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RESEARCH ARTICLE

Renewable energies and biodiversity: Impact of ground-mounted solar photovoltaic sites on bat activity

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Abstract

1. Renewable energy is growing at a rapid pace globally but as yet there has been little research on the effects of ground-mounted solar photovoltaic (PV) developments on bats, many species of which are threatened or protected.
2. We conducted a paired study at 19 ground-mounted solar PV developments in southwest England. We used static detectors to record bat echolocation calls from boundaries (i.e. hedgerows) and central locations (open areas) at fields with solar PV development, and simultaneously at matched sites without solar PV developments (control fields). We used generalised linear mixed-effect models to assess how solar PV developments and boundary habitat affected bat activity and species richness.
3. The activity of six of eight species/species groups analysed was negatively affected by solar PV panels, suggesting that loss and/or fragmentation of foraging/commuting habitat is caused by ground-mounted solar PV panels. *Pipistrellus pipistrellus* and *Nyctalus* spp. activity was lower at solar PV sites regardless of the habitat type considered. Negative impacts of solar PV panels at field boundaries were apparent for the activity of *Myotis* spp. and *Eptesicus serotinus*, and in open fields for *Pipistrellus pygmaeus* and *Plecotus* spp.
4. Bat species richness was greater along field boundaries compared with open fields, but there was no effect of solar PV panels on species richness.
5. *Policy implications*: Ground-mounted solar photovoltaic developments have a significant negative effect on bat activity, and should be considered in appropriate planning legislation and policy. Solar photovoltaic developments should be screened in Environmental Impact Assessments for ecological impacts, and appropriate mitigation (e.g. maintaining boundaries, planting vegetation to network with surrounding foraging habitat) and monitoring should be implemented to highlight potential negative effects.

Jérémy S.P. Froidevaux and Gareth Jones contributed equally as senior authors.

KEYWORDS
Chiroptera, echolocation calls, energy-wildlife conflict, environmental policy, farmland, green energy, photovoltaic panels, solar farm

1 | INTRODUCTION

Renewable energy is growing at a rapid pace globally, bolstered by almost all countries having renewable energy support policies in place (REN21, 2022). Renewable technology currently contributes an estimated 11% to global "total final energy consumption" with the potential to supply two thirds of total global energy demand, and Europe has the highest proportion of renewable energy and fastest growth in its use globally (Gielen et al., 2019; REN21, 2020; Singhal et al., 2015; Xu et al., 2019). Three technologies contribute the most capacity to global renewable power (3146 GW): hydro-electric (1195 GW 44%), wind (845 GW 25%) and solar photovoltaic (PV) (942 GW 24%), with solar PV increasing by 25% in 2021, the largest annual capacity increase recorded to date (REN21, 2022). The development of solar PV sites within the British rural landscape has grown over the last 10 years from virtually zero capacity in 2010 to over 13 GW capacity in 2020, with the majority of solar installations (92%) being <4 kW developments scattered throughout the landscape (Department for Business Energy and Industrial Strategy, 2021).

Renewable technologies are important in meeting energy demands sustainably, particularly with the associated benefits of favourable economics, low carbon footprints, ubiquitous resources, scalable technology and significant socio-economic benefits (Gielen et al., 2019). In the UK, solar PV has become recognised as the most popular renewable energy technology available to landowners due to opportunities for supporting environmental improvements, such as contributing to sustainable energy, while cutting business costs and providing substantial additional incomes through subsidies and ground rent (Chel & Kaushik, 2011; Jones et al., 2014; Mbzibain et al., 2013). In addition, the solar PV developments are temporary, with a 25–40 year life span, so once decommissioned the installation site can be restored to its original use almost immediately if necessary (Hernandez et al., 2014; Jones et al., 2014).

At present in Europe ground-mounted solar PV developments do not automatically trigger the scoping process for an Environmental Impact Assessment (EIA) (European Commission, 2021). The lack of formal assessment is a concern, as ground-mounted solar PV installation is permissible in undesignated ecologically sensitive areas (Gove et al., 2016). Conservation implications must, therefore, be given consideration when solar PV sites are in development, operation and during decommissioning to ensure any impacts are minimised and mitigated (Gibson et al., 2017). Renewable technologies such as hydro-electric and wind energy are already associated with detrimental effects on wildlife, leading to advice that improved policy and complex trade-off metrics are required to balance biodiversity impacts when planning for meeting energy demands (Holland et al., 2019; Kuvlesky Jr et al., 2007; Popescu et al., 2020). The need to balance wider impacts sparks a complex "green-green" dilemma, where the two desirable goals of clean energy and improved biodiversity have conflicting and potentially unresolvable effects on each other's success (Straka et al., 2020).

A well-considered and applicable decision support tool has been developed in the UK to assess Solar Park Impacts on Ecosystem Services but currently the focus of this is on localised ecological management for co-benefits rather than the initial appropriate and sensitive siting of developments within the ecological landscape (Randle-Boggis et al., 2020). Making this initial assessment is important to ensure that strategic decisions for land allocation align with energy policy (Popescu et al., 2020). This is particularly important as ground-mounted solar PV may have mixed to negative impacts on biodiversity.

On one hand, ground-mounted solar PV sites have the potential to positively influence biodiversity across the agricultural landscape where the existing land management does not consider ecology, and biodiversity is poor. For example, when properly sited, sensitively designed with biodiverse planting beneath and surrounding the panels, and carefully managed with ecological preservation in mind, the assigned land has the potential to develop a habitat network for pollinating species at a landscape scale and provide ecosystem services, including pest management to local crop production (Armstrong et al., 2021; Blaydes et al., 2021; Semeraro et al., 2018). This network approach could also make it possible to compensate for any cumulative and potentially detrimental impacts of developments near each other.

On the other hand, and despite the benefits of renewable energy in tackling energy demand and climate change, utility-scale solar PV developments are considered to potentially cause negative effects on biodiversity (Gielen et al., 2019). The alteration of land use, land cover, soils and water resources result in changes to microclimate and hydrological conditions, which have direct and indirect impacts on ecosystems (Hernandez et al., 2014; Pizzo, 2011). The resultant change can cause three key ecological effects: habitat loss and fragmentation, microclimate changes, and behavioural alterations, all of which may introduce barriers to relatively sedentary species by disrupting gene flow, while also reducing habitat availability for wide-ranging species which may disperse beyond the development sites (Hernandez et al., 2014; Pizzo, 2011), such as flying animals.

Bats are valuable bioindicators of change in ecological systems, as well as providing ecosystem services such as pest suppression, particularly in agricultural landscapes (Aguiar et al., 2021; Boyles et al., 2011; Jones et al., 2009; Kemp et al., 2019; Russo & Jones, 2015; Russo et al., 2018, 2021). This is in part due to their wide-ranging distributions and their position at the top of food chains, meaning they are affected by factors which have altered the prevalence of other species, such as habitat loss and fragmentation that may decrease the availability of invertebrate prey (Jones et al., 2009; Park, 2015; Russo & Jones, 2015). In the UK, 18 bat species comprise a third of all mammal species (Mathews et al., 2018). As such understanding the interactions of bats with solar PV installations is crucial in ensuring their protection, and to determine any effects on ecosystem health and services.

Parallels can be drawn between land development for solar PV and for wind turbines, especially in terms of habitat modification. Bats have been studied extensively in relation to wind energy, encompassing fatalities at turbines potentially caused by collision, flight paths affected by vortices, turbines being mistaken for roosts, used as mating sites and because insect prey can be attracted to turbines (Baerwald et al., 2008; Cryan, 2008; Cryan & Barclay, 2009; Cryan et al., 2014; Dahl et al., 2012; de Jong et al., 2021; Horn et al., 2008; Rydell et al., 2016; Voigt et al., 2022). Wind turbines also cause habitat loss due to bats avoiding surrounding wind turbines farms (Barré et al., 2018, 2022; Minderman et al., 2012, 2017). Successful mitigation has been developed accordingly, including curtailment and using acoustic deterrents (Adams et al., 2021; Arnett et al., 2013; Baerwald et al., 2009; Mitchell-Jones & Carlin, 2014; Weaver et al., 2020).

The potential implications of solar PV developments on bat species in Britain, as well as other wildlife, segments into direct and indirect impacts (Chock et al., 2021). A key potential direct impact is that bats may collide with solar panels, as bats perceive smooth, horizontal surfaces as water, and will approach such surfaces attempting to drink (Greif & Siemers, 2010; Greif et al., 2017; Russo et al., 2012). The indirect impacts of solar panels on bats may be subtler, with panels potentially increasing reflective temperature at night following a day of hot weather and also altering microclimate by blocking sunlight, rainfall and affecting drainage potentially reducing the availability of invertebrate prey (Froidevaux, Louboutin, et al., 2017; Horváth et al., 2010; Pizzo, 2011). In addition bats may actively avoid solar PV sites, as a consequence of habitat loss and fragmentation as solar energy can require large land footprints (Pang et al., 2014). A recent comparison of bat activity in solar farms and adjacent habitats in Hungary indicated that while some bat species may exploit solar farms others avoid them (Szabadi et al., 2023).

Despite the potential impacts solar PV sites could have on bats, there is no empirical evidence to inform their appropriate siting or informed mitigation because the effects of solar PV panels on bats have not been tested empirically yet. Thus, the aim of the study was to assess the potential impacts of ground-mounted solar PV sites on bat activity and bat species richness. More specifically, our objectives were to investigate species-specific bat activity and bat species richness in different habitats (field boundaries and open fields) within ground-mounted solar PV sites in the UK in simultaneous comparison with matched sites nearby that did not contain solar PV panels (control sites). Due to bats generally avoiding anthropogenic alterations, we predicted reduced activity and species richness at ground-mounted solar PV sites (Bender et al., 1998; Coleman & Barclay, 2013). We also predicted that bat species would be mainly affected at their foraging/commuting habitats, that is open space foragers will show reduced activity in fields containing solar PV panels, whereas species that utilise edge and cluttered habitats would be more affected along boundary habitats.

2 | MATERIALS AND METHODS

2.1 | Sampling design

We implemented a paired study design across 19 solar PV sites to assess whether bat species richness and activity were higher in fields and along boundary habitats that contained PV panels, compared with "empty", matched control sites. This resulted in 19 sampling points for solar boundary habitat, 19 for solar open habitat, 19 for control boundary habitat, and 19 for control open habitat. All sites were located in south-west England, where the highest concentration of solar PV sites and greatest bat species richness in the UK coincide (Department for Business Energy and Industrial Strategy, 2021; Mathews et al., 2018). Where private land was entered, permissions were granted by land owners and the relevant solar farm companies. No ethical approval was required for this study as we passively monitored bats through acoustic recordings.

The control sites were within the same land management boundary as the solar PV site, and matched as closely as possible in plot size, habitat type, land use and boundary habitats. There was no difference in the average size of solar PV and control fields (solar PV mean = 59.6 ha, SD = 32.0; control mean = 53.2 ha, SD = 28.4; paired *t*-test: $t(18) = 1.3$, $p = 0.203$) (see Appendix S3 in Supporting Information). All solar PV sites were on grassland that was either grazed or managed through mowing or were on cut arable crops. Field boundaries corresponded to hedgerows, treelines, woodland or vegetated ditches and were exactly matched. The paired fields were a minimum of 500 m apart and not adjacent to each other to maximise the chances of obtaining independent data within comparable landscapes (Froidevaux, Louboutin, et al., 2017).

2.2 | Bat echolocation call recording and species identification

Fieldwork was completed between July and October 2019 and the same period in 2020. Bat activity was monitored for seven consecutive nights at each site (30 min before sunset to 30 min after sunrise), simultaneously across the four locations (open and boundary habitats within the field with solar PV panels and paired control). Recordings were made using SM3 bat detectors (Wildlife Acoustics, Inc.). All detector microphones (SMM-U2f [frequency response +/− 6 dB 20–100 kHz see https://www.wildcare.co.uk/amfile/file/download/file/56/product/94208/], Wildlife Acoustics) were elevated to 1.27 m using identical tripods. Detectors were set to auto trigger between 8–120 kHz and 1–88 dB and recorded for a maximum of 10 s (384 kHz, sampling rate). A detector was placed within the centre of the control and solar fields, and along the associated boundary habitats of the control and solar fields. Detectors recording the open and boundary habitat within the solar and control field were a minimum of 50 m apart.

Sampling took place during optimal weather condition for bats to forage (i.e. no rain, low wind speed and temperature >10°C). The mean (±SD) temperature at dusk over the recording period was 16.2 ± 3.1°C (https://www.timeanddate.com/weather/).

Sound files were analysed using zero crossing software Kaleidoscope Pro (v. 5.4.1, Wildlife Acoustics, Inc.) with Bats of Europe Classifiers (United Kingdom) (v. 5.4.0) selected. All 10 s recordings were automatically scanned and the call sequences were identified and then manually checked to confirm the species (*Barbastella barbastellus*, *Eptesicus serotinus*, *Pipistrellus nathusii*, *P. pipistrellus*, *P. pygmaeus*, *Rhinolophus ferrumequinum* and *R. hipposideros*) or species group (*Nyctalus* spp., *Myotis* spp., *Plecotus* spp.). The grouping of *Myotis* spp. is widely used due to the difficulty of separating the echolocation calls of the different species (Russ, 2012). Similarly *Nyctalus noctula* and *N. leisleri*, as well as *Plecotus auritus* and *P. austriacus* could not always be separated so these calls were grouped as *Nyctalus* spp. and *Plecotus* spp., respectively. All files which Kaleidoscope Pro could not automatically assign a species to were identified manually (Russ, 2012).

All files which Kaleidoscope Pro classified as "Noise" (195,375 files) were run through the full spectrum software Bat Classify (https://bitbucket.org/chrisscott/batclassify/src/master/). This was to ensure no call sequences within the large number of "Noise" labelled files were missed. Following analysis, 0.5% of labelled files were randomly checked to ensure that the automated identification was reliable (Rowse et al., 2018). For all call sequences with >80% certainty in the automated identification, the classification to species was accepted, except for *Myotis* species where >50% certainty was accepted to ensure call sequences were not excluded from the dataset. These parameters were designed to apply a precautionary approach based on the Precision-Recall metric of the Bat Classify software (https://bitbucket.org/chrisscott/batclassify/src/master/).

2.3 | Statistical analysis

All analyses were performed in R statistical software v.4.1.1 (R Core Team, 2021) and all statistical tests were considered significant at $p < 0.05$. We performed generalised linear mixed-effect models (GLMMs) with "GLMMTMB" package (Brooks et al., 2017) to assess the effects of PV panels on species-specific bat activity and bat species richness in agricultural landscapes. Echolocation call sequence data were pooled by site and location over the seven-night period, and we defined bat activity as total number of bat call sequences for species or species groups. Due to their low occurrences (<40% of the sites), *R. hipposideros* and *P. nathusii* were disregarded for the analysis on species-specific activity. GLMMs on bat species were fitted with a Gaussian distribution (since diagnostic plots were largely unsatisfactory with Poisson or negative binomial distributions) and we applied a squared transformation to the response variable to meet the normality assumption. GLMMs on bat activity were fitted with a negative binomial distribution and we employed zero-inflated models when necessary. We included the presence/absence of PV panels (treatment: solar vs. control site) in interaction with the habitat type surveyed (boundary vs. open field) as explanatory variables while pair ID were considered as random factors to account for the paired-sampling design.

We also included in the models landscape variables that could potentially affect bat activity in agricultural landscapes, including the proportion of urban, arable land, grassland and broadleaf woodland, and the Euclidean distance to the nearest watercourse. For area-based landscape variables, we considered eight spatial scales (buffers ranging from 250 m to 10 km radii) to qualify local habitats around each site, and to encompass the wide foraging ranges of the bat species studied (Laforge et al., 2021). Landscape variables were derived in QGIS using the Land Cover Map (Environmental Information Data Centre, 2019) (20 m resolution) supplied by the Centre of Ecology and Hydrology. When comparing solar PV sites with control sites no statistical differences occurred in the distance to the nearest water source, or in cover of arable land, grassland, broadleaved woodland or urban areas at the different spatial scales with the exception of cover of grassland and arable habitat surrounding the control and solar PV site at the 250 and 500 m scales (Appendix S2). To reduce the number of landscape variables and avoid model overparameterisation, we assessed independently the relationships between the response variables and each landscape variable using GLMMs with the same model structure as described above (i.e. including the same random effect and the interaction and using the same distribution family). We compared the second-order Akaike information criterion (*AICc*) of each model with the model that included the interaction only and retained in the final models only landscape variables at their best scale of effect (Martin, 2018) that led to lower *AICc* (i.e. $\Delta AICc \geq 2$) (Burnham & Anderson, 2002). For highly correlated variables (Spearman coefficient correlation $|r| > 0.7$), we retained the one leading to lower *AICc*. From the final full models, we finally ran post hoc pairwise comparisons corrected for multiple testing using the Tukey method in the "LSMEANS" package (Lenth, 2014). Residual diagnostics were checked with the "DHARMA" package (Hartig, 2022). We also checked for multicollinearity, overdispersion, influential outlier and zero inflation with the "PERFORMANCE" package (Lüdecke et al., 2023).

3 | RESULTS

3.1 | Bat acoustic sampling

A total of 133 nights of recording took place simultaneously on each of the four bat detectors across 19 different sites, resulting in 532 individual nights of recording. This produced a total of 51,464 call sequences, comprising 10 species or species groups. The bat species most frequently recorded was *P. pipistrellus* (24,017 call sequences) with over twice the number of recordings of any other species or species group. The species most infrequently recorded were *P. nathusii* and *R. hipposideros* (106 and 170 call sequences, respectively). All species or species groups were recorded at each of the treatments (solar vs. control site) and habitat features (boundary vs. open field) (Table 1).

3.2 | Effect of solar PV panels on the activity of bats

Overall, we recorded more bat activity at the control sites than the solar PV sites, and more bat activity at the boundary habitats compared to the open field (Table 1). We found statistical evidence that the activity of six of eight species/species groups (i.e. *E. serotinus*, *Myotis* spp., *Nyctalus* spp., *P. pipistrellus*, *P. pygmaeus* and *Plecotus* spp.) were negatively affected by solar PV panels (Table 2 and Figure 1). For all these taxa, our full models on bat activity that included the presence/absence of solar PV site in interaction with the habitat type were more informative than the null one (Δ*AICc* >2; Appendix S1 in Supporting Information).

The effects of solar PV panels on bat activity were largely dependent on the habitat type investigated. Only *P. pipistrellus* and *Nyctalus* spp. were significantly, negatively affected by solar PV panels regardless of the habitat type considered. For other taxa, our models indicated a significant negative effect of solar PV sites on *Myotis* spp. and *E. serotinus* along the boundary habitats at the solar sites compared to control ones while *P. pygmaeus* and *Plecotus* spp. were significantly less active in the open habitat at solar sites compared to control ones (Table 2 and Figure 1). Finally, we found no difference in bat species richness between habitats at the solar sites and matched control ones.

3.3 | Effect of habitat type and landscape variables on the activity of bats

Regardless of the presence/absence of solar panels, all species/species groups (except *Nyctalus* spp. and *Plecotus* spp.) were significantly more active along field boundaries compared with open fields ($p < 0.05$). Similarly, there was greater bat species richness at field boundaries compared with open fields (See Appendix S1).

Arable land cover at the largest scale (10 km) positively influenced *B. barbastellus* activity and urban area at the largest scale had a positive effect on *P. pipistrellus* (See Appendix S2 in Supporting Information). Grassland cover had a significant positive effect on *E. serotinus* activity (500 m radius scale) and *Nyctalus* spp. activity (1 km radius scale). The number of species recorded was greater on farms located near freshwater sites.

4 | DISCUSSION

Our predictions regarding bat activity were largely supported, though species-specific differences were apparent. For several species, there was lower activity in fields with solar PV panels, in both open and boundary habitats, compared to matched fields without solar PV panels. Specifically, solar PV sites had a

TABLE 1 The number of bat call sequences recorded at boundary and open habitats at matched control and solar photovoltaic (PV) sites. Totals are for seven consecutive nights of recording at 19 habitat replicates in each column.

Species	Control, boundary	Solar PV, boundary	Control, open	Solar PV, open	Total
Barbastella barbastellus	314 (2.36 ± 3.6)	437 (3.29 ± 6.3)	31 (0.23 ± 0.6)	28 (0.21 ± 0.52)	810 (1.52 ± 3.88)
Eptesicus serotinus	1569 (11.8 ± 34.8)	457 (3.44 ± 12.31)	316 (2.38 ± 4.53)	155 (1.17 ± 3.73)	2497 (4.69 ± 19.1)
Myotis spp.	915 (6.88 ± 15.26)	6731 (25.3 ± 76.39)	2529 (19.02 ± 39.85)	755 (5.68 ± 6.68)	3284 (12.35 ± 29.29)
Nyctalus spp.	1283 (9.65 ± 13.65)	899 (6.76 ± 9.56)	1463 (11 ± 15.14)	773 (5.81 ± 7.24)	4418 (8.3 ± 11.98)
Pipistrellus nathusii	29 (0.22 ± 1.13)	25 (0.19 ± 0.95)	37 (0.28 ± 0.93)	15 (0.11 ± 0.81)	106 (0.2 ± 0.96)
Pipistrellus pipistrellus	11,855 (89.14 ± 163.04)	7156 (53.8 ± 121.64)	4404 (33.11 ± 96.48)	602 (4.53 ± 5.46)	24,017 (45.14 ± 116.45)
Pipistrellus pygmaeus	4176 (31.4 ± 138.77)	1219 (9.17 ± 16.65)	781 (5.87 ± 12.64)	250 (1.88 ± 5.48)	6426 (12.08 ± 70.96)
Plecotus spp.	472 (3.55 ± 4.4)	462 (3.47 ± 8.07)	941 (7.08 ± 13.13)	265 (1.99 ± 2.25)	2140 (4.02 ± 8.28)
Rhinolophus ferrumequinum	182 (1.37 ± 3.51)	565 (4.25 ± 16.84)	38 (0.29 ± 0.78)	80 (0.6 ± 2.52)	865 (1.63 ± 8.82)
Rhinolophus hipposideros	100 (0.75 ± 2.13)	62 (0.47 ± 1.24)	3 (0.02 ± 0.15)	5 (0.04 ± 0.23)	170 (0.32 ± 1.27)
Total	25,796 (193.95 ± 327.67)	13,811 (103.84 ± 160)	8929 (67.14 ± 120.64)	2928 (22.02 ± 19.31)	51,464 (96.74 ± 201.9)

Means ± SDs are presented under the totals in brackets.

TABLE 2 Results of the post hoc pairwise comparisons applied to the GLMMs relating the effects of the presence/absence of solar photovoltaic panels (treatment: solar vs. control site) in interaction with habitat type (boundary vs. open field) on species-specific bat activity and bat species richness.

Dependent variable	Pairwise differences: Control versus solar	Est. & SE	*t* value	*p*
Species richness[a]	Boundary	−0.35 ± 4.82	−0.07	0.942
	Open	5.23 ± 4.82	1.09	0.282
Barbastella barbastellus activity	Boundary	0.06 ± 0.31	0.15	0.836
	Open	0.11 ± 0.41	0.26	0.795
Eptesicus serotinus activity	Boundary	1.23 ± 0.44	2.79	0.007**
	Open	0.74 ± 0.46	1.62	0.109
Myotis spp. activity	Boundary	0.69 ± 0.30	2.26	0.027*
	Open	0.14 ± 0.31	0.44	0.661
Nyctalus spp. activity[b]	Boundary	0.55 ± 0.22	2.54	0.013*
	Open	0.46 ± 0.21	2.19	0.032*
Pipistrellus pipistrellus activity	Boundary	0.80 ± 0.37	2.17	0.033*
	Open	1.31 ± 0.43	3.06	0.003**
Pipistrellus pygmaeus activity	Boundary	0.51 ± 0.42	1.21	0.232
	Open	0.93 ± 0.42	2.22	0.030*
Plecotus spp. activity	Boundary	0.23 ± 0.29	0.77	0.446
	Open	0.90 ± 0.30	3.02	0.004**
Rhinolophus ferrumequinum activity	Boundary	0.17 ± 0.60	0.28	0.782
	Open	0.81 ± 0.71	1.14	0.257

[a] Species richness was modelled using a Gaussian distribution. We applied a squared transformation to the response variable to meet the normality assumption.

[b] We employed a zero-inflated model to account for excess zeros in the response variable.

Est.: estimate, SE: standard error of the estimate. **$p \le 0.01$, *$p \le 0.05$, $p \le 0.10$.

significant, negative effect on six out of the eight bat species and species groups analysed. *Eptesicus serotinus* and *Myotis* spp. had significantly lower activity along the boundary habitats at solar PV sites, compared to equivalent features at control sites. *Pipistrellus pygmaeus* and *Plecotus* spp. had significantly less call sequences recorded in the open habitat at solar PV sites compared with the centre of control fields. *Pipistrellus pipistrellus* and *Nyctalus* spp. were negatively affected by solar PV sites in both habitats (open and boundary habitats).

Hedgerows and connective features are important commuting and foraging features for bats (Froidevaux, Boughey, et al., 2017; Leroux et al., 2022). The significantly reduced numbers of *E. serotinus* and *Myotis* spp. along boundaries bordering PV solar sites suggests that the panels may be causing some bats to alter their flight paths, potentially resulting in further fragmentation of the ecological landscape. The reduced number of *P. pygmaeus* and *Plecotus* spp. in the open habitats suggests that solar PV is resulting in habitat loss for these species. *Nyctalus* spp. and *P. pipistrellus* were the only species found to be significantly affected at both open and boundary habitats.

We found that bat species that feed in both cluttered (some *Myotis* species) and edge habitats (*E. serotinus*) were affected along boundary habitats, and that species that feed in open space (*Nyctalus* spp.), cluttered (*Plecotus* spp.) and edge habitats (*P. pipistrellus*, *P. pygmaeus*) (Denzinger & Schnitzler, 2013) were negatively affected by the presence of solar panels in the open fields. *Barbastella barbastellus* and *R. ferrumequinum* activity did not differ between any of the sampling locations, which compliments results found in a similar study of solar farms. This may be due to the smaller sample size for these species providing low statistical power, their foraging strategies meaning the sampling habitat was not favourable, or because the panels where inconsequential for these species. The impacts of solar PV on bat activity are therefore best assessed on a species-specific basis, rather than trying to pool risk categories as has sometimes been done for other renewable energy technologies such as wind farms (Scottish Natural Heritage et al., 2021).

Our findings share some similarities with a recent study from Hungary (Szabadi et al., 2023), where *P. pygmaeus* (compared with open grasslands) and *Myotis* spp. (compared with both open

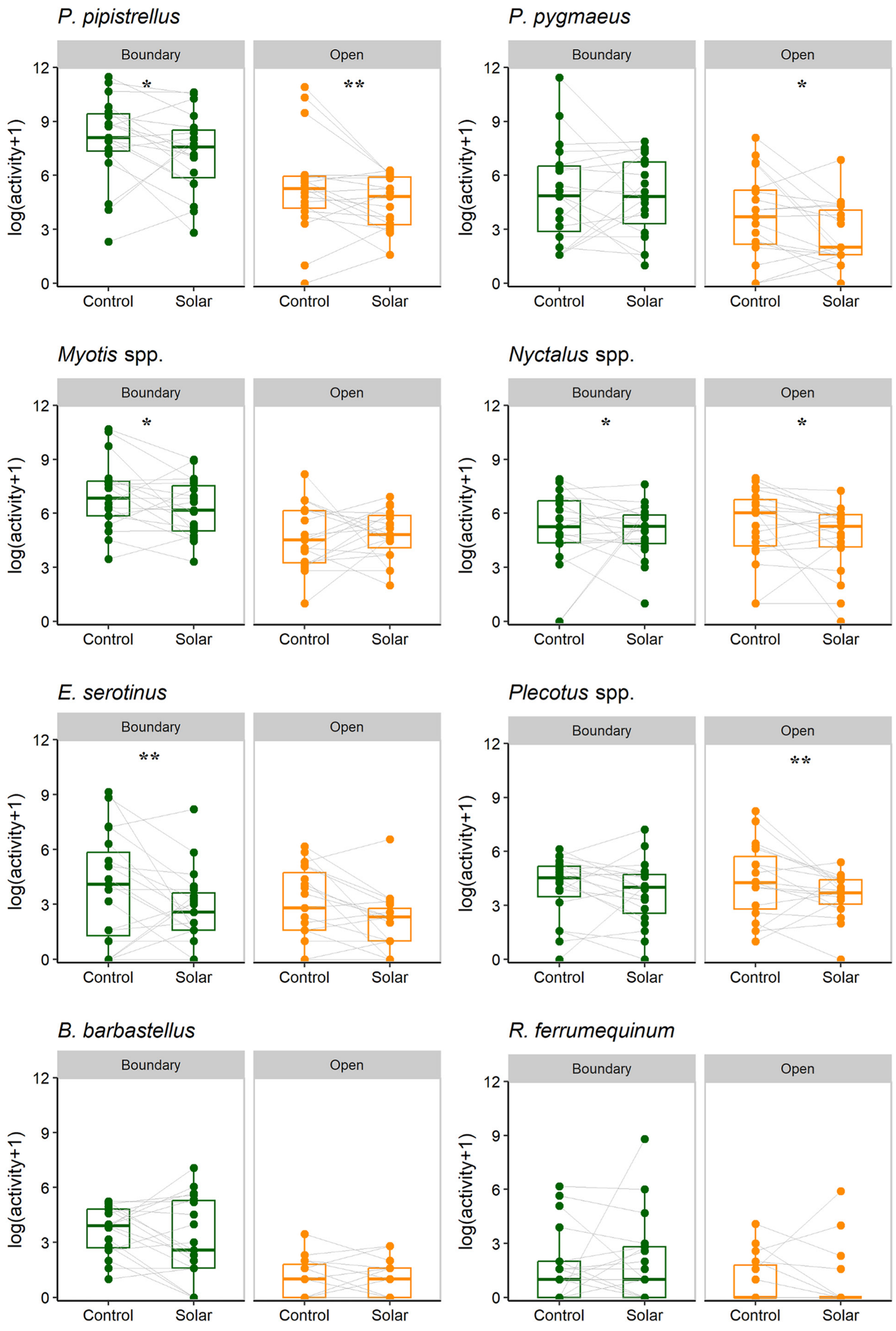

FIGURE 1 Boxplots showing medians and interquartile ranges of species-specific bat activity (i.e. total number of bat call sequences per site on a logarithmic scale to the base 2) at control and solar PV sites. Dots represent raw data with paired sites linked with a grey line. $^{**}p < 0.01$ and $^{*}p < 0.05$.

grassland and forest) showed lower activity at solar PV sites. Hence, solar PV sites may reduce bat activity over broad geographical scales.

The implications of these findings for bat conservation are considerable and understanding why solar PV sites are negatively affecting bat species is crucial, as has been done for other renewable energies (Frick et al., 2020). Bats are known to be affected by anthropogenic noise (Jones, 2008; Luo et al., 2014, 2015; Schaub et al., 2008), development associated with urbanised environments (Jung & Threlfall, 2016), the presence of smooth surfaces (Greif & Siemers, 2010; Greif et al., 2017; Ingeme et al., 2018) and habitat fragmentation (Meyer et al., 2016) all of which can be associated with ground-mounted solar PV sites.

There has been a "lack of consistency among evaluation or assessment methods" when assessing the ecological footprint of solar panels and other renewable energies (Burger & Gochfeld, 2012), as well as a disconnection between energy models and ecological assessment in policy which is well established in economic and emission modelling (Pang et al., 2014). In Europe, under legislation (The Conservation of Habitats and Species Regulations, 2017) it is an offence to deliberately disturb wild animals including bat species (Regulation 43, (1b)) and to affect significantly the local distribution or abundance of the species (Regulation 43, (2b)). The potential significant direct and indirect disturbance caused by solar PV on British bats foraging and commuting habitats, means that their impacts on bats should be assessed under legislation (The Town and County Planning (Environmental Impact Assessment) Regulations, 2017). This is in line with wind turbine developments and other energy generation projects.

Under this process, we suggest appropriate effort should be given to assess the presence of bats roosting, foraging and commuting within close proximity to the proposed development location due to the known risks of bats not tolerating anthropogenic disturbance, as detailed above. Where necessary, mitigation to support bats should be designed and activity should be monitored over extended periods. Mitigation may include, but is not limited to, reducing the density of panels within the site footprint, ensuring boundary habitat is maintained and improved in its area and diversity, and ensuring appropriate planting to improve foraging resources for those species identified as being at risk from the development (Boughey et al., 2011; Olimpi & Philpott, 2018). This should take place both within the solar PV sites and in the surrounding area. Where a solar PV site is proposed in proximity to a roost, or on a known important commuting route, of the species which have so far been identified as affected, then consideration should be given to whether alternate siting of the development, at a less sensitive location within the ecological landscape, would be more appropriate.

Further research is required to assess bat behaviour at and in proximity to solar PV sites to understand why some bats avoid solar PV sites, for example for example whether prey sources are negatively affected by solar PV developments or potentially panels are creating a collision risk with bats attempting to drink from them (Greif & Siemers, 2010; Greif et al., 2017; Horváth et al., 2010; Russo et al., 2012). Further work should be for the purposes of ensuring focused and effective mitigation that can be implemented and monitored through the EIA process.

Our study identifies some detrimental effects of solar PV sites for bat activity, and as such we conclude that assessing, mitigating and monitoring bat activity needs to be factored into solar PV development planning and operation. As highlighted by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services and the Intergovernmental Panel on Climate Change biodiversity loss and climate change will continue to mutually reinforce each other unless tackled simultaneously (Pörtner et al., 2021). Successful mitigation measures at solar PV developments will be an opportunity to manage climate change while supporting biodiversity.

AUTHOR CONTRIBUTIONS

Elizabeth Tinsley, Gareth Jones and Jérémy S. P. Froidevaux conceived the ideas and designed methodology; and Elizabeth Tinsley collected the data; Elizabeth Tinsley and Jérémy S. P. Froidevaux analysed the data. Elizabeth Tinsley, Gareth Jones and Jérémy S. P. Froidevaux led the writing of the manuscript. All authors contributed critically to the drafts, including Sándor Zsebők and Kriszta Lilla Szabadi, and gave final approval for publication. *Statement of inclusion*: we include authors who contributed towards writing from a country outside of where the study was conducted.

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CONFLICT OF INTEREST STATEMENT

The authors do not have a conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available via the Dryad Digital Repository https://doi.org/10.5061/dryad.n2z34tn2p (Tinsley et al., 2023).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Table S1. Outputs of the full GLMMs relating the effects of the presence/absence of solar photovoltaic panels (treatment: solar vs. control site) in interaction with habitat type (boundary vs. open field) on species-specific bat activity and bat species richness. Marginal and conditional R^2 as well as delta *AICc* between the full and the null models are given. Delta *AICc* >2 indicates that the full model was more informative than the null one. Est., estimate; SE, standard error of the estimate.

Appendix S2. Table S2. The mean area (ha) of different landscape variables found around each of the recording sites/distance (km) to water to the control and solar study sites. Habitats were identified as per the UK Land Cover Map 2020. Pairwise comparisons were conducted using the Wilcoxon test for paired data. Significant differences are indicated in bold.

Appendix S3. Table S3. The approximate area (m^2) of the solar and control field at each site, with the corresponding open and boundary habitat where the bat detectors were placed. Open habitat management type: 1 grazed, 2 mown, 3 arable, Boundary habitat type: 4 hedgerow, 5 treeline, 6 woodland, 7 wet ditch.

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