On-site floral resources and surrounding landscape characteristics impact pollinator biodiversity at solar parks

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On-site floral resources and surrounding landscape characteristics impact pollinator biodiversity at solar parks

H. Blaydes[1] | S. G. Potts[2] | J. D. Whyatt[1] | A. Armstrong[1,3]

[1]Lancaster Environment Centre, Lancaster University, Lancaster, UK
[2]Centre for Agri-Environmental Research, School of Agriculture, Policy and Development, University of Reading, Reading, UK
[3]Energy Lancaster, Lancaster University, Lancaster, UK

Correspondence
H. Blaydes
Email: h.blaydes@lancaster.ac.uk

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Abstract

1. There is increasing land use change for solar parks and growing recognition that they could be used to support insect pollinators. However, understanding of pollinator response to solar park developments is limited and empirical data are lacking.
2. We combine field observations with landcover data to quantify the impact of on-site floral resources and surrounding landscape characteristics on solar park pollinator abundance and species richness. We surveyed pollinators and flowering plants at 15 solar parks across England in 2021, used a landcover map to assess the surrounding high-quality habitat and aerial imagery to measure woody linear features (hedgerows, woodland edges and lines of trees).
3. In total, 1397 pollinators were recorded, including 899 butterflies (64%), 171 hoverflies (12%), 161 bumble bees (12%), 157 moths (11%), and nine honeybees (<1%). At least 30 pollinator species were observed, the majority of which were common, generalist species.
4. Pollinator biodiversity varied between solar parks and was explained by a combination of on-site floral resources and surrounding landscape characteristics. Floral species richness was the most influential on-site characteristic and woody linear feature density generally had a greater impact than the cover of surrounding high-quality habitats, although drivers differed by pollinator group.
5. Our findings suggest that a range of factors affect pollinator biodiversity at solar parks, but maximising floral resources within a park through appropriate management actions may be the most achievable way to support most pollinator groups, especially where solar parks are located in resource-poor, disconnected landscapes.

KEYWORDS
biodiversity, conservation, land use change, pollinator, renewable energy, solar park

1 | INTRODUCTION

Over recent years there have been dramatic declines in insect pollinators with profound effects on ecosystem function and society, but interventions to reinstate critical resources, including those for foraging and reproduction, can help to support and boost populations (IPBES, 2016). Insect pollinators, including bees, butterflies, hoverflies, moths and other groups play significant roles in crop pollination and food security but also provide a suite of additional beneficial services to human society (e.g. contributing to farmer livelihoods and supporting social and cultural values) and wider ecosystems (e.g. sustaining wild populations of plants that underpin ecosystem function; Potts et al., 2016). However, decreases in bee diversity (Biesmeijer et al., 2006; Powney et al., 2019) and declines in the occurrence and abundance of butterflies (Fox et al., 2023) and moths (Fox et al., 2021) have been reported, raising concerns about pollinator conservation status and how this will impact the services pollinators provide (Ollerton et al., 2014). Declines are a result of multiple, interacting factors but among the primary drivers are habitat loss (Dicks et al., 2021; Potts et al., 2010; Vanbergen & the Insect Pollinators Initiative, 2013) and the decline in floral abundance and diversity (Goulson et al., 2015). Reinstating critical pollinator resources, including the creation of wildflower strips or patches in agroecosystems, can be effective at enhancing abundance and diversity (Scheper et al., 2015).

Given increasing land use pressure, it is imperative that means to enhance pollinator biodiversity are embedded into new and expanding land use change, such as that for solar parks (Randle-Boggis et al., 2020). Comprised of arrays of solar photovoltaic modules mounted on metal supports in fields, solar parks currently occupy ~15,000 ha of land in the UK (DESNZ, 2023), with growing implications for biodiversity as land use change for solar increases (Committee on Climate Change, 2019). Solar park infrastructure and management can alter the microclimate, soil and vegetation, with consequences for other taxa (Armstrong et al., 2016). Although such consequences are largely unresolved, there could be potential to increase biodiversity at solar parks, especially if the land was previously intensively managed for agriculture (Solar Energy UK, 2023). Specifically, much of the land within a solar park is available for habitat enhancement, as infrastructure and access tracks disturb just 5% of the land and solar panels are typically raised 80–90 cm above the ground at the lowest edge (BRE, 2014a, 2014b). Moreover, solar parks are secure and relatively long-term developments (25–40 year lifespan), meaning there is often minimal human disturbance and sufficient time for habitats to establish (Solar Energy UK, 2019). Consequently, coupled with renewable energy production, land use change for solar parks could provide opportunities to support biodiversity, including insect pollinators.

Whilst there has been limited quantification of pollinators at solar parks, understanding of their potential to contribute to pollinator conservation is emerging. Much empirical data come from water-limited ecosystems and indicate both positive (e.g. Graham et al., 2021) and negative (e.g. Grodsky et al., 2021) impacts depending on siting, management and the local environment. In temperate ecosystems, solar parks could support pollinators through providing resources for foraging and nesting, undergoing targeted management practices, increasing landscape heterogeneity and connectivity and providing microclimatic niches (Blaydes et al., 2021). Maximising the resources available on site through appropriate management is attainable and simulations indicate that solar parks managed as a resource-rich wildflower meadow could support four times as many foraging bumble bees as solar parks managed as resource-poor turf grass (Blaydes et al., 2022). Insight provided by one-day surveys across 11 solar parks indicate that bumble bees and butterflies were more diverse on sites with wildlife interventions, such as those seeded with a species-rich flower mix (Montag et al., 2016). However, resources established at solar parks may be more or less valuable to biodiversity depending on the availability of suitable habitat in the surroundings (Scheper et al., 2013; Senapathi et al., 2017) and this could subsequently inform the prioritisation of resource enhancements both between solar parks (e.g. if an operator manages multiple sites) and within solar parks (e.g. if a solar park is large and/or characteristics vary across the site).

To further understand the factors that affect pollinators at solar parks and the potential to enhance them, there is a pressing need for rigorous and systematic surveying. Consequently, we undertake what we believe are the first repeat multiple site visit pollinator surveys across UK solar parks. Using a combination of primary field data and secondary landcover data, we aim to investigate how on-site floral resources and surrounding landscape characteristics impact pollinator biodiversity at solar parks. We hypothesise that: (i) pollinator biodiversity is greater at solar parks that provide more on-site floral resources and (ii) pollinator biodiversity is lower at solar parks surrounded by more suitable habitat given greater ecological contrast. We also discuss the potential implications of the findings for solar park management.

2 | MATERIALS AND METHODS

A combination of field- and desk-based methods were used to explore the factors affecting solar park pollinator biodiversity. This involved vegetation and pollinator surveys across 15 solar parks, characterisation of the surrounding landscapes using a Geographical Information System (GIS) and statistical analyses to quantify the effects of potential drivers of variation in pollinator biodiversity.

2.1 | Field surveys

Field surveys were undertaken in England, where solar parks are typically located in lowland, agricultural landscapes often dominated by crops and pastureland, with patches of semi-natural habitats and developed areas (Norton et al., 2012). Surveys took place at 15 solar parks (Figure 1a), selected based on existing vegetation data and landcover data, ensuring field sites varied in terms of flowering plant

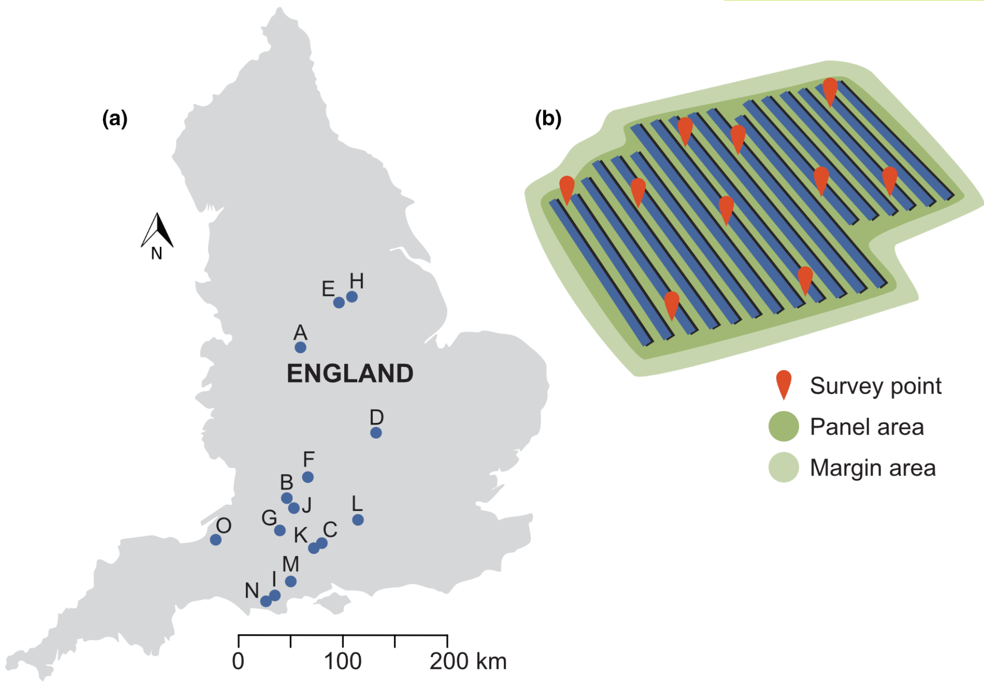

FIGURE 1 (a) The locations of the solar parks where flowering plant and pollinator surveys were undertaken. Solar parks have been anonymised using letters A–O. (b) An example solar park and 10 survey points randomly distributed between the rows of solar panels.

species richness and landscape diversity (Table A.1). Permission was sought from site operators prior to field surveys taking place. Visits were then made to each solar park once in July, August and September of 2021, approximately 1 month apart. However, Site K was only visited once (during July) and Site J only twice (during August and September) due to access permissions. The most geographically southern sites were visited first during each of the three survey periods, and most northern sites visited last, to help account for seasonal differences with latitude. Surveys were focused between the rows of solar panels, with 10 points randomly generated prior to the first visit to each site (Figure 1b). General observations of vegetation management were also made on each visit.

At each survey point, flowering plant and pollinator biodiversity were assessed. All species in flower at the time of the survey were recorded and the vegetative cover of each flowering species was estimated inside a 1 m^2 quadrat (hereafter floral cover). The maximum vegetation height at the centre of the quadrat was measured using a 1 m ruler. A pollinator transect, based on Bumblebee Conservation Trust (Bumblebee Conservation Trust, 2021) and UK Butterfly Monitoring Scheme (UKBMS, 2021) guidance was walked at each survey point on each visit. Ten transects were walked in total on each visit to each solar park (n = 420, across all visits to all solar parks). Transects were 100 m in length and each took around 5 min to walk at a slow pace, although this varied depending on vegetation height and the accessibility of areas between the rows of solar panels. Any pollinator (bumble bee, solitary bee, honeybee, butterfly, hoverfly or moth) within 2 m either side and 4 m ahead were recorded along each transect. Bumble bees, honeybees and butterflies were recorded to species level whilst other groups were recorded to the lowest level possible. Ambient air temperature (°C) and wind speed (m/s) were also measured before each transect using a Kestrel 2500 Weather Meter (r-p-r, 2012). Transects were predominantly walked between 9 AM and 4 PM in warm and bright conditions (13–17°C in sunshine and 17°C or above, with or without sunshine) with no more than moderate wind (~2 m/s) and not when it was raining (UKBMS, 2021).

2.2 | Landscape characteristics

A landcover map and a GIS were used to assess the landscape surrounding each solar park. Using ArcGIS Pro version 2.5.0 (Esri, 2020), the percentage cover of high-quality habitat and the density of woody linear features (WLFs) were calculated within buffer zones extending 0–500 m and 500–1 km from the solar park boundaries. The 500 m and 1 km buffer zone distances represent foraging and dispersal zones, respectively, based on data collated for bumble bees (Häussler et al., 2017). The distances are relevant to other groups, although there is variation between species.

Spatially explicit habitat quality information was derived from a landcover map produced by Gardner et al. (2020). The map is 10 m in resolution and based on the UKCEH Landcover Map 2015 but supplemented with Ordnance Survey orchard polygons and crop data derived from rural payments agency databases. High-quality habitat was defined using expert-derived scores of floral quality, where ten UK experts scored landcover classes within the Gardner et al. (2020) map based on their floral cover and floral attractiveness to bumble bees. Any landcover class with a floral quality (floral cover × floral attractiveness) score of >100 (a natural break in the data, below which landcovers were generally unsuitable pollinator habitats) were considered high-quality (Table A.2). Crops and other ephemeral landcovers were excluded due to their temporary nature.

Woody linear feature density was calculated by manually digitising any woody linear feature (hedgerows, woodland edges and lines of trees) observable from basemap imagery in ArcGIS Pro. The total length of WLF inside each buffer zone was generated and then divided by buffer area to calculate WLF density. Density, rather than total length of WLF, was used to account for the differences in area of buffer zones as larger solar parks had larger surrounding buffer zones.

2.3 | Statistical analysis

All statistical analyses were performed in R (version 4.3.0; R Core Team, 2023). The sampling units used in analyses were at the survey point level for pollinator (per 100 m transect), on-site resource (per 1 m^2 quadrat) and weather variables, but the solar park level was used for landscape variables. Exploratory analyses at the solar park level were also performed and are presented in Table A.3. Honeybees were excluded from analyses due to the low numbers recorded and the fact that their local abundance is primarily driven by beekeeper behaviour. Moreover, only abundance analyses were performed for hoverflies and moths given species could not be reliably identified in the field.

To understand broadly how biodiverse pollinators may be at solar parks, the mean abundance of bumble bees, butterflies, hoverflies and moths and the mean species richness of bumble bees and butterflies was calculated per month. Data from individual transects were used to calculate mean values ($n = 140$, per month). Mean floral species richness, floral cover and vegetation height inside quadrats were also calculated by month. The rstatix package (Kassambara, 2020) was then used to perform analysis of variance (ANOVA) to investigate differences between means across months, followed by pairwise comparison tests using Tukey post-hoc tests. Assumptions of normality and equal variances were checked graphically.

To investigate the effect of all variables on each pollinator group, individual generalised linear mixed models (GLMMs), with a Poisson distribution and a log link, were built for bumble bee abundance, butterfly abundance, bumble bee species richness, butterfly species richness, hoverfly abundance and moth abundance using the lme4 package (Bates et al., 2015). Data from individual transects were included in models as replicates ($n = 280$), but data from September surveys were excluded due to the high proportion of zero values. On-site resource variables (floral species richness, floral percentage cover and vegetation height), landscape variables (percentage cover of high-quality habitat and density of WLF in 0–500 m and 500–1 km buffer zones), weather variables (air temperature and wind speed) and month of survey were entered as fixed effects for all models. WLF density was multiplied by 1000 to align with the scale of other fixed effects. Solar park was entered as a random effect to ensure the relationships between repeat measurements were recognised in all models. Variables were checked for collinearity and the homogeneity of variance. The distribution of residuals were checked using the DHARMa package (Hartig & Lohse, 2022), with no significant deviations from expectations. Finally, data were checked for overdispersion using the "blmeco" package (Korner-Nievergelt et al., 2019).

3 | RESULTS

3.1 | Site characterisation

3.1.1 | Vegetation

A total of 33 flowering plant species were recorded across all sites and the majority were typical of grassland habitat or species commonly found in seed mixtures for pollinators (Table A.4). The mean number of flowering plant species recorded was 1 ± 0.06 per m^2 (across July and August surveys), ranging from 0.0 ± 0.0 at Sites J and O to 2.0 ± 0.2 at Site C. The cover of flowering plant species between the rows of solar panels also varied, where mean cover was $9.0 \pm 1.0\%$ (across July and August). Mean cover was lowest at Sites J and O ($0.0 \pm 0.0\%$) and greatest at Site N ($30.2 \pm 4.8\%$). Moreover, vegetation height varied between sites and quadrats, but measured 29.6 ± 1.7 cm on average, across all quadrats. Mean floral species richness, floral cover and vegetation height were lower in September, compared to July and August (Figure A.1). Specific management regimes for most solar parks were unknown, but sheep were present at two sites (G and I, on at least one visit), with the remaining sites appearing to be managed through cutting at different intensities.

3.1.2 | Landscape characteristics

The landscapes surrounding solar parks differed in terms of the percentage cover of high-quality habitat and the density of WLF (Table A.3). High-quality habitat made up 59% (±8%, ranging from 3% at Site K to 100% at Site B) of 500 m buffer zones and 64% (±8%, ranging from 12% at Site K to 100% at Site B) of 500 m–1 km buffer zones, on average. WLF density was less variable and the average density was 0.01 m/m^2 (±0.0005 m/m^2) in both zones (ranging from 0.007 m/m^2 at Site K to 0.01 m/m^2 at Site O in 500 m buffer zones and from 0.006 m/m^2 at Site K to 0.01 m/m^2 at Site O in 500 m–1 km buffer zones).

3.1.3 | Pollinators

Across all site visits, 1397 pollinators were recorded. Butterflies made up most observations ($n = 899$, 64%), followed by hoverflies ($n = 171$, 12%), bumble bees ($n = 161$, 12%), moths ($n = 157$, 11%) and honeybees ($n = 9$, <1%). No solitary bees were recorded. At least 29 species were observed, although only butterflies (19 species), bumble bees (6 species) and honeybees (1 species) were recorded to species level, with hoverflies (at least 1 species) and moths (at least 2 species) recorded to group level (Table A.5). Butterflies were recorded at all solar parks surveyed, with moths and hoverflies present at most sites (93% and 87%, respectively). However, bumble bees were only observed at 67% of solar parks. The most frequently recorded species was the meadow brown (*Maniola jurtina*, $n=396$). While the majority of species were common and widespread, small heath butterflies (*Coenonympha pamphilus*; a Priority Species under the UK Post-2010 Biodiversity Framework; JNCC, 2012) were observed at three sites.

Pollinator biodiversity varied across and within solar parks, but abundance and species richness were highest in July (Figure 2; Table A.6). For example, 2.0±0.1 butterfly species and 6.0±0.5 individuals were recorded per transect in July, compared to 0.3±0.05 species and 0.4±0.07 individuals in August, on average (Figure 2). Similar patterns were observed across groups, but abundance and species richness were lower compared to butterflies. For bumble bees, 0.0±0.08 species and 1.0±0.2 individuals were recorded per transect on average in July (Figure 2). Similarly, the mean number of hoverflies counted was 1.0±0.9 and 1.0±0.1 moths were observed per transect in July (Figure 2).

3.2 | Factors affecting pollinator biodiversity at solar parks

A combination of on-site resources and landscape characteristics affected pollinator biodiversity at solar parks, as did the month of survey and weather variables (Figure 3; Tables A.7–A.12). However, the factors that were important varied with pollinator group and between abundance and species richness.

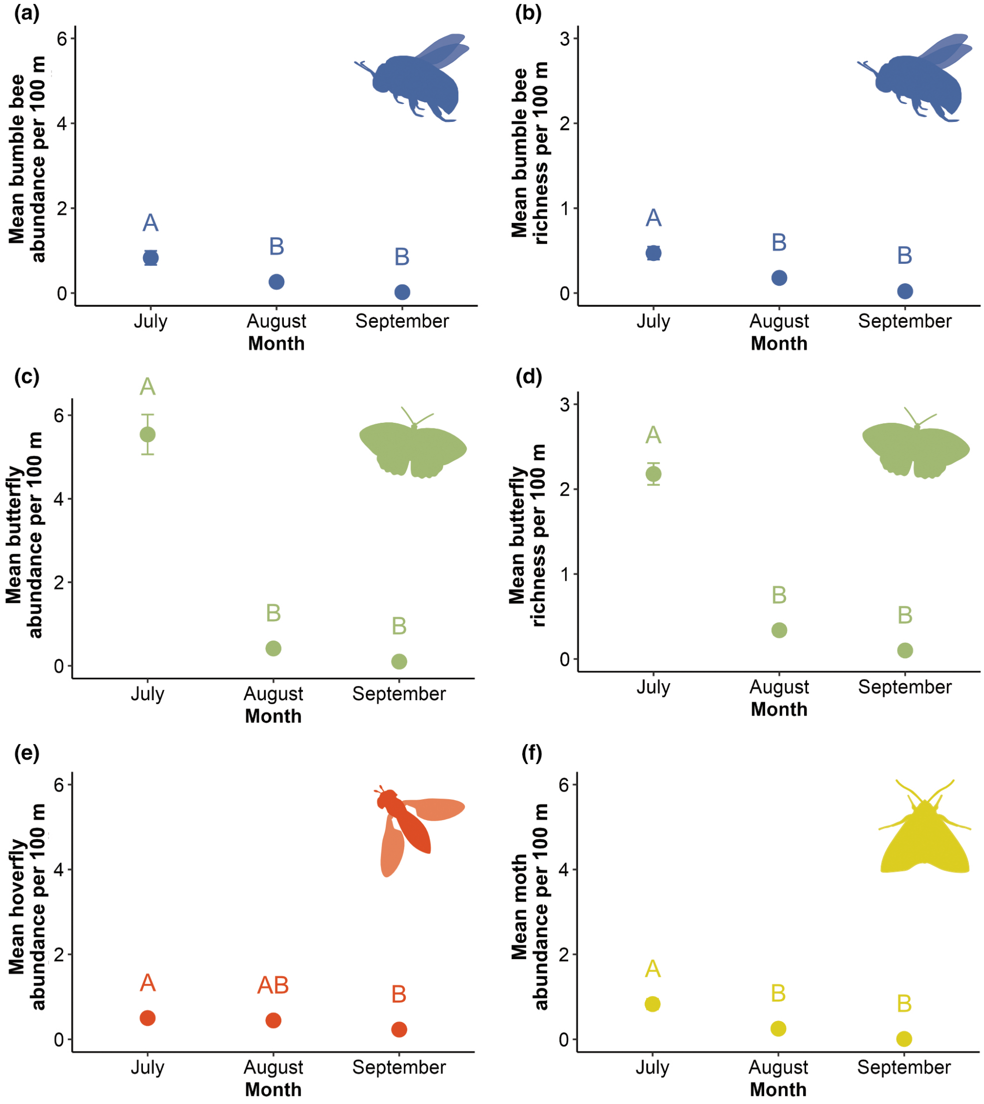

FIGURE 2 Mean (a) bumble bee abundance and (b) richness, (c) butterfly abundance and (d) richness, (e) hoverfly abundance and (f) moth abundance along 100 m transects walked inside solar parks, by survey month ($n=140$). Transects were 2 m wide. Surveys were undertaken at 15 solar parks across England and most sites were visited in July, August and September. Error bars represent standard error and within each plot, points that share letters are not significantly different at the $p<0.05$ level according to ANOVA and Tukey post-hoc analyses.

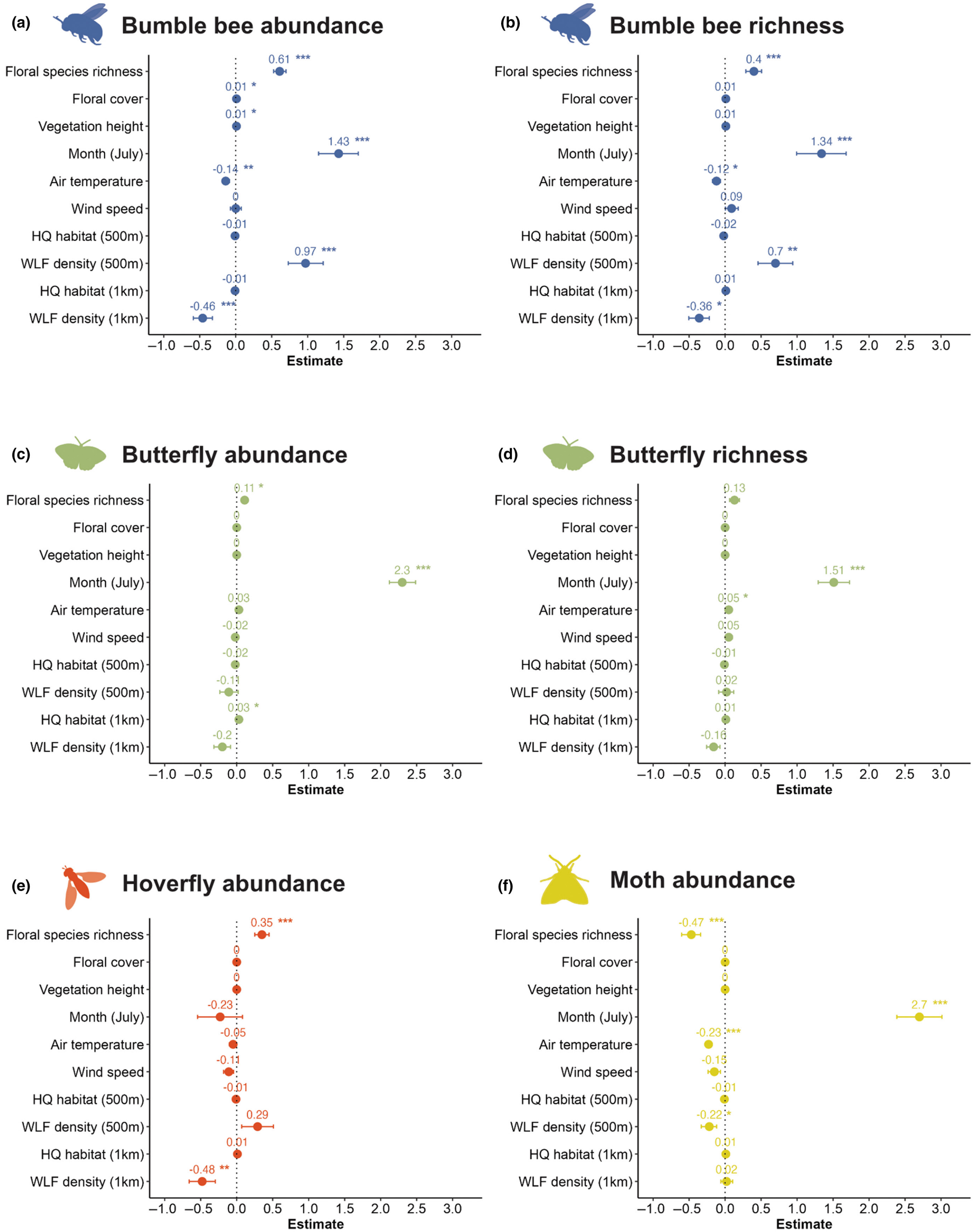

FIGURE 3 Estimates of the effect of on-site resource variables, landscape characteristic variables, month and weather variables on (a) bumble bee abundance and (b) richness, (c) butterfly abundance and (d) richness, (e) hoverfly abundance and (f) moth abundance at solar parks. Data are from surveys undertaken in July and August ($n=280$). HQ habitat refers to high-quality habitat and WLF to woody linear feature. Asterisks indicate level of significance of each effect, whereby * represents significance to the 0.05 level, ** to 0.01 level and *** to the >0.001 level.

Floral species richness was the most influential on-site resource variable and affected all pollinator groups, with positive effects on bumble bee abundance ($\beta=0.61$, $p<0.001$), bumble bee species richness ($\beta=0.40$, $p<0.001$), butterfly abundance ($\beta=0.11$, $p=0.03$) and hoverfly abundance ($\beta=0.35$, $p<0.001$), but with a negative effect on moth abundance ($\beta=-0.47$, $p<0.001$; Figure 3). Floral cover was less influential and had a small positive effect on bumble bee abundance ($\beta=0.008$, $p=0.04$). Vegetation height also had little impact on pollinator biodiversity, but positively affected bumble bee abundance ($\beta=0.007$, $p=0.04$; Figure 3).

Landscape characteristics had a significant effect on all pollinator groups, but this varied by group, characteristic and scale. Bumble bee abundance and species richness were positively affected by WLF density within 0–500 m of the solar park boundary (abundance: $\beta=0.97$, $p<0.001$; species richness: $\beta=0.70$, $p=0.004$), but negatively affected by WLF density within 500–1 km of the solar park (abundance: $\beta=-0.46$, $p<0.001$; species richness: $\beta=-0.36$, $p=0.02$; Figure 3). Hoverflies were also negatively affected by WLF density within 500–1 km of the solar park boundary ($\beta=-0.48$, $p=0.008$) and moths were negatively affected by WLF density within 0–500 m ($\beta=-0.22$, $p=0.03$; Figure 3). Butterflies were not significantly affected by WLF density, but the cover of surrounding high-quality habitat in 500–1 km buffer zones had a slight positive effect on abundance ($\beta=0.03$, $p=0.01$; Figure 3).

The month of survey had a large effect on most groups, including bumble bees (abundance: $\beta=-1.43$, $p<0.001$; species richness: $\beta=1.34$, $p<0.001$), butterflies (abundance: $\beta=2.30$, $p<0.001$; species richness: $\beta=1.51$, $p<0.001$) and moths (abundance: $\beta=2.70$, $p<0.001$), where more individuals and species were predicted in July, compared to August (Figure 3). Air temperature also significantly impacted some groups, with negative effects on bumble bee abundance ($\beta=-0.13$, $p=0.007$), bumble bee richness ($\beta=-0.12$, $p=0.03$) and moth abundance ($\beta=-0.23$, $p<0.001$), but a small positive effect on butterfly species richness ($\beta=0.05$, $p=0.02$; Figure 3). Wind speed did not significantly affect any pollinator group (Figure 3).

4 | DISCUSSION

Our results indicate that a combination of local and landscape scale factors affect pollinator biodiversity at solar parks and our hypotheses, that (i) pollinator biodiversity is greater at solar parks that provide more on-site resources and (ii) pollinator biodiversity is lower at solar parks surrounded by more suitable habitat, were partially supported by the findings. Below, we contextualise the findings with studies in other ecosystems and discuss the impacts of on-site resources and landscape characteristics on solar park pollinator biodiversity, before examining the potential management implications.

4.1 | Comparison of pollinator biodiversity

The abundance and species richness values reported in this study appear to be within the lower bounds of similar ecosystem types, indicating that solar park pollinator biodiversity could be comparable to broader agroecosystems. For example, Potts et al. (2009) report 0–2 bumble bees along 50 m transects walked within intensively managed grasslands, comparable to the mean of 0.0 ± 0.09 bumble bees per transect recorded here. Moreover, Holland et al. (2015) observed 2–4 butterflies per 100 m transect within farmland habitats, similar to values reported in this study (3 ± 0.29 butterflies per transect). However, Holland et al. (2015) also recorded 0.5–5 hoverflies per 100 m in farmland habitats (where values varied by management), which are relatively high compared to recorded here (0 ± 0.06 hoverflies per transect).

Whilst pollinator biodiversity may be low within the bounds of broader agroecosystems, adhoc survey results from transects walked within flower rich areas (away from solar panels; $n=4$) within this study demonstrate that different areas of the solar park have different potential for delivering biodiversity. For example, 13 ± 9.0 butterflies per transect were observed in areas managed to provide pollinator resources, comparable to observations from grasslands sown with complex seed mixes (Potts et al., 2009). However, pollinator biodiversity is influenced by many factors including ecosystem condition, land management, landscape characteristics and meteorology and further research is required to isolate the specific impacts of solar parks on pollinator biodiversity compared to similar ecosystem types.

Further research is also required to be able to compare the biodiversity of other pollinator groups at solar parks to agroecosystems, such as moths and solitary bees. On average, 1 ± 0.07 moths per transect were recorded in this study, but comparison to similar habitats is challenging given most studies focus on night-flying species and use light trapping techniques, rather than recording day-flying species along transects. In addition, it is not feasible to compare solitary bee biodiversity at solar parks to other habitats as none were recorded in this study, which may be due to true low abundance, or the sampling technique used. Whilst transects can be used to survey solitary bees (Wood et al., 2017), pan traps (Hutchinson et al., 2022) or trap nests for cavity nesting species (Westphal et al., 2008) are thought to be more effective. Undertaking a combination of sampling approaches would therefore provide a fuller insight into pollinator biodiversity at solar parks and allow for a more complete comparison to similar habitats.

4.2 | On-site floral resources

The biodiversity of most pollinator groups increased with greater on-site floral resource availability, supporting our first hypothesis. Floral species richness had a positive effect on bumble bees, butterflies and hoverflies, supporting findings at sites without the disturbance caused by solar park infrastructure (e.g. Carvell, 2002; Field et al., 2006; Lucas et al., 2017; Scheper et al., 2015; Woodcock et al., 2009). Floral cover was positively associated with bumble bee abundance, which has also been reported in other habitats (e.g. Holland et al., 2015), but no effect on other groups were detected. Floral cover can impact butterfly biodiversity (Sparks & Parish, 1995), but may have been difficult to detect given the low floral cover inside most quadrats. Whilst hoverflies also benefit from higher floral cover, this group requires a wide range of resources to support different life stages (Meyer et al., 2009), possibly explaining the lack of effect detected. Similarly, moth abundance was unaffected by floral cover, and negatively impacted by floral species richness, although resource-rich grasslands and field margins are associated with greater moth abundance (Alison et al., 2017; Blumgart et al., 2023). This may not have been detected given the small number of moth observations. Further surveys to target both day- and night-flying moth species, including identification to species level, would further understanding of the factors affecting moths at solar parks.

Whilst floral species richness had a positive effect across pollinator groups, there was little effect of vegetation height. However, taller swards and variation in vegetation structure can promote a diversity of microclimatic niches (Morris, 2000). Bumble bees often respond positively to taller vegetation as some species nest in tussocky grass (Kells & Goulson, 2003) and some butterfly species require more complex vegetation (Aguirre-Gutierrez et al., 2017). Instead, solar park infrastructure could be providing microclimatic niches, potentially reducing the effect of vegetation height, given changes to the local microclimate (Armstrong et al., 2016). Alternatively, the vegetation during many surveys appeared to have been recently managed which could have affected the findings. Intensive cutting removes pollinator foraging resources and reduces structural variation (Morris, 2000) and as such, there could be an opportunity to improve resource availability at solar parks by delaying vegetation management to after the pollinator active period.

Management actions may account for some of the unexplained variation in pollinator communities at solar parks. Whilst there are insufficient field sites to robustly conclude the impact of management, solar parks with the least biodiversity were those where sheep were present during most visits. Thus, a grazing regime whereby sheep are excluded from the solar park during the pollinator active period may be better placed to support groups reliant floral resources. In contrast, less intensive management approaches may partially explain higher pollinator biodiversity recorded on some sites. For example, pollinator biodiversity was greatest at Site F, where shading cuts (only cutting a narrow strip of vegetation in front of the solar panels) had taken place and areas away from the panels with taller vegetation/seeded with a floral-rich mixture had been established. Such observations support industry assessments, whereby pollinators were more diverse at solar parks with targeted management for biodiversity, including those where floral-rich seed mixes had been sown and sheep were not present throughout the summer (Montag et al., 2016; Solar Energy UK, 2023).

4.3 | Landscape characteristics

Landscape characteristics affected all pollinator groups and biodiversity was lower at solar parks surrounded by more suitable habitat in some cases, partially supporting our second hypothesis. WLF density was more influential than the cover of high-quality habitat surrounding solar parks, where bumble bees, hoverflies and moths were generally less abundant or species rich where the surrounding landscape contained a higher density of hedgerows, woodland edges or lines of trees. Whilst this seems counterintuitive, WLFs could attract pollinators from the solar park as they provide a high density of foraging resources due to the combination of woody and herbaceous flowering plant species (Donkersley, 2019; Rivers-Moore et al., 2020), can support breeding pollinators (Osborne et al., 2008), and create microclimatic variation and shelter (Pywell et al., 2004). Moreover, higher WLF density could indicate a greater cover of woodland in the surrounding landscape, which can be an important habitat for some bees (Donkersley, 2019), butterflies (Pywell et al., 2004), hoverflies (Speight, 2006) and moths (Fuentes-Montemayor et al., 2012) and can support more pollinators than improved grassland habitats in intensive landscapes (Alison et al., 2021). As such, landscapes with higher WLF densities may generally be more heterogenous, potentially offering increased resource diversity and continuity to pollinators (Cole et al., 2017), therefore reducing pollinator reliance on resources provided by solar parks.

A higher density of WLFs in the surrounding landscape may also enable pollinators in solar parks to move more easily across landscapes in search of alternative resources. WLFs enhance landscape connectivity (Cranmer et al., 2012; Garratt et al., 2017) and therefore resources provided by solar parks may be more valuable in disconnected landscapes, where suitable habitat is more scarce or difficult to access. However, the mobility and life histories of pollinator groups can also affect how interactions with landscape components like WLFs. For example, bumble bees were negatively affected by greater WLF density in 500–1 km buffer zones surrounding the solar park, but positively affected by greater WLF density in 0–500 m buffer zones. Nearby resources may have a positive impact on bumble bees given they are central place foragers, are anchored to nest sites and have foraging distances of ~500 m (Häussler et al., 2017). Resources within this distance could therefore support bumble bees inside the solar park but when resources are further afield, bumble bees may be drawn to habitats outside of the solar park.

Whilst WLF density affected most pollinator groups, the cover of surrounding high-quality habitat had less of an impact. The proportions of different habitats in the landscape are thought to effect bumble bee and moth biodiversity (Carvell et al., 2011; Fuentes-Montemayor et al., 2011) and impacts on hoverflies may have been expected given their reliance on a wide range of resources, including habitats less likely to be present within solar parks (Lucas et al., 2017; Meyer et al., 2009; Speight, 2006). However, in this study, habitat quality was based on scores for bumble bees and may therefore not fully reflect all the needs of other pollinator groups. Landscapes were also characterised based on secondary data and the habitats surrounding solar parks were not surveyed. It was therefore not possible to directly assess the quality of surrounding habitats, although this can be important for pollinators (Carvell et al., 2011; Garratt et al., 2017). Collecting empirical data from habitats surrounding solar parks would allow for more accurate estimates of the resources provided and therefore a better understanding of how pollinators use these habitats in comparison to solar parks.

4.4 | Implications

While it is likely that a combination of local and landscape factors impact pollinators, it is more feasible to modify in-park habitats than those outside of the solar park boundaries. Maximising the resources available within the solar park could therefore be the most achievable way to support pollinators and could be attained by sowing floral-rich mixtures or tailoring vegetation management (Blaydes et al., 2021). Within solar parks, margin areas may be the most suitable location to enhance floral species richness and cover to minimise impacts on solar park operation. A diverse flowering plant community could also be established between the rows of panels, but these areas would require more frequent management to prevent impacts on electricity generation. Allowing vegetation to grow taller in some areas could also benefit pollinators by increasing heterogeneity in vegetation structure across the solar park (Milberg et al., 2016). Wherever possible, delaying management will provide taller vegetation on site and ensure floral resources are available to pollinators during their active period (March–September). Management throughout the season that takes place less frequently, less intensively or more leniently (i.e. a higher cutting height) will also help to establish pollinator resources (Potts et al., 2009). Rotational cutting or grazing would also ensure that some areas of the solar park always provide resources, although this may be more challenging to implement given the need for more site visits by management contractors.

The solar parks surveyed supported predominantly common and generalist species, possibly because many sites were previously low-grade agricultural land, which is less likely to provide suitable habitat for specialists. However, given the less intensive management regimes of some solar parks, habitat for threatened species and/or those with specific requirements could be provided, but colonisation and the maintenance of viable populations may depend on the longer-term availability of sufficient areas of high-quality habitat in the surroundings. Nevertheless, there is value in providing habitats for generalist species given their importance for wider ecosystem functioning and the long-term declines recorded in some groups (Hayhow et al., 2019).

Lastly, this study was undertaken in a temperate environment but many of the findings could apply to other systems. Solar parks managed to provide more on-site resources are likely to have positive effects on pollinator biodiversity in most environments given the basic requirements of pollinators apply across systems. Although, the most effective resources to provide will differ based on local pollinator communities and conservation priorities. As such, the potential for solar parks to contribute to pollinator conservation is being increasingly recognised elsewhere, including continental Europe (Semeraro et al., 2018) and the United States (Dolezal et al., 2021; Walston et al., 2018). Indeed, the inclusion of pollinator habitat in solar developments is being promoted through legislation in some US states, where programmes to develop best management practices for pollinator habitat enhancement have been created and solar parks are assessed against scorecards, where conforming sites can be classified as "pollinator-friendly" (Terry, 2020). Such policies could encourage good practice and be adopted elsewhere, helping to ensure that solar park developments include benefits to biodiversity, as well as contribute to meeting renewable energy goals.

5 | CONCLUSIONS

Ultimately, the findings suggest that a combination of on-site resources and surrounding landscape characteristics impact pollinator biodiversity at solar parks. Through systematic surveys over multiple site visits, our findings are among the first to show that the solar parks support pollinator biodiversity to a similar level as broader agroecosystems and support mostly generalist species, but in some cases these can be abundant and diverse dependent on local resources and landscape characteristics. Encouraging floral species richness and cover through appropriate management actions (e.g. delaying cuts to vegetation and managing less intensively throughout the pollinator active period) could enhance biodiversity, but any potential benefits may be moderated by the surrounding landscape and levels of ecological contrast. Nevertheless, solar parks managed appropriately should be able to support a diverse pollinator community and contribute towards meeting requirements for environmental policies and strategies.

AUTHOR CONTRIBUTIONS

Hollie Blaydes, Simon G. Potts, Duncan Whyatt and Alona Armstrong conceived the ideas and designed the methodology. Hollie Blaydes collected the data, analysed the data and led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

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DATA AVAILABILITY STATEMENT

Data available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.qrfj6q5pf (Blaydes et al., 2024).

ORCID

H. Blaydes https://orcid.org/0000-0002-7753-4938

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SUPPORTING INFORMATION

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

Table A.1. The floral richness of solar parks visited based on data collected by ecological consultants, the year that ecological consultants visited and the Connectance Index (CI) for each site calculated using a GIS and FRAGSTATS.

Table A.2. Landcover classes considered high-quality for pollinators and associated floral quality (floral cover × floral attractiveness) scores for bumble bees according to ten UK pollinator experts.

Table A.3. Solar park summary information for sites surveyed in this study between July and September 2021.

Table A.4. Flowering plant species recorded across 42 visits to 15 different solar parks across England between July and September 2021, the number of sites each species was observed at and the mean cover (±standard error) of each species across quadrats it was observed in.

Table A.5. Pollinator species recorded across 42 visits to 15 different solar parks across England between July and September 2021, the number of sites each species was observed at, the number of transects each species was observed along and the total number of individuals of each species recorded.

Table A.6. Analysis of variance (ANOVA) and post hoc Tukey analyses results evaluating differences in the abundance and species richness of pollinator groups at solar parks across months.

Table A.7. Generalised linear mixed effect model output estimating the impacts of on-site, landscape and climatic variables on bumble bee abundance at 15 solar parks in July and August 2021 ($n=280$).

Table A.8. Generalised linear mixed effect model output estimating the impacts of on-site, landscape and climatic variables on bumble bee species richness at 15 solar parks in July and August 2021 ($n=280$).

Table A.9. Generalised linear mixed effect model output estimating the impacts of on-site, landscape and climatic variables on butterfly abundance at 15 solar parks in July and August 2021 ($n=280$).

Table A.10. Generalised linear mixed effect model output estimating the impacts of on-site, landscape and climatic variables on butterfly species richness at 15 solar parks in July and August 2021 ($n=280$).

Table A.11. Generalised linear mixed effect model output estimating the impacts of on-site, landscape and climatic variables on hoverfly abundance at 15 solar parks in July and August 2021 ($n=280$).

Table A.12. Generalised linear mixed effect model output estimating the impacts of on-site, landscape and climatic variables on moth abundance at 15 solar parks in July and August 2021 ($n = 280$).

Figure A.1. The mean (A) floral species richness, (B) floral cover and (C) vegetation height inside $1\,m^2$ quadrats surveyed within solar parks, by survey month.

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