can exploit bare ground are likely to be present on site. Although recovery of species could also occur in the short term after initial disturbance effects subside, longer-term impacts are likely more complex as there are several factors that may affect the composition of bird communities on solar parks, including land cover, vegetation cover, vegetation composition, and solar park design (Jarčuška et al., 2024). Over time, as ecological succession takes place and vegetation cover is reestablished, habitat heterogeneity is likely to increase, thereby supporting a wider range of species as sites grow older, as demonstrated by Zaplata and Dullau, (2022). Furthermore, solar parks have been shown to promote restoration in degraded grasslands (Zhang et al., 2023), and in the UK context, where most solar parks are constructed on 'poor-quality' agricultural land (Palmer et al., 2019), enhancement of existing vegetation cover may be quicker than solar parks located in other landscapes; vegetation is already cut in a yearly cycle for cultivation, which may therefore represent an opportunity to help improve habitat for bird species over a solar park's life cycle (Jarčuška et al., 2024). It must also be noted that bird abundance and diversity will eventually plateau until a climax community is established. In this study there was no evidence of a plateauing of species richness, indicating that sites in this sample of sites had not reached their full capacity for bird species richness. Therefore, sites greater than ten years old, (the oldest site in this study; Table 1) should be included in future studies to establish when bird communities on solar parks reach their full potential. Farmland birds in the UK have the lowest species richness compared with other habitat types (e.g. woodland, wetland, urban), and have also suffered the steepest declines (Chamberlain and Fuller, 2000; DEFRA, 2021). They therefore stand to benefit the most from any benefits solar parks may offer, such as improved foraging resources. A comparison of pre-construction and post-construction species richness over a protracted period would help to determine whether pre-existing species richness can be improved by the construction of solar parks. Unfortunately, this study did not have access to such data, so it cannot be conclusively determined. Further work should look to improve monitoring protocols on solar parks and include pre-construction survey data in any future analysis of species richness trends over time.

Grazing also affected species richness, skylark abundance, and skylark presence; all were negatively associated with the presence of grazing in solar park management regimes. Grazing is a common practice included in 'agrivoltaics' (Jain et al., 2021; Al Mamun et al., 2022), and has been promoted as a sustainable way to mutually benefit solar energy and agricultural production (Andrew et al., 2021). However, increased grazing pressure can have detrimental effects on birds (Martin and Possingham, 2005). Firstly, reduction of sward height through intensive grazing may alter vegetation structure, changing the abundance and species composition of invertebrate prey, thereby altering the suitability of the sward for nesting and feeding (Vickery et al., 2001). This can be beneficial for species that prefer to forage in shorter swards, and heavily sheep-grazed swards can provide attractive feeding sites for a small number of species, such as starling, blackbird *Turdus merula*, carrion crow, jackdaw, magpie, rook, and mistle thrush *Turdus viscivorus* (Tucker 1992; Wilson et al., 1997). Although not shown to have a major effect in the analyses of this study, sward height, which is likely closely related to grazing regimes, was present in the best-fitting models of skylark abundance, skylark presence, and species richness, indicating a possible marginal effect. However, these results should be treated with caution and more data are needed. Specifically, sward height is likely to vary widely across a solar park, with areas such as the margins typically being much taller than between array rows. Therefore, a less simplified approach where analysis of sward height takes place at a finer scale would help improve understanding of the effects of sward height on birds.

Short swards can also increase predation pressure, which can occur through two mechanisms; 1) it could act to increase predator numbers by providing carrion and increased soil invertebrates (Fuller and Gough, 1999; Grant et al., 1999), and 2) it could affect predation rates more directly by increasing the likelihood of a predator detecting the nest, chicks or adult (Baines, 1990; Fuller and Gough, 1999).

In this study, corvid abundance was not associated with the abundance of skylarks, although this was a relatively crude proxy for predation pressure, and more work is needed. Surveys of mammalian predators, which are a major cause of ground-nesting bird nest failure (Angelstam, 1986; Weidinger, 2009), would also be beneficial to understand their impacts on bird species at solar parks. The most direct impact of heavily grazed swards, particularly on ground-nesting species, is the destruction of nests through trampling (Green, 1988; Beintema and Muskens, 1987). The rate of nest destruction has been shown to be heavily dependent on the type and density of stock, the timing of grazing, and the bird species involved (Vickery et al., 2001). Therefore, in a solar park context, assessment of management practices, and understanding how they can benefit bird species within the wider landscape, is likely to be of high importance. Grazing was only included as a binary measure in our analyses, and an improvement for any future study would be to include factors such as timing of grazing and stocking density to help better understand their effects.

Solar park size was positively associated with skylark presence, and appeared to be related to skylark abundance. In contrast to other variables, such as sward height, the mechanism by which size impacts skylark abundance can only act in one way; larger solar parks are more likely to harbour a greater number of birds than smaller solar parks simply because there is more space in which to establish territories. Nonetheless, the results do suggest that larger solar parks have the potential to support a greater number of birds. Most of the sites in the dataset were below 40Ha in area, which, while similar to the average size of solar parks at the time of writing (Department for Energy Security and Net Zero, 2023), does not include many sites that represent the increasing number of large-scale utility solar parks that are being constructed in the UK. The fact that skylarks were present at over half of sites (57%) strongly suggests that solar parks can support skylarks, but more data are needed across a broader spectrum of sites to understand in what capacity, as the conclusions that can be drawn from simple occupancy data are limited; for example it cannot be determined whether a skylark recorded as present was actively using the site for key behaviours, such as foraging, or if the bird was simply flying over. Measuring the density of skylarks on solar parks may be a more reliable way to compare their potential to support skylarks against other land use types. The results from this study appear to show a comparable density of skylarks in set-aside, which was the habitat with the greatest density of skylarks across all habitats (30.61 pairs per km^2) according to Browne et al. (2000). On the largest solar park in this study, the density of skylarks was found to be 29.59 individuals per km^2. Across all other solar parks where skylarks were observed the mean density was 25.73 individuals per km^2. Whilst Browne et al. measured pairs rather than individuals, the figures are comparable as recording singing male skylarks was the main method of detection in the BBS surveys, and therefore it is highly likely a large proportion of the birds detected in the original data collection for this study were males. By comparison, skylark densities in winter cereals and all types of grazed pasture were some of the lowest measured by Browne et al., ranging between 2.99 and 10.37 pairs per km^2. As a result, even smaller scale solar parks may have the potential to host a comparatively greater density of skylarks than other agricultural land uses, indicating that solar parks could help to buffer skylarks to the changes in agricultural practices which have contributed to their decline. Whilst no other study has investigated the effect of solar park size on birds, evidence does exist for other taxa. Blaydes et al., (2022) found that solar park size, shape and landscape context had a smaller impact on bumblebee response inside solar parks than management practices, but that large, elongated resource-rich solar parks most effectively increased bumblebee density inside solar parks. This reinforces the fact that management practices are a key predictor of biodiversity on solar parks, which likely translates to bird species and may determine how many are present and how they are using these sites, but more data are needed to understand these effects. Therefore, further work should look to complete more comprehensive count surveys across a broad range of sites, including larger sites over 50Ha, to investigate the effects of solar park structural composition and management regimes on skylark abundance.

Finally, previous land use is one potentially key variable, to which this study unfortunately did not have access, which may impact the composition of bird species on solar parks. Whether a solar park is constructed on land previously used as arable fields, pastoral land, or potentially other habitats, such as woodland, will likely influence the species present due to factors such as site fidelity (Jarčuška et al., 2024). This has been shown to cause birds to return to wind energy sites in the year after construction, but not in subsequent years due to intolerance of the turbines (Shaffer and Buhl, 2015), but effects of site fidelity are still poorly-understand in the context of solar parks. Previous land use will also likely determine the habitat surrounding a solar park, which will have an impact on the species using the site. For example, a solar park surrounded by woodland is unlikely to be useful for farmland species, such as skylarks, but may prove useful for others. As a result, more data are required to assess the effects of where a solar park is constructed on the species that use the site post-construction, which will require yearly monitoring of biodiversity after a site has become operational, such as that outlined by Carvalho et al., (2023).

Solar parks are known to support farmland birds, including species of conservation concern (Parker and McQueen, 2013; Montag et al., 2016; Shotton, 2019; Jarčuška et al., 2024). The results of this study suggest that age is an important predictor of all bird and farmland bird species richness, which may be due to ecological succession after the initial disturbance during construction. Grazing also appears to be an important factor in the number of bird species present on solar parks, and the abundance of skylarks. However, as this study was limited to a relatively small sample size, and grazing was recorded in a rather crude fashion, marked as either present or absent in management regimes, more data are needed on factors such as stocking density, timing of grazing, and details of plant composition to understand if this holds true across a wider sample of sites. It is important to note that the solar parks in this study were primarily designed for electricity generation. As a result, it can be assumed that the benefits for biodiversity could be greater, should solar parks adopt management practices with a stronger focus on wildlife and in line with the habitat requirements of species of conservation concern in the wider landscape. Indeed, there is still an urgent need for further work investigating how site location, design, infrastructure, and management practices impact the abundance of bird species on a wider scale.

Chapter 2

Behaviour of ground-nesting farmland birds on UK solar parks

Introduction

With construction of solar parks set to increase over the coming years due to concerns about the finite supply of fossil fuels, global climate change and energy security (EIA, 2021), understanding their impact on wildlife is becoming of increasing importance, both from an academic and industry perspective. Solar parks in the UK are generally constructed on agricultural land (Palmer et al., 2019), so understanding their impact on farmland bird species, which have declined exponentially in the post-war period (Siriwardena et al., 1998; Woodward et al., 2018), is of particular importance. Unfortunately, little is known at present about the impacts of solar parks on these birds. It has been suggested that increased habitat heterogeneity produced through the management regimes of solar parks may promote increased avian diversity (Jarčuška et al., 2024), but most of the evidence collated so far has focused on occupancy and abundance of species. Thus, there is no current understanding of how these species are using solar parks, and if they can be beneficial for key behaviours such as breeding and foraging. This crucial information is not only required to improve understanding of the benefits and negative impacts of solar parks on birds but also to help inform management practices on operational solar parks.

The skylark is one ground-nesting farmland bird species that has suffered particularly marked declines over recent decades; according to British Trust for Ornithology (BTO) data, this species declined by around 60% between 1967 and 2016 (Tucker & Heath, 1994; Siriwardena et al., 1998; Woodward et al., 2018). At the national scale, their decline has largely been attributed to agricultural intensification, with habitat changes through the loss of rough grassland (Chamberlain & Vickery, 2002), the switch from spring-sown to autumn-sown cereals (Donald & Vickery, 2000), and conversion of mixed farms to cereal or intensive grass monocultures (Chamberlain & Gregory, 1999; Chamberlain et al., 1999, 2000; Donald et al., 2002) all outlined as key drivers. Preliminary ecological appraisals have observed skylarks to be relatively common on solar parks (Shotton, 2019; Solar Energy UK, 2023a), which has led to an increasing amount of interest from within the renewable energy sector regarding their use of solar parks.

The potential for solar parks to provide nesting habitat for skylarks has been the subject of particularly strong interest, but there are currently no studies which have specifically sought to assess whether they breed there, and there have been no confirmed records to date. Montag et al. (2016) did report one potential observation of a nest at a site in their study, where birds were observed carrying food to a location within the margins of the array, but the presence of a nest was never confirmed. Shotton (2019) also observed breeding behaviour, in the form of singing males, across six of his nine study sites, but no effort was made to systematically search for evidence of a nest. Skylarks typically nest in open habitats and avoid taller vegetation and structures (Cramp, 1988; Wilson et al., 1997; Chamberlain et al., 1999), which cause visual obstruction for foraging birds, thereby increasing predation risk (Butler & Gillings, 2004; Metcalfe, 1984; Cresswell, 1994). These factors are known to reduce breeding success in ground-nesting birds (Baines, 1990; Grant et al., 1999), so tall ground-mounted solar panels may present barriers to nesting, but to date this has not been investigated.

Corn buntings are another farmland ground-nesting species which have suffered major population reductions in the post-war period, declining by around 67% between 1967 and 2016 (Tucker & Heath, 1994; Siriwardena et al., 1998; Woodward et al., 2018). The drivers behind their decline are mainly congruent with those of the skylark, with a shift in agricultural intensity and loss of arable cultivation some of the main factors in the UK (Donald and Forrest, 1995; Brickle et al., 2000; Wilson et al., 2006). Alongside skylarks, previous evidence has suggested this species has also been using solar parks across multiple sites (Shotton, 2019). Furthermore, there is anecdotal evidence that corn buntings have been nesting on at least one solar park in the UK. However, as with skylarks, confirmed evidence through systematic surveys is non-existent, and more research into these claims is required to establish how farmland birds are using solar parks.

This study aims to address these issues by conducting the first systematic nest searches for skylarks on solar parks in the UK, using a combination of traditional survey methods and advanced thermal imaging technology. This study also reviews existing evidence of nesting corn buntings on a community-owned solar park. In addition, previous studies have focused on analysing abundance and species diversity, and there has been little attempt to conduct behavioural analysis of how birds are using these sites. Therefore, this study includes the first assessment of skylark behaviour on solar parks in the UK; time spent in different behaviours was recorded to create ‘activity budgets’ for skylarks using the sites. This new information will help to improve understanding of the value of solar parks in the UK for ground-nesting birds during the breeding season and will help provide guidance for industry stakeholders to implement tailored management practices to improve conditions for ground-nesting farmland bird species on solar parks in the UK.

Methodology

Study sites

The study took place in June and July of 2023 at four solar parks located across southern and central England. Three of these sites were utility-scale solar parks owned by two large renewable energy asset holders (hereafter 'industry sites'), and the fourth was a community-owned solar park (hereafter 'community site'). Although the sites included in this study were small to medium sized solar parks, ranging from 12.1 to 21.3Ha in area and 5.3 and 24.2MW in output capacity, they were close to the average capacity of ground-mounted solar parks in the UK, according to the government database at the time of writing (Department for Energy Security and Net Zero, 2023). Two visits to each site were completed during the summer of 2023: once in early June, and once in mid-late July, which are mid- and late-season visits for breeding skylarks and peak season visits for corn buntings (Ferguson-Lees et al., 2011). Logistic complications meant that no visits could be made during the early part of the season. Sites of this size were selected so that systematic nest searches could be completed within the one day allocated for the site visit.

All the industry sites were constructed with a focus on electricity generation, but each included measures to improve biodiversity on site, resulting in varied general management practices. Site 1 was cut with machinery twice between April and August; once in mid-summer in June, and once in late summer in September. The site was seeded with wildflowers throughout the margins of the site, which were left uncut until the end of the summer and bird breeding season. Site 2 had a similar regime, with two cuts in the summer, but was also grazed periodically throughout the summer between cuts when required. This site was also planted with extensive wildflower areas in the margins of the site, which were left uncut during the first summer mowing. Site 3 was separated into three fields and was grazed throughout the year with a large flock of sheep and was not cut using machinery. This site had several small strips of wildflowers planted along the edge of the fence line which were fenced off to prevent grazing by the sheep. Site 4 (the community site) had a strong emphasis from the landowner on promoting biodiversity and was managed with a minimal interference approach and differed in its structure compared to industry sites. It was left uncut by machinery throughout the entire summer, with short periods of grazing by a small herd of sheep when required. The entire site was seeded with a wildflower mix during construction, where the earth was turned over and seeds planted, allowing wildflowers to grow alongside other species. This, combined with large gaps between the arrays, meant that wildflowers were present throughout the entire site, including in between the panel rows where vegetation was still less dense than in the margins.

Nest searches

Nest searches aimed to identify whether skylarks and corn buntings were using solar parks to nest. Finding nests of these species using traditional methods can be extremely challenging; it is possible to narrow down to a small area from behavioural cues (e.g. birds seen carrying food, birds flushing at short distances, males landing on the ground following a song flight), but the nests themselves are often very well hidden and, in the case of skylarks, the birds typically land some distance away before walking to the nest out of sight (Ferguson-Lees et al. 2011). However, the recent development of using thermal imaging camera to detect nests has been ground-breaking; it is possible to see incubating females or chicks from many metres away and has been used in various bird survey applications for a variety of species (Boonstra et al., 1995; Galligan et al., 2003; Stephenson et al., 2019; Hughes et al. 2021; Shewring & Vafidis, 2021; Payne et al. 2022)). Their use has also helped to promote an increase in the efficiency of surveys, a reduction in disturbance of birds, and an improvement in the accuracy of counts for birds of conservation concern (Hughes et al., 2021). This study used the Pulsar Helion 2 XP50 Pro, which is generally considered the most advanced and high-resolution handheld thermal imaging camera currently available and has been used in numerous previous studies of birds and other vertebrate species (e.g. Nightingale et al., 2018; Gray, 2021, 2023; Rosti et al., 2022, 2023). The intended use of the camera was to effectively identify nests without relying on behavioural cues and long periods of observation, whilst also minimising disturbance to any nesting birds. Prior testing of the camera on arable farmland, with similar vegetation structure to that on most solar parks confirmed it was efficient at identifying several species of ground-nesting birds, including skylarks, and their nest sites.

Nest searches were conducted close to the time of arrival on site, around 8:00am due to restrictions in site access, to ensure the ground vegetation was still cool and thereby maximising the opportunity to view birds sitting on eggs. The whole site was searched by starting at one end of the site and walking a zig-zag pattern along the vehicle tracks intersecting the solar park, stopping at each row of panels to view between and under them with the camera. The rows of panels at each site were a maximum of 150m long, hence when viewed from both sides, any hotspots would be clearly visible within 75m when viewed from either side of each row due to the short vegetation between panels. The margins were defined as the vegetation between the edge of the array and the perimeter fence, and the distance between the two was no more than 50m at each industry site. The margins were surveyed with the thermal imaging camera by walking around the edges of the array, stopping at intervals of 50m to scan the margin vegetation for nests, which was necessary due to generally denser vegetation compared with between the panels. The margins at the community site were similar to the other sites on three sides, but differed at the southern end of the site where they were more extensive and had denser vegetation, ranging in depth from 50-100m. Therefore, surveying this area required a different approach; the observer walked a transect through the middle of the margins, stopping at 25m intervals to observe the surrounding vegetation. The thermal camera was used to check directly in front of the observer before proceeding to the next transect point to avoid damaging nests and disturbing birds. At each transect point, the surrounding vegetation would be observed by searching the vegetation for hotspots. At all sites, more concentrated searches with the thermal imaging camera were conducted around areas where behavioural cues indicating breeding activity were observed during the site visit; these behaviours included singing males, carrying nesting material or food, and alarm calling.

Focal watches

Focal watches were carried out in this study in an attempt to quantify how ground-nesting farmland birds are using solar parks, by observing key behaviours such as singing, foraging, and carrying food. This is crucial information to inform industry stakeholders how solar farms can be enhanced for farmland bird species, maximising any benefits they may offer. Corn buntings were only recorded on one of the four sites, so focal watches were conducted for skylarks only. Focal watches could be completed throughout the rest of the day, from around 9:30 until 17:00, although the middle of the day was avoided as bird activity is generally reduced during this period (Robbins, 1981). One focal watch per bird was completed at each visit. For any sites with many birds present, succeeding watches were conducted from different parts of the site, at least 100m away from the preceding watches, to minimise the risk of sampling the same bird multiple times. A focal watch was carried out by locating an individual skylark, usually by sound through singing or calling, and observing it with binoculars from a suitable distance, around 20 to 50 metres, for between 10 and 30 minutes, or until the bird disappeared, whichever occurred sooner. A minimum of 10 minutes was considered enough time to get a representative sample of the behaviour of a bird on the site after consideration of other studies of focal watches of bird species (e.g. Drachmann et al., 2000; Ridley et al., 2007). Behaviour and location were recorded by speaking into a Dictaphone (iPhone 13) every time a bird's behaviour changed, allowing time spent performing each behaviour to be calculated at a later date. To describe the time budget and activity patterns, the behaviours observed were divided into six mutually exclusive categories: singing, resting/perching, interacting with other skylarks, foraging, carrying nesting material, and carrying food.

Focal watches were only conducted at site 1 and 2, as no skylarks were observed at site 3 (see results). A total of 28 focal watches were recorded at industry sites over the course of the two visits, with fourteen each during the June and July visits across the two sites. These data were then pooled across the industry sites for each visit, as all were of a similar size and had broadly similar management regimes. Pooling the data also prevented analysing data taken from the same bird during each visit and facilitated an assessment of change in behaviour between visits. Industry sites were separated from the community site due to the differences in the structural composition and management practices at this site. Twelve focal watches were completed at the community site, with six at each visit.

Previous nesting evidence

Data from the breeding season at the community site spanning four years between 2019 and 2023 were collected and made available for analysis by West Oxfordshire Farmland Group. The group have been monitoring a small population of corn bunting within a kilometre radius of the site on land owned by the same farmer as the solar park, as well as nesting attempts within the perimeter. These data were used to conduct simple comparisons between nests on the solar park and nests outside the solar park. Standard BTO Nest Recording Scheme (Ferguson-Lees et al., 2011) methods were used to monitor the nests and thereby record clutch size, nest success, number of chicks fledged, and cause of nest failure. ArcGIS (Version 2.2.8; ESRI, 2021) was used to map the nests on the solar park and surrounding land, within 1km of the solar park boundary, with success or failure indicated. During the late season site visit to the community site, one corn bunting nest had just fledged, and so detailed photos of the nest site were taken.

Results

Nest searches

Nest searches failed to locate any skylark nests within the perimeter of any of the four solar parks included in this study. Behavioural cues observed during the focal watches reinforce these results, with no evidence of skylarks carrying or depositing food within the perimeter boundary of the solar park (see below). Indeed, there was no evidence of nesting by any farmland or ground-nesting species at any of the three industry sites. Evidence of nesting corn bunting was collected on the community solar park (see below).

Focal watches

Although previous monitoring indicated skylarks had been present on site 3 in preceding years, none were observed there in 2023, so focal watch data were collected exclusively on sites 1 and 2. Skylarks allocated their time relatively evenly across the three most common behaviours, although there were differences in time allocation between visits. During the first visit to industry sites, skylarks spent the highest proportion of time singing, followed by perching, with foraging third most common (Figure 8). By contrast, skylarks spent a comparatively lower proportion of time singing at the community site during the first visit, and allocated a higher proportion of their time foraging, with singing the second most common behaviour, followed by perching. There was no evidence of food carrying or carrying nesting material during the first visit to any of the sites.

During the second visit, skylarks spent a higher proportion of time foraging on industry sites, which was marginally the second most common behaviour, behind perching (Figure 9). Proportion of time spent singing reduced, possibly reflecting the fact the visit was later in the breeding season, and territory establishment was likely already complete. Food carrying behaviour was observed on industry sites during the second visit (Figure 9), but all birds carrying food were observed taking the food offsite to adjacent grassland or arable fields. In total, food carrying was observed by skylarks on five separate occasions. This behaviour also adds further evidence, alongside the nest searches, that skylarks were not nesting on the solar parks themselves.

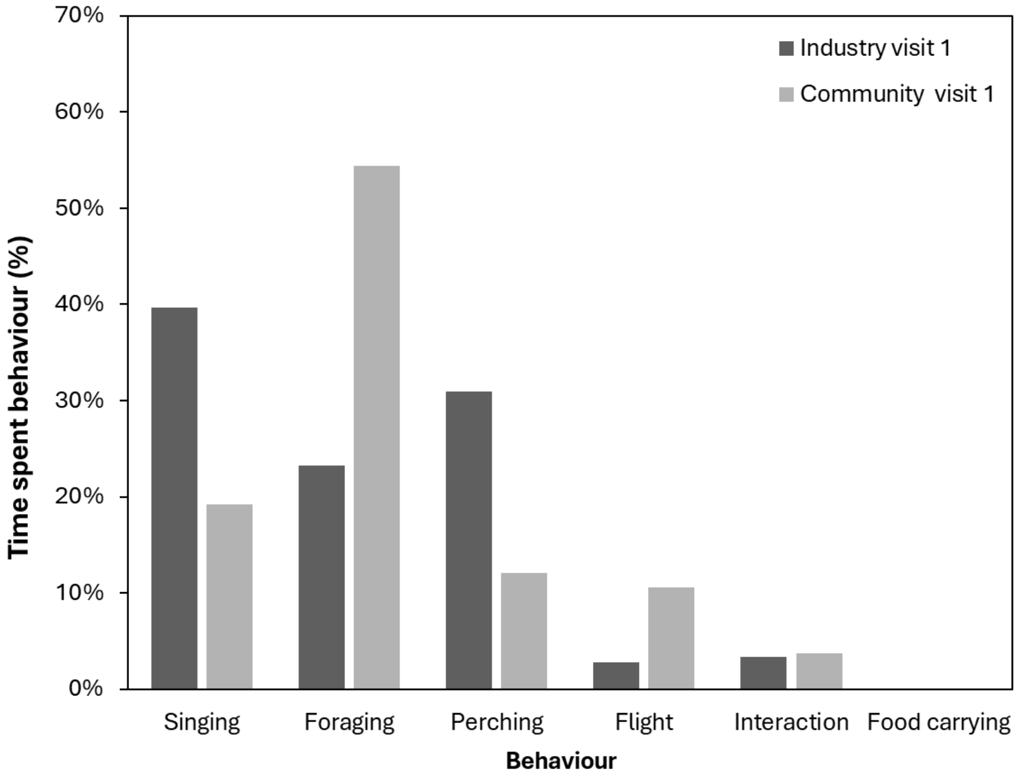

Figure 8. *Proportion of time skylarks were observed performing different behaviours in focal watches during the mid-season visit at industry sites vs the community-owned site. For industry sites, data are pooled across two sites*

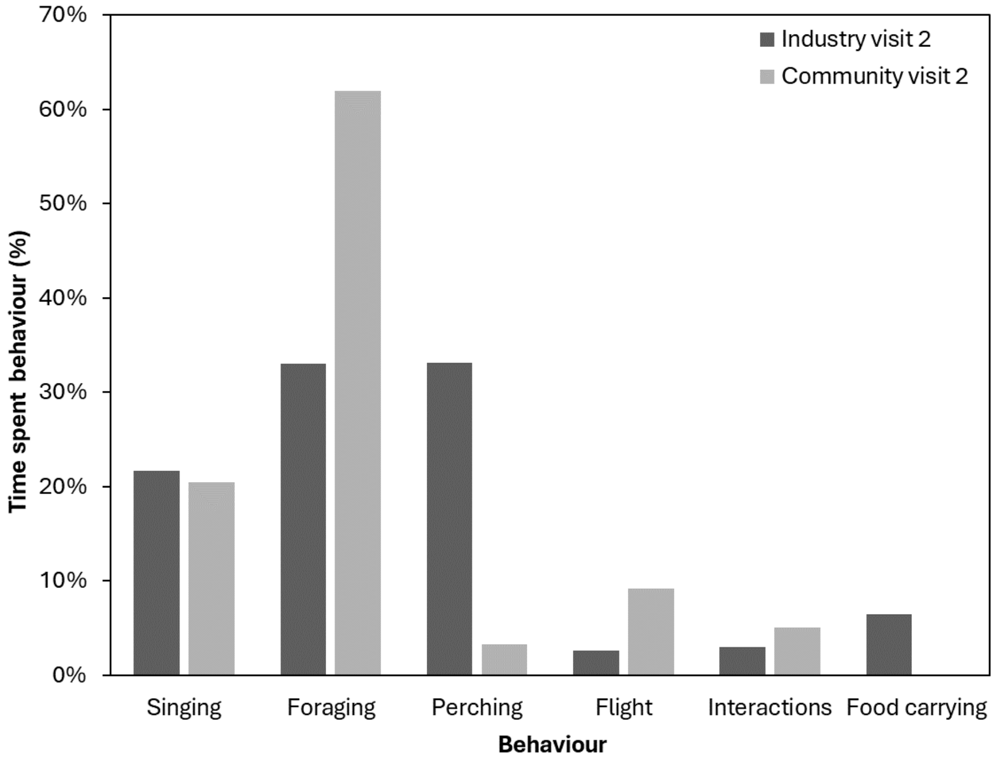

Figure 9. *Proportion of time skylarks were observed performing different behaviours in focal watches during the late-season visit at industry sites vs the community-owned site. For industry sites, data are pooled across two sites.*

Previous nesting evidence

Previous data show a total of five corn bunting nests on the community-owned solar park between 2020 and 2023, the locations of which are shown in Figure 10. These data reveal that of the five nests recorded inside the solar park, 100% were successful, fledging a mean (± SD) of 3.8 ± 0.4 chicks. The 36 nests outside the perimeter of the solar park had a success rate of 61.1%, but the mean number of chicks fledged per successful nest was the same (3.8 ± 0.2). Of the unsuccessful nests, 64.2% of nests failed by egg predation, 21.4% failed by predation of nestlings, and the remaining 14.3% failed with unhatched eggs.

Figure 10. *Corn bunting nesting locations in years where corn buntings attempted to nest on the solar park, in 2020, 2022, and 2023. Green dots indicate successful nests, red dots indicate unsuccessful nests. The red outline indicates the perimeter of the solar park.*

The only nest identified within the solar park in 2023 was located between the panels at the northern end of the site, details of which are shown in Figure 11 and were recorded during the late season visit after the nest had fledged. The nest was located 28.3m away from the perimeter fence. The female produced five eggs, all of which subsequently hatched and the chicks fledged successfully. Six corn buntings were observed within the perimeter fence of the solar park during both visits during the breeding season.

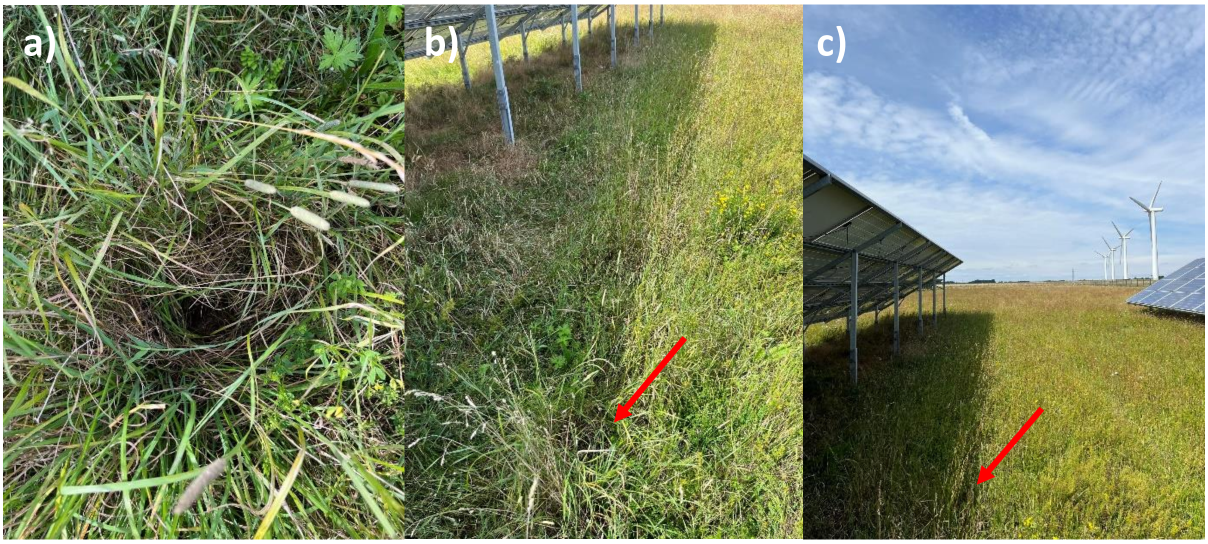

Figure 11. *Details of the location of a corn bunting nest found in 2023 on the community-owned solar park. Images illustrate a) close-up of the nest, b) vegetation structure and concealment, and c) the location between the panels towards the end of the first row in the array at the northern end of the site. The red arrows indicate the location of the nest.*

Discussion

The impact of solar parks in relation to ground-nesting bird conservation has been a subject of debate within the solar industry, yet the true potential of these sites to provide useful breeding habitat for these species is currently unclear. Evidence collected as part of this study indicates solar parks are unlikely to be used by skylarks for nesting on a large scale; at all study sites, neither systematic nest searches nor focal watches provided any evidence to suggest that skylarks were nesting within the perimeter, even where relatively common. Widespread and successful breeding by skylarks on solar parks is perhaps unlikely given existing knowledge of skylark breeding ecology; skylarks generally, but not exclusively, avoid tall structures when nesting (Wilson et al., 1997), and the presence of ground-mounted solar panels may therefore deter them. Unfortunately, this study was limited by a small number of sites and by timing of access. Only mid- and late-season visits were carried out, so it cannot be conclusively ruled out that skylarks had nested earlier in the season, although no evidence of abandoned or previously fledged nests, or of recently fledged young, was ever detected. A larger sample of solar parks, and access throughout the breeding season, would help build a clearer picture of nesting potential across a broader range of sites with different infrastructure and management regimes. This should be a key focus of future work, especially given their red-listed conservation status (Stanbury et al., 2021), and previous special consideration on solar parks, including the deployment of 'skylark plots'. Despite being widely recommended as a mitigation measure for displaced skylark territories, these plots have been shown to have limited benefits (Smith et al., 2009; Field et al., 2010), and so their deployment should be carefully judged and used as one of several options available (Fox, 2022).

Despite the lack of evidence of nesting, focal watches did show that skylarks were using solar parks as foraging habitat, and may have been breeding close by, outside of the perimeter fence. Skylarks take a wide variety of invertebrate prey during the breeding season, particularly when feeding chicks (Poulsen & Aebischer, 1995), and food carrying is a strong indication of breeding activity in a localised area (Poulsen et al., 1998; Ferguson-Lees et al., 2011). Six different skylarks were observed carrying food at two of the industry sites, all of which were observed during the late season visit. These birds were seen taking the invertebrate prey offsite to the adjacent grassland and arable fields where, it is assumed, it was fed to chicks in the nest or recently fledged young. This suggests that solar parks may provide useful habitat for breeding skylarks, even if nesting is rare. This is further supported by the fact that skylarks spent at least 20% of their time foraging on industry sites, and at least 30% at the community site during the first visit, increasing on the second visit to 54.4% and 62.0% at industry sites and the community site, respectively. A possible explanation for this difference in proportion of time spent feeding between the different sites could be a difference in invertebrate abundance, which could be attributed to more biodiversity-orientated management regimes at the community site. In grasslands, vegetation height is positively correlated with invertebrate abundance, and negatively correlated with the number of foraging birds (Hoste-Danyłow et al., 2010). Further evidence that management regimes are key for foraging birds is illustrated by the fact that no skylarks were observed on one of the industry solar parks (Site 3), where grazing was the main management practice and where sheep were present on site year-round. Ecological monitoring from previous years indicated that skylarks had been present on the site previously and were also observed in the surrounding arable fields during the site visit, suggesting management of the solar park may have been a factor behind their loss from the site. Further work to compare factors such as vegetation composition, habitat heterogeneity, and prey item availability on solar parks compared to adjacent land throughout the breeding season is required to improve understanding of the potential for solar parks to be key foraging habitat for skylarks during the breeding season.

The fact that food carrying was only observed during the late season visit may also be significant and may indicate that solar parks can supplement food resources in the local landscape throughout the breeding season. Since around 1970, the use of high-yielding varieties of autumn-sown crops have become a key component of intensified cultivation (Matson et al., 1997, Chamberlain et al., 2000). The earlier sowing of these crops, in comparison to traditional spring-sown crops, means that they develop earlier in the season, and the advanced sward development in crop fields and pesticide use may reduce food availability and productivity (Wilson et al., 1997; Poulsen et al., 1998; Chamberlain and Siriwardena, 2000). Although only skylarks were included in focal watches, improved foraging resources on solar parks compared to surrounding land is supported by Jarčuška et al. (2024), who observed higher abundance of ground-foragers within solar parks compared to grassland control plots. It may therefore be the case that skylarks were commuting to solar parks in order to forage, as a result of depleted food resources in the surrounding landscape. Similar effects have also been suggested in other taxa; for example, Blaydes et al.'s (2021) review suggested solar parks could be important sources of nutrition to pollinators through late-flowering species. Improved invertebrate foraging resources on solar parks could help to fill a similar 'hunger gap' for farmland bird species, as food availability declines in the wider landscape as the breeding season progresses; the switch from spring to autumn-sown of crops means that tall, dense vegetation reduces food availability and depresses reproductive output (Donald et al., 2001a; Wilson et al., 2005; Douglas et al 2005). Further work may look to assess the productivity of skylark nests in land adjacent to solar parks relative to similar habitat elsewhere. This information would also help to inform solar park siting, mitigation strategies, and management regimes to protect existing nesting skylark habitat, but locating in areas where the existing level of habitat is poor to help to promote biodiversity at the local scale.

Corn buntings were absent from the three industry sites, which is perhaps unsurprising given their low population density and restricted range in the UK (Balmer et al., 2013; Massimino et al., 2023). However, evidence of corn bunting nesting at the community site shows that, when managed with biodiversity in mind, solar parks can provide useful habitat for ground-nesting birds, including species of conservation concern. Seeding with wildflower-rich mixes at the time of construction and sensitive management of vegetation through low livestock densities has led to a rich mosaic of vegetation across the site. A larger distance between rows of the arrays, comparative to most utility-scale solar developments, has further improved conditions for floral biodiversity, which has in turn likely increased the number of invertebrates on which corn buntings are able to feed their chicks. In total, five nests were recorded within the perimeter fence of the solar park over a four-year period, all of which were successful. The average success rate (nests that fledged one or more chicks) of nests in the survey area surrounding the site was 61.1%, which whilst higher than the success rate observed by Brickle et al. (2000) in an agricultural setting in the UK, is still lower than the success rate inside the solar park. Nest monitoring on the land surrounding the solar park shows predation of eggs was responsible for 64.2% of nest failures, with predation of young responsible for 21.4%, and unhatched eggs explaining the remaining failures. Whilst the sample sizes are too small to draw firm conclusions, it is possible that higher breeding success inside the solar park relates to reduced predation; fences may present a barrier to mammalian predators of ground-nesting bird nests, such as red fox *Vulpes vulpes* and badger *Meles meles*, (Maag et al., 2022), and panels could potentially reduce detection by aerial predators (Nordberg et al., 2021). Lower livestock densities may also be a driver behind lower numbers of avian predators attracted to the site to feed. However, evidence from other sources indicates that whilst predator control and exclusion appear to increase hatching success and post-breeding population size in birds, they generally have little impact on the overall population (Coté & Sutherland, 1997; Newton, 1998). Therefore, benefits of improved productivity on this site for the wider population are likely limited, especially given the small number of nests that have been recorded. Furthermore, as this is the only site where, to date, ground-nesting bird nests have been recorded and monitored, and the site is a relative anomaly in its structure compared to most utility-scale solar parks in the UK, it is unclear whether these promising results can translate into wider scale impacts. Instead, this site could be used as a potential model for other solar park designers and asset-holders to follow in order to improve biodiversity.

In conclusion, the lack of evidence of nesting skylarks on industry solar parks indicates an urgent need to complete further wide-scale assessment of the potential for solar parks to be nesting habitat for ground-nesting birds in the UK. Whilst some have highlighted the potential values of solar parks to skylarks (Shotton, 2019), this study suggests more careful evaluation of how the birds use them is required if conservation benefits are to be realised. In the meantime, implementation of mitigation measures to avoid disruption of existing breeding skylark territories during the proposal, design, and construction of new solar parks is crucial. There is also more promising evidence to suggest that these sites can be useful for skylarks and corn buntings, if managed in a sensitive manner for biodiversity. Specifically, solar parks appear to be useful foraging habitat for skylarks, particularly later in the breeding season. This offers hope that solar parks could play a role in improving the fortunes of declining farmland bird species at the local scale, but developments in management practices at utility-scale solar parks are likely required for them to become beneficial habitat for ground-nesting bird species at the national scale.

General discussion

The impacts of solar energy infrastructure on biodiversity depend on the conservation value of the habitat in which the facilities are developed (Cameron et al., 2012). In many countries where agricultural practices are less intensified, and where bird species richness in agricultural landscapes remains relatively high, solar parks can have negative impacts on farmland bird species (Morelli et al., 2018). However, in biodiversity depleted countries, including the UK, the installation of solar parks is seen as an opportunity to enhance biodiversity in farmland landscapes (Harrsion et al., 2017; Taylor et al., 2019). Given that birds are a well-studied and ubiquitous taxon, it is surprising that there is little evidence of their abundance, diversity, and behaviour currently available in relation to solar parks. The results of this study suggest the effects of solar parks on bird species are mixed and are likely highly species-specific. The first systematic skylark nest searches using thermal imaging on UK solar parks failed to provide any evidence that this species uses these sites to nest, which was further reinforced by focal watches. Despite this, this study does present evidence that skylarks are using solar parks as potentially important foraging habitat, and birds were observed carrying food towards the end of the breeding season. This may represent an opportunity for solar parks to be beneficial for ground-nesting species, particularly later in the breeding season when foraging resources are depleted in the wider landscape.

Evidence of nesting corn buntings over multiple years at a community-owned solar park in this study shows the potential conservation benefits of such sites and is the first confirmed record of ground-nesting birds using a solar park to nest in the UK. Reduced nest predation rates compared to the immediate surrounding habitat may indicate one mechanism by which solar parks can improve productivity. Despite these early encouraging signs, it is important to note that this site is unusual with regards to its management practices and structure relative to most utility-scale solar parks in the UK, and highlights that management is likely one of the most important predictors of the value of solar parks to bird species. This is further evidenced by the results of chapter one of this study, where presence of grazing in solar park management practices was shown to be associated with the diversity of species; all bird species richness was greater at non-grazed sites, and grazing was included in the best-fitting models for skylark presence. Intensively grazed grasslands typically have low value as nesting sites for ground-nesting birds (Vickery et al., 2001), provide attractive feeding sites for only a small number of species, including corvids (Tucker, 1992; Wilson et al., 1996), and have a higher risk of trampling by livestock (Beintema & Muskens, 1987; Shrubb, 1990; Vickery et al., 2001). Further study is needed to determine if the timing of grazing and stocking density can have a pervasive impact on birds at solar parks. Future research may also look to assess the influence of sward height, vegetation structure, and habitat heterogeneity to further inform management regimes of operational solar parks in the UK.

The community-owned site included in this study, though unusual, could act as a model for other solar parks to follow. Although some features of this site will be hard to replicate on utility-scale sites, for example large gaps between panel rows, others are more achievable. The seeding of sites with wildflowers, combined with more sustainable livestock stocking densities would help encourage a greater diversity of vegetation to colonise the site, thereby increasing the number of invertebrates and providing foraging habitat for insectivorous bird species. The industry sites in this study, despite primarily operating for electricity generation, included measures to improve biodiversity on site, and were shown to be useful foraging habitat for skylarks. Therefore, if biodiversity measures were further enhanced and adopted on a greater scale across ground-mounted solar parks in the UK, that would help move closer towards fulfilling the claims that solar parks can be beneficial for biodiversity. However, as researchers and industry stakeholders endeavour to learn more about the interactions between these sites and biodiversity, standardised monitoring is essential to evaluate changes in natural capital and ecosystem services resulting from solar park development and operation (Carvalho et al., 2023). Specifically, and particularly in relation to birds, good quality pre-construction data (including charting previous land use and comprehensive surveys of the species present) coupled with yearly post-construction monitoring, will improve researchers' capacity to evaluate spatial and temporal changes in bird diversity, abundance and behaviour as a consequence of solar park design, infrastructure and management regimes. Ideally, monitoring should take place across a wide breadth of sites that employ a range of different, and crucially well-quantified, management regimes. Given that most solar parks are relatively young in ecological terms and most have poor pre-construction monitoring data, this is of particular importance.

It is well-recognised that balancing the development of new technologies to help address climate change whilst also reducing declines in biodiversity and maintaining food production is a challenging prospect. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem services and the Intergovernmental Panel on Climate Change have highlighted that biodiversity loss and climate change will continue to mutually reinforce each other unless they are tackled simultaneously (Pörtner et al., 2021). Therefore, it is crucial to continue to promote sustainable management practices and find successful mitigation measures at solar developments to ensure renewable energy infrastructure does not play a contributary role to the loss of rapidly declining species. This study adds to the growing, but still relatively sparse evidence base (e.g. Blaydes et al., 2021, 2022, Jarčuška et al., 2024) that solar parks can benefit biodiversity, provided they are constructed on areas of land of low existing conservation value and employ management regimes with a strong focus on biodiversity. Industry stakeholders and researchers alike must ensure all possible measures are taken to help enhance understanding of the role of solar parks in the conservation of bird species, and more work is required to improve conditions for them on solar parks in the UK.

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Author's declaration

In submitting this document, I declare that this submission is my own work. I have not submitted it in substantially the same form towards another degree or other qualification. It has not been written or composed by any other person, and all sources have been appropriately referenced or acknowledged. In submitting this work, I consent for this submission to be stored in electronic format for use in the LEC archive and for sharing with relevant funding bodies and external partners.

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