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Disentangling the drivers of solar farm biodiversity

Hollie Blaydes[1,*], Daniel Clarkson[2], Emma Eastoe[3], Rachel McCrea[3], Hannah Montag[1,4], Guy Parker[5], Conor MacKenzie[5], Joseph Monkhouse[5], Adèle Remazeilles[4], Miranda Jones[4], John W Redhead[6], Christopher J Feeney[7] and Alona Armstrong[1,8]

1 Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, United Kingdom
2 Department of Health Research, Lancaster University, Lancaster LA1 4YG, United Kingdom
3 School of Mathematical Sciences, Lancaster University, Lancaster LA1 4YR, United Kingdom
4 Clarkson & Woods Ecological Consultants, Blackford, Somerset BS28 4PA, United Kingdom
5 Wychwood Biodiversity, Aveton Gifford, Kingsbridge TQ7 4NQ, United Kingdom
6 UK Centre for Ecology & Hydrology, Maclean Building, Benson Lane, Crowmarsh Gifford, Wallingford OX10 8BB, United Kingdom
7 UK Centre for Ecology & Hydrology, Deiniol Road, Bangor, Gwynedd LL57 2UW, United Kingdom
8 Energy Lancaster, Lancaster University, Lancaster LA1 4YF, United Kingdom
* Author to whom any correspondence should be addressed.

E-mail: h.blaydes@lancaster.ac.uk

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Abstract

Alongside renewable electricity generation, solar farms can be designed and managed to incorporate biodiversity benefits. Understanding of site management impacts are emerging and the abundance or diversity of some taxonomic groups can be enhanced through biodiversity-focused practices. However, other factors are also likely to drive species abundance and diversity, but have been less well explored, primarily due to a lack of data. Recent efforts to standardise ecological monitoring approaches at solar farms in Great Britain have enabled the amalgamation of biodiversity data from sites across the nation, creating a unique database containing information about multiple biodiversity groups. Using field data collected at 86 solar farms across England and Wales, plus site and landscape characterisation using a geographic information system, we assess how a range of drivers affect vegetation, butterflies and birds recorded within solar farms. In total, 289 plant species were recorded, along with 25 butterfly species (2589 individuals) and 81 bird species (6527 individuals). The abundance and diversity of these groups varied between solar farms and was explained by a combination of solar farm characteristics, landscape characteristics, other biodiversity present on site and survey methods used. Drivers differed across groups, but site management was linked to most aspects of biodiversity and soil type explained much variation in invertebrate and bird biodiversity. While some of the key drivers of biodiversity are largely fixed, site management emerged as the most actionable lever to enhance ecological outcomes. Our findings suggest that focused management can deliver biodiversity benefits, but the effectiveness may depend on site-specific conditions. Embedding biodiversity into the siting, design and management of solar farms is therefore essential to promote ecological benefits alongside renewable energy development.

1. Introduction

Land use change is the primary threat to biodiversity and has led to the loss, fragmentation and degradation of natural habitats globally [1]. Agricultural expansion has been among the most significant land use changes, negatively affecting biodiversity directly and indirectly [2]. Pressures associated with agricultural land use changes are set to continue to drive biodiversity decline as demand for farmed products increases alongside the global population [3]. Concurrently, land use demand for renewable energy infrastructure is projected to increase given the urgent need to decarbonise energy systems and meet Net Zero targets [4]. Renewable energies require two orders of magnitude more land compared to conventional technologies (i.e. coal, gas and nuclear), meaning pressure on land to produce food and generate electricity will be intensified [5]. Land use changes for renewables and agriculture are also occurring against the backdrop of policy targets aiming to protect and conserve a minimum of 30% of land for biodiversity by 2030 [6].

Solar photovoltaic (PV) is projected to lead global renewable capacity additions, accounting for 80% of growth by 2030 [7]. Solar PV has already grown rapidly in some countries, such as the UK, where capacity has increased tenfold since 2012, reaching 18 GW in 2025 [8]. The UK Government aims to increase generation capacity to 70 GW by 2035 [9] and targets set by the climate change committee suggest up to 90 GW may be required by 2050 [10], necessitating further land surface change for solar. Currently, ∼57% of solar PV is deployed as ground mounted solar farms, which occupy ∼0.07% of total UK land area, but up to 0.72% could be needed if the most ambitious targets are to be met [11]. As at the global scale, this may result in land use conflict with agriculture (given ∼95% solar farms in the UK have been deployed on agricultural land [11]) and nature (given the national target to restore or create 500 000 hectares of wildlife-rich habitat outside of protected sites by 2042 [12]).

To ease land use pressures, solar farms can be managed for multiple purposes, including biodiversity conservation [13]. There is significant scope to design and manage solar farms for nature [11] and methods include adopting low intensity management regimes (e.g. reducing or stopping agrochemical use) and creating new habitats within solar farms (e.g. flower rich grasslands or hedgerows) [14]. A growing body of evidence suggests that solar farms managed with a biodiversity-focus can support greater plant, invertebrate and bird populations. Industry assessments indicate that plant species richness at solar farms was highest at sites where less intensive cutting or grazing took place [15]. Managing a solar farm as a wildflower meadow (compared to agriculturally improved grassland) could increase bumblebee abundance [16, 17] and the diversity and abundance of other pollinator groups has been shown to be higher at solar farms with greater plant species richness [18]. Similarly, bird abundance and species richness were higher at solar farms containing more complex habitat as a result of infrequent cutting or grazing, which allowed greater sward height and wildflower establishment [19].

Whilst approach to site management has shown to be a driver of biodiversity within solar farms, other factors such as landscape context [20], site characteristics [21] and interactions between biodiversity groups [22] are also likely to have an impact. Understanding of landscape effects are emerging, for example, pollinator biodiversity within solar farms can be affected by surrounding landscape composition [17], including the amount of woody linear features, such as hedgerows or lines of trees [18]. The impacts of site characteristics remain relatively unexplored, but biodiversity within solar farms could vary with geographic location given latitudinal diversity gradients [23]. Moreover, solar farm soil type and previous land use are likely to influence vegetation characteristics, with impacts on higher trophic levels and potential interactions with management actions, as observed in similar contexts [24]. Finally, interactions between different biodiversity groups at solar farms is likely, but so far, groups have largely been studied in isolation.

Given increasing land demands for solar farms and nature conservation driven by policy targets, as well as agricultural land use pressure, incorporating biodiversity benefits into land use change for solar farms represents an opportunity to alleviate land use pressures by simultaneously enabling low carbon electricity generation and ecological enhancement. However, a better understanding of how biodiversity varies across solar farms, and the factors that drive this variation, is required to ensure future policies and practice effectively promote biodiversity in this context. Recent efforts to standardise ecological monitoring at solar farms has enabled the amalgamation of biodiversity data from sites across Great Britain, including for multiple biodiversity groups [25, 26]. As far as we are aware, this unique database represents the largest field-based solar farm dataset globally and enables insights into solar farm biodiversity, and its drivers, at a relatively large scale. As such, our study uses this database, consisting of monitoring data from 86 solar farms across England and Wales, alongside site and landscape characteristics derived from a geographic information system (GIS) to (i) quantify biodiversity at solar farms and (ii) examine the major drivers of solar farm biodiversity.

2. Methods

Both field- and GIS-based methods were used to explore the factors affecting variation in plant, butterfly and bird biodiversity at solar farms in England and Wales. This involved field surveys at 86 solar farms, followed by site and landscape characterisation using a GIS and statistical analyses, allowing investigation into how solar farm characteristics, site management, characteristics of the surrounding landscape, other biodiversity groups, and survey methods are linked to solar farm biodiversity (figure 1).

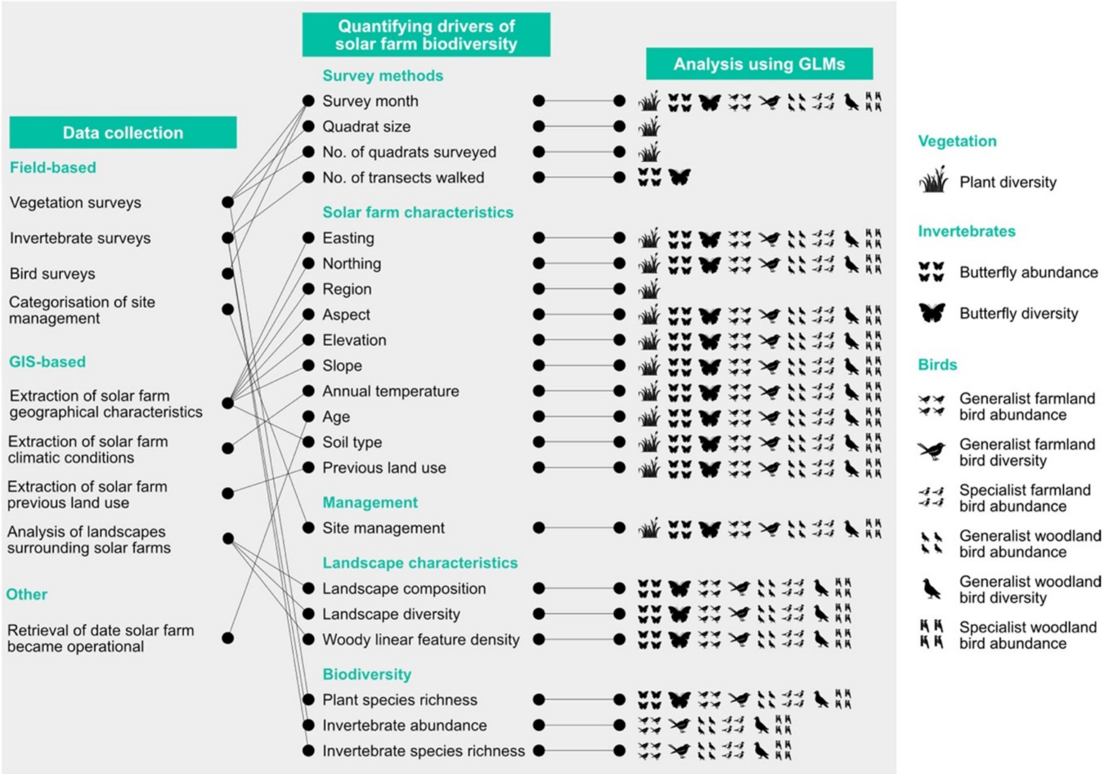

Figure 1. A summary of the methods, representing how field- and GIS-based data collection enabled the quantification of potential drivers of solar farm biodiversity using generalised linear models (GLMs). Annual precipitation was also explored as a driver of solar farm biodiversity but was ultimately not included in models due to collinearity.

2.1. Field surveys

Field surveys were undertaken at south-facing fixed-tilt solar farms across England and Wales by ecological consultants from Clarkson & Woods and Wychwood Biodiversity, with sites visited once between April and October of 2023 (figure 2). Data were collected during surveys commissioned by solar companies as part of routine monitoring and followed a standardised approach [26]. The biodiversity groups monitored at each site were determined by the solar companies commissioning the surveys, whereby vegetation was surveyed at 86 solar farms, invertebrates at 72 solar farms and birds at 59 solar farms.

General observations of site management were made at all solar farms, and each site was assigned a management category (1–5) based on its focus on biodiversity (figure 2). Categories followed the standardised approach to monitoring biodiversity on solar farms [26], which provides a way to broadly summarise how solar farms are managed when detailed management information is challenging to ascertain from field surveys alone. Solar farms assigned to Category 1 were those with optimal biodiversity management, with cutting and grazing limited to outside the summer months, removal of arisings, no herbicide use and a diversity of habitats (e.g. tussocky grassland, hedgerows or woodland planting). Category 2 was similar but included solar farms where there was limited herbicide use (e.g. spot treatment) and arisings were left *in situ*. Category 3 included solar farms that were cut or grazed throughout the summer, arisings were left *in situ* and more intensive herbicide use was apparent (e.g. blanket spraying), though some habitat diversity remained. Solar farms assigned to Category 4 were similar, but no other habitats were present. Finally, Category 5 included sites that did not fit these categories or were unmanaged.

2.1.1. Vegetation surveys

Vegetation within all solar farm grasslands was surveyed using quadrats placed between the rows of solar panels, under the solar panels themselves, in areas managed for biodiversity (if present) and within margin or open areas away from panels. The number of quadrats assessed within an individual site depended on the size of the solar farm, with more quadrats sometimes surveyed at larger sites or at those where management, or previous land use, differed within the site. Quadrats were 1 × 1 m (75% of quadrats) or 2 × 2 m (25% of quadrats), depending on the consultancy carrying out the survey. Inside each quadrat, all plant species were identified to species level where possible.

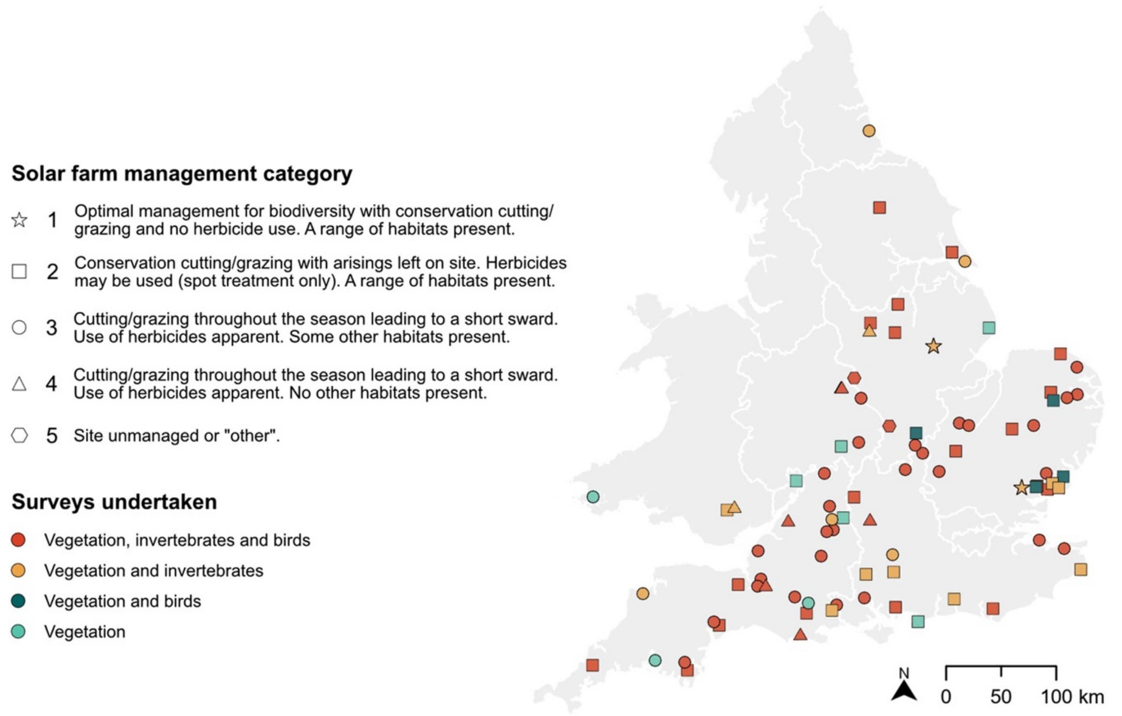

Figure 2. The locations of solar farms in England ($n = 81$) and Wales ($n = 5$) where field surveys were undertaken in 2023. Point shape represents the management category in which the solar farm was placed, where stars represent sites assigned to Category 1 ($n = 2$), squares for those in Category 2 ($n = 36$), circles for Category 3 ($n = 38$), triangles for Category 4 ($n = 8$) and hexagons for Category 5 ($n = 2$). Point colour represents the surveys undertaken at the solar farm, where red signifies sites where grassland vegetation, invertebrates and birds were surveyed ($n = 55$), orange where grassland vegetation and invertebrates were surveyed ($n = 17$), dark blue where grassland vegetation and birds were surveyed ($n = 4$) and blue where only grassland vegetation was surveyed ($n = 10$).

2.1.2. Invertebrate surveys

Transects were walked between the rows of solar panels and in margin areas, open areas or those managed for biodiversity (if present). Each transect was 100 m in length and all butterflies and bumblebees were recorded within 2.5 m either side of the transect and 5 m ahead to species level [26]. Transects were generally walked between 9 am and 4 pm in suitable conditions (i.e. in warm and bright weather, with no more than moderate winds and not when it was raining [27]), but some transects were walked in suboptimal conditions due to the inflexible nature of survey schedules.

2.1.3. Bird surveys

A single site wide transect was walked at each solar farm, encompassing all habitats within 50 m and birds were counted and identified to species level using sight and sound [26]. Surveys were conducted during the main breeding bird season (April to July) in suitable weather conditions (i.e. avoiding heavy rain or strong winds) and took place between sunrise to 11 am to capture peak bird activity. Birds that were flying over the site or were observed or heard outside of the solar farm (i.e. in adjacent habitats) were not included in analyses, as were species that were not interacting directly with solar farms (table S1). Each bird species was assigned into one of five groups: (i) farmland generalist, (ii) farmland specialist, (iii) woodland generalist, (iv) woodland specialist and (v) water specialist. Grouping was agreed by the ecologists who undertook the solar farm bird surveys, with foraging habitat and nest location preferences determining if they were generalists or specialists (for more details see Text S1).

2.2. Site characterisation

The boundary of each solar farm was manually digitised in ArcGIS Pro (version 3.1.0) using high resolution satellite imagery available through ESRI's world imagery Basemap at scales of 1:1000 to 1:2000 [28]. The resulting polygons were overlaid onto spatial data layers to extract site climatic and geographical characteristics including mean annual temperature [29], mean annual precipitation [30], mean elevation, slope and aspect [31], majority soil type [32] and previous land use [33] (table S2). Previous land use was derived from the UK centre for Ecology & Hydrology Landcover Map 2007 [33] by extracting the majority landcover class within each solar farm boundary polygon. Landcover data from 2007 was used as it predates solar farm deployment in England and Wales. Solar farm age was derived from the renewable energy planning database, which includes information about when developments became operational [34].

2.3. Landscape characterisation

To capture characteristics relevant to most invertebrates and birds [35, 36], the landscapes within 500 m buffer zones from solar farm boundaries were characterised in terms of composition, diversity and connectivity. To assess composition, the percentage cover of arable landcover classes, improved grassland, broadleaf woodland and semi-natural habitats was calculated, using the UKCEH landcover Map 2021 [37]. Diversity of the surrounding landscape was assessed by calculating the Simpson's diversity (D) of all landcovers in each buffer zone, where $D = 1 - \sum_{i=1}^{S} \rho_i^2$ and ρ_i is the proportion of landcover i and S is the number of landcovers. Lastly, connectivity was considered by calculating the density of woody linear features by dividing the total length of woody linear features (hedgerows and lines of trees; [38]) within each buffer zone by the area of the buffer.

2.4. Statistical analyses

The number of plant species recorded across all quadrats was summed to give a total plant species richness value for each solar farm. Similarly, multiple transects were walked at each solar farm, with the number of individual butterflies and bumblebees, and the number of species, summed to give a total abundance and species richness value at the site level. As a single site-wide transect was walked during bird surveys, totalling across multiple surveys was not necessary. Solar farm level abundance and species richness values were then used to calculate a Simpsons diversity value (D) for plants, invertebrates and birds at each site, where $D = 1 - \sum_{i=1}^{S} \rho_i^2$ and ρ_i is the proportional abundance of species i and S is the number of species. Analyses were undertaken in *R* (version 4.3.0) [39] using the 'diversity' function in the 'vegan' package [40]. Abundance and Simpsons diversity values were then used as response variables in Generalised Linear Models (GLMs).

2.4.1. Regression modelling

The data consisted of nine response variables, of which five were counts ((i) butterfly abundance, (ii) generalist farmland bird abundance, (iii) specialist farmland bird abundance, (iv) generalist woodland bird abundance and (v) specialist woodland bird abundance) and four were diversity indices ((i) plant diversity, (ii) butterfly diversity, (iii) generalist farmland bird diversity and (iv) generalist woodland bird diversity; figure 1). Each variable was modelled using a multivariable regression model. The count data were modelled using either a Poisson or Negative Binomial GLM with both-ways stepwise selection used to determine the best model. The stepwise selection ensures that all covariates are considered in each model whilst balancing model complexity due to the number of covariates considered in the analysis. The diversity scores, which are bounded between 0 and 1, were modelled using beta regression models. For computational reasons, stepwise selection was not implemented on the beta regression models and all variables that were initially considered were retained in the final fitted models.

A total of 20 covariate variables were considered for each model and were included where methodologically and ecologically appropriate. Covariate variables included those relating to survey methods (survey methods, quadrat size, number of quadrats surveyed and number of transects walked), solar farm characteristics (easting, northing, region, aspect, elevation, slope, annual temperature, age, soil type and previous land use), site management, landscape characteristics (composition, diversity and woody linear feature density) and other biodiversity (plant species richness, invertebrate abundance and invertebrate species richness; figure 1). For each categorical covariate variable, the factor level with the most occurrences in the data was used as the reference factor level against which the other factor levels were compared to aid interpretation and the reliability of the estimated terms. For survey month this was May, for region this was the South West, for soil type this was brown soils, for site management this was Category 4, and for previous land use it was arable and horticulture.

2.4.2. Data filtering

Whilst Poisson and Negative Binomial models can include zero counts, beta regression models cannot. For three of the beta regression models, there were zeros present in the response variable. In two cases this was very limited (two zeroes) and in the third case the zeroes were more prevalent (eight for butterfly Simpson's diversity). Entries with zeroes were removed from the data since these are likely to be a repercussion of weather conditions on the survey day. This allowed a beta regression model to be used for all diversity indices, enabling direct cross-species model comparisons.

Five of the covariate variables were factors with multiple levels (survey month, region, soil type, previous land use and site management). After sub-setting the data for each model some factor levels were reduced to a single instance, resulting in unreliable estimates of the corresponding regression coefficients. Consequently, for each model, observations that included a covariate with a factor level that was present only once was removed.

In some cases, the covariates had a degree of missing data because not all covariates were recorded in all surveys. This ranged from one or two missing observations to almost 30%. To create parsimonious models and to retain a variety of covariates, observations with missing data in any of the covariates included in each model were removed before modelling. Imputation was considered for the missing data, however, given the exploratory nature of the analysis and the extent with which imputation would be needed, we chose not to impute the missing values.

2.4.3. Multicollinearity

The correlation between the available covariates was assessed to assess multicollinearity. There were a small number of pairs of covariates with correlation coefficients of $|r| > 0.7$ [41]. For two of these pairs (percentage covers of improved grassland and arable landcover, and invertebrate richness and invertebrate count) no covariates were removed from the dataset due to the exploratory nature of the analysis and the possibility of some of these variables being dropped from the final model during model selection. However, mean annual precipitation had correlations above the 0.7 threshold with multiple other variables, so it was not included in the regression models to limit the multicollinearity present in the dataset. Further details of model validation can be found in Text S2.

3. Results

3.1. Quantifying solar farm biodiversity

3.1.1. Vegetation

A total of 1475 quadrats were assessed across all 86 solar farms, with a mean of 17.2 ± 0.5 (standard error here and throughout) surveyed per site, ranging from 14 to 33 quadrats. Most quadrats were assessed in between rows of solar panels (501 quadrats), under solar panels (498 quadrats) or in other areas (margin or open areas away from panels; 382 quadrats), and some were surveyed in areas managed especially for biodiversity (94 quadrats). A total of 289 plant species were recorded within quadrats, which were mostly species typical of grassland habitats or those included in seed mixtures for biodiversity (table S3). The mean number of plant species recorded per solar farm was 28, but this ranged from nine to 52 (table S4).

3.1.2. Invertebrates

A total of 783 transects were walked across 72 solar farms, either between the rows of solar panels (377 transects), in margins, open areas or areas managed for biodiversity (365 transects) or where the location was not specified (41 transects). On average, 10.9 ± 0.3 transects were walked per solar farm, ranging from five to 19. Along all transects, 3088 individual invertebrates were recorded, comprising 2589 butterflies and 499 bumblebees. At least 24 butterfly species and six bumblebee species were observed (table S5), with most species relatively common, although the small heath butterfly (*Coenonympha pamphilus*), which is classified as Vulnerable on the Red List for Great British Butterflies [42], was recorded at ten solar farms.

On average, 36 ± 6 individual butterflies were recorded per solar farm, ranging from zero to 205. A mean of 3.6 ± 0.3 butterfly species were recorded per site, ranging from zero to ten. For bumblebees, abundance per solar farm ranged from zero to 51, with a mean of 7 ± 1. On average, 1.5 ± 0.2 bumblebee species were recorded per site (ranging from zero to five). Numbers of species and individuals were too low to conduct further analyses for bumblebees.

3.1.3. Birds

A total of 59 bird surveys were undertaken across all solar farms (one per site), with 6527 individuals comprising 81 species (table S6), including farmland generalists (2481 individuals, 27 species), farmland specialists (748 individuals, ten species), woodland generalists (3062 individuals, 22 species), woodland

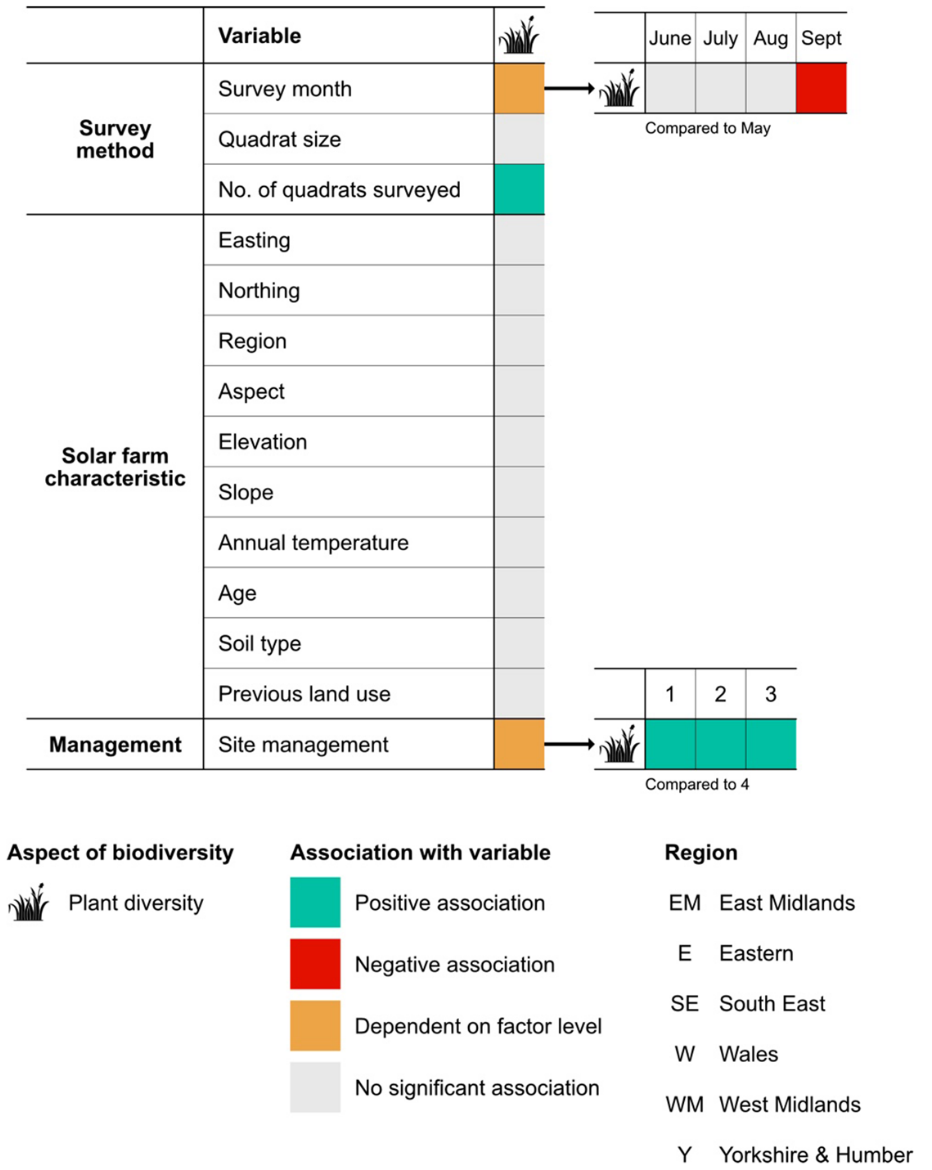

Figure 3. A summary of generalised linear model results for plant diversity (Simpsons) at solar farms, using data from 80 sites across England and Wales. Blue boxes indicate a variable had a significant positive association with plant diversity, red boxes indicate a significant negative association and grey indicate no significant association at the $p < 0.05$ level. Orange boxes indicate that the association varies depending on the factor levels being compared.

specialists (143 individuals, 14 species) and water specialists (93 individuals, eight species). Water specialists were excluded from further analyses given low numbers and as such, the mean number of farmland and woodland birds recorded at a solar farm was 109 $\pm$ 12 individuals, ranging from one to 380 and the mean number of species observed was 22 $\pm$ 1, ranging from one to 44.

3.2. Examining the drivers of solar farm biodiversity

3.2.1. Vegetation

Variation in solar farm plant diversity was linked to a combination of site management and survey methods. Plant diversity was greater at solar farms assigned to site management Categories 1, 2 and 3, compared to sites in Category 4 (i.e. with less management focus on biodiversity; figure 3, table S7). Plant diversity was lower during surveys that were undertaken in September (compared to May) but increased with the number of quadrats surveyed within a solar farm (figure 3, table S7). Plant diversity was not associated with solar farm characteristics including geographical location, aspect, elevation, slope, annual temperature, soil type, age of the solar farm or previous land use (figure 3, table S7).

3.2.2. Invertebrates

A combination of solar farm characteristics, site management, landscape characteristics, other biodiversity and survey methods was associated with butterfly biodiversity across solar farms. Whilst site characteristics were not linked to butterfly abundance, diversity was lower when sites were located further north, there was a greater mean elevation or aspect across the site or where annual temperatures were higher (figure 4, table S8). Diversity was also linked to soil type and was lower at solar farms with made ground soils and higher at sites with pelosol soils (compared to brown soils; figure 4, table S9). Site management was associated with both butterfly abundance and diversity, with more individuals counted at solar farms in Category 2, but lower diversity recorded at sites assigned to Category 1 (compared to Category 4; figure 3, tables S8 and 9). Butterfly biodiversity was associated with landscape characteristics, whereby lower diversity was associated with solar farms surrounded by a greater cover of arable land and higher abundance was associated with a greater density of woody linear features in the surroundings (figure 4, tables S8 and 9). A positive association between butterfly abundance and plant species richness was also observed (figure 4, table S8 and 9). Moreover, both abundance and diversity were linked to survey month. More individuals were counted in June, July and August and diversity was lower in June, but greater in August (compared to May; figure 4, Tables S8 and 9). More individual butterflies were recorded where more transects were walked within a solar farm, although there was no association with butterfly diversity (figure 4, table S8).

3.2.3. Birds

Solar farm characteristics, including location, were linked to bird biodiversity, where generalist farmland bird diversity was higher at sites further east, and farmland and generalist woodland bird abundance was higher at sites further north (figure 5, tables S10–15). Specialist farmland bird abundance and woodland bird biodiversity was greater at older solar farms, but soil type was the only variable associated with all aspects of bird biodiversity, with greater biodiversity generally associated with solar farms with pelosol compared to brown soils (figure 5, tables S10–15). Previous land use was linked to most aspects of bird abundance, but not diversity, with higher numbers of individuals recorded at solar farms that were previously rough grassland and lower numbers at those that were previously improved grassland (figure 5, tables S10–15). Site management was linked to specialist farmland bird abundance, with more individuals recorded at solar farms in Category 3, and aspects of woodland bird biodiversity, with a greater diversity of generalists at solar farms in Categories 2 and 3, but a lower abundance of specialists associated with solar farms in Category 2 (compared to sites in Category 4; figure 5, tables S10–15). The abundance of generalist birds and the diversity of farmland specialists were associated with survey month, with differences noted for June and July in particular (compared to May; figure 5, tables S10–15).

Landscape characteristics were also linked to solar farm bird biodiversity, where farmland bird abundance and generalist woodland bird abundance were lower at sites with greater surrounding arable cover, but specialist woodland bird abundance was higher (figure 5, tables S10–15). Similarly, farmland bird abundance was lower at solar farms with greater surrounding grassland cover and semi-natural habitat cover (for generalists only), but specialist woodland bird abundance was higher when landscapes contained more semi-natural habitat (figure 5, tables S10–15). The abundance of generalist farmland birds was lower inside solar farms where surrounding landscapes were more diverse in terms of composition (figure 5, tables S10–15), although solar farm woodland bird abundance was greater where landscapes had a higher density of woody linear features (figure 5, tables S10–15).

Lastly, other biodiversity groups influenced solar farm bird biodiversity, which was mostly higher at solar farms with greater plant species richness (figure 5, tables S10–15). Farmland bird abundance and generalist woodland bird abundance was greater with invertebrate species richness, but generalist farmland bird abundance and generalist woodland bird diversity were lower at solar farms with greater invertebrate abundance (figure 5, tables S10–15).

4. Discussion

Our results suggest that a combination of site characteristics, management, landscape context and survey methods are linked to solar farm biodiversity. Although there are differences across biodiversity groups, soil type, site management and survey month were variables which were most frequently associated with variation in abundance or diversity. Below, we discuss the potential drivers of solar farm biodiversity,

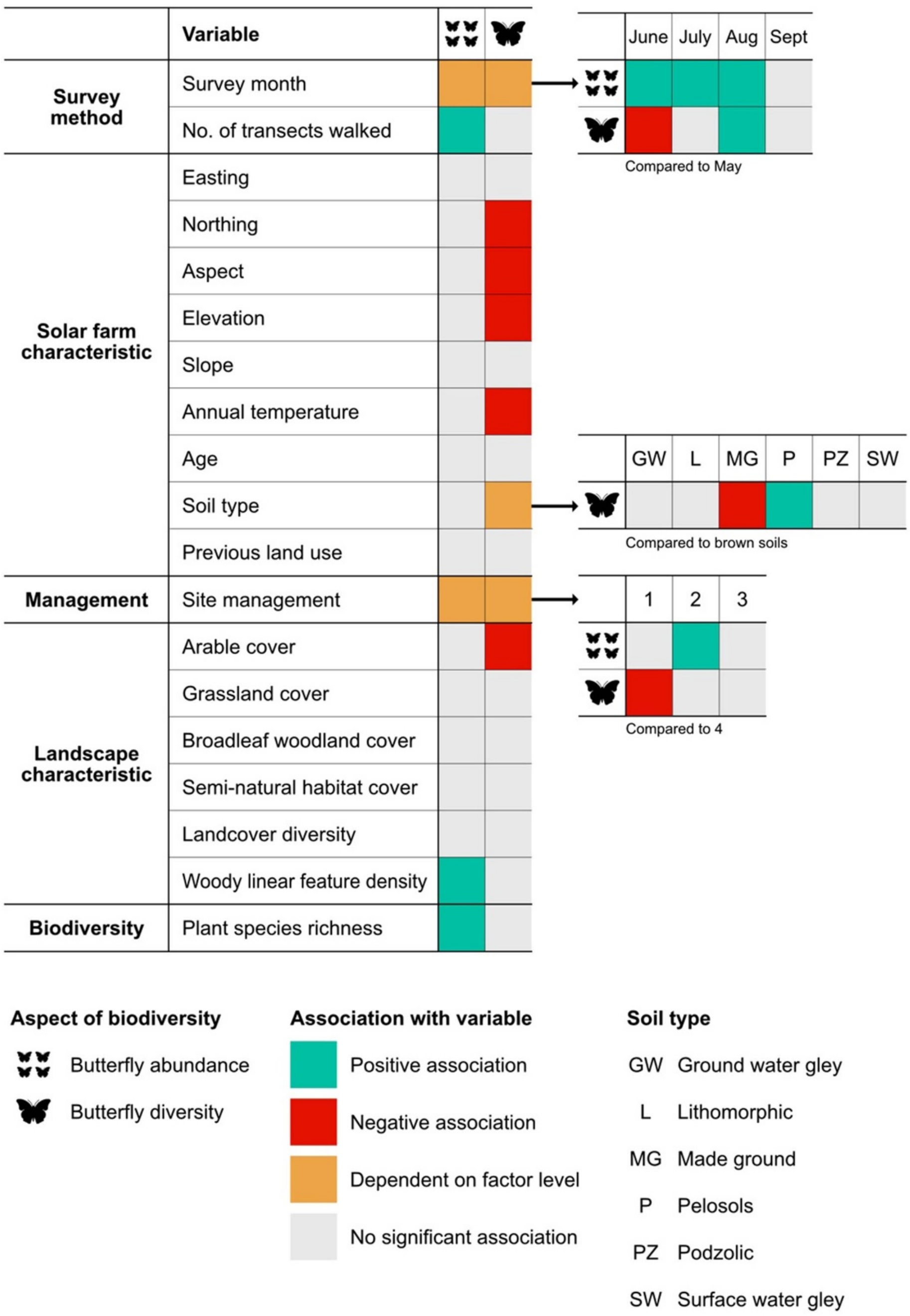

Figure 4. A summary of generalised linear model results for butterfly abundance and diversity (Simpsons) at solar farms, using data from 67 and 54 sites respectively across England and Wales. Blue boxes indicate a variable had a significant positive association with butterfly diversity, red boxes indicate a significant negative association and grey indicate no significant association at the $p < 0.05$ level. Orange boxes indicate that the association varies depending on the factor levels being compared. Landscape characteristics refer to those within a 500 m buffer extending from the solar farm boundary.

the implications for site management and how scaling up ecological monitoring across solar farms could help to assemble a national picture of solar farm biodiversity, along with highlighting avenues for future research.

4.1. Drivers of solar farm biodiversity

A range of site characteristics, including location, previous land use and solar farm age were linked to biodiversity within solar farms. Response to solar farm location differed across groups, with lower butterfly diversity recorded at higher latitudes and greater bird diversity at sites located further east or north. This is expected given well established biodiversity trends with latitudinal gradients, due in part to variation in climate, soils and habitats [43]. Indeed, annual temperature was associated with some aspects of biodiversity within solar farms, but soil type was linked to butterfly diversity, along with all aspects of bird biodiversity measured. Soil type is likely important due to influences on vegetation and

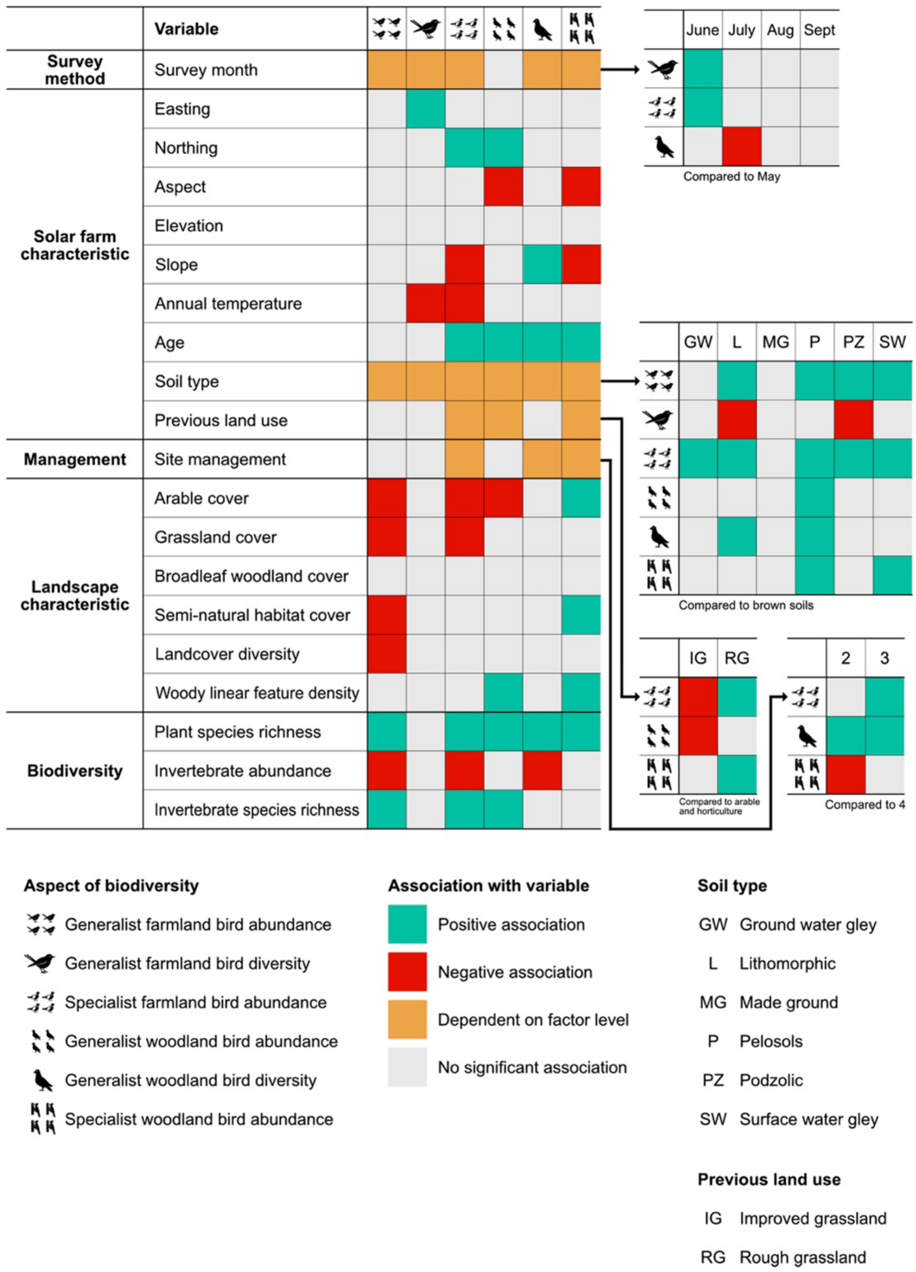

Figure 5. A summary of generalised linear model results for bird abundance and diversity (Simpsons) at solar farms, using data from ∼50 sites across England and Wales, where the number of sites included in each final model varied due to data filtering. Blue boxes indicate a variable had a significant positive association with bird diversity, red boxes indicate a significant negative association and grey indicate no significant association at the $p < 0.05$ level. Orange boxes indicate that the association varies depending on the factor levels being compared. Landscape characteristics refer to those within a 500 m buffer extending from the solar farm boundary.

its characteristics, which can impact higher trophic levels. When solar farm soil types were broken down into sub-groups, most lithomorphic soil and pelosols were found to be calcareous (with the opposite being true for brown soils; figure S1), suggesting that sites dominated by these soil types could support calcareous grassland communities, which tend to be more biodiverse than other grassland habitats [44, 45]. Although no association between soil type and vegetation diversity was detected, it is possible that other characteristics of vegetation aside from diversity, such as plant traits, density of vegetation cover and community composition and function were affected instead [24]. Similarly, previous land use was linked to some aspects of bird biodiversity and could also be related to soils and vegetation, where impacts of historical management have persisted over time [46]. Bird biodiversity was also positively associated with solar farm age, likely because habitats within older solar farms have had longer to recover from the initial disturbance of construction, although no significant associations with plant or butterfly biodiversity were found.

A range of surrounding landscape characteristics were also associated with solar farm biodiversity. For example, more butterflies were recorded at solar farms with a greater density of woody linear features in the surroundings, such as hedgerows and lines of trees, likely because of the array of benefits associated with these features. Hedgerows provide foraging and reproductive resources [47], support movement across landscapes [48] and offer places to shelter from unsuitable weather conditions [49] and the findings support another study linking higher bumblebee abundance and species richness at solar farms with surrounding woody linear feature density in England [18]. In contrast, butterfly diversity was lower at solar farms with a greater cover of arable land in the surrounding landscape, possibly because agriculturally dominated landscapes, especially if intensively managed, are less likely to be able to support biodiverse butterfly populations [50].

The cover of arable land (and improved grassland in some cases) surrounding solar farms was also linked to bird biodiversity within the solar farm, whereby predominantly negative correlations with abundance were observed. As with butterflies, this could be due to lower numbers of individuals in the landscape if surrounding arable land is resource poor [49]. Conversely, abundance may be lower if individuals are using other habitats or resources outside of the solar farm, which might include targeted habitats for farmland birds, such as those created under agri-environment schemes [51]. In contrast, woodland specialist abundance was positively associated with arable cover in the landscape, possibly because farmland habitats are less suitable for woodland bird species with specific requirements, whereas solar farms are often developed alongside hedgerow and tree planting, which could offer more woody species than surrounding habitats.

Conversely, the abundance of generalist farmland birds was negatively associated with increasing cover of surrounding semi-natural habitats and with landcover diversity. In these landscapes, individuals may be more likely to access resources outside of the solar farm and generalist species in particular can utilise a range of habitats provided by other land use types or interventions. However, to further understand the mechanisms driving relationships between solar farm biodiversity and landscape characteristics, habitats surrounding solar farms should be assessed in terms of habitat quality and the resources provided to biodiversity.

Alongside associations with landscape context, there were interactions between different biodiversity groups within solar farms. For example, the abundance of farmland birds and woodland generalists was greater with higher invertebrate diversity, likely because many farmland birds are insectivorous and some seed eating species rely on invertebrates as a food source for chicks during the breeding season [52]. However, some aspects of bird biodiversity were lower where invertebrate abundance was greater but this could be because invertebrate abundance included only bumblebees and butterflies, rather than other invertebrates (e.g. beetles, grasshoppers, sawflies and spiders) which are important food sources [52]. In contrast, at solar farms with greater plant diversity, butterfly and bird abundance (and bird diversity in most cases) was greater, supporting previous research [18] and industry analyses [15]. Indeed, positive relationships between plant diversity and other biodiversity groups demonstrates how solar farm management to increase the number of plant species on site could have positive impacts across trophic levels.

Solar farm management was linked to most aspects of biodiversity and generally, abundance and diversity was greater at solar farms with more optimal management for biodiversity (i.e. sites assigned to Categories 1, 2 or 3) compared to those less optimally managed, with no other habitats present on site (i.e. sites assigned to Category 4), suggesting that biodiversity responds positively to focused management, aligning with other assessments [15, 16, 18]. However, butterfly diversity was lower at solar farms considered to be most optimally managed for biodiversity (i.e. sites assigned to Category 1), compared to those with more intensive grassland management practices, extensive herbicide use and fewer habitats (i.e. sites assigned to Category 4), but this could be because only two sites were assigned to Category 1 and results were impacted by the small sample size. Specialist woodland bird abundance was also lower at solar farms in Category 2, compared to Category 4, possibly because management categories primarily focus on grassland management, rather than the management of woody habitats or hedgerows, which are more relevant to woodland specialists.

4.2. Implications for solar farm management and siting

Management of habitats within solar farms can be adapted at existing sites and biodiversity-focused practices can be implemented at new developments, meaning that site management offers a significant opportunity for solar farms to deliver for nature [13]. Indeed, as understanding of solar farm management impacts begin to emerge, there is growing interest from the solar industry to manage solar farms with a biodiversity focus [15]. Management for biodiversity can include establishing or restoring semi-natural habitats including grasslands and hedgerows, often through actions including cutting, mowing or grazing, and in some cases, herbicides are used to control certain plant species [53]. Other interventions, including providing artificial habitat structures, can also be undertaken at solar farms [54]. Whilst a better understanding of individual management actions on solar farm biodiversity is required to ensure effective practices, general habitat management principles taken from similar contexts could be drawn on and applied to solar farms in the meantime [55].

Although biodiversity-focused management practices can enhance the abundance or diversity of some taxonomic groups at solar farms, other drivers are likely to moderate this response. Our findings show that characteristics of the solar farm itself, and the surrounding landscape, can influence solar farm biodiversity alongside management actions. As these characteristics are largely unrealistic to modify for existing developments, solar farms are likely to be inherently different in terms of biodiversity in part due to these factors. This should be considered when assessing effectiveness of solar farm management actions across developments as applying the same management techniques is likely to lead to different outcomes given variation in sites themselves and surrounding landscapes.

Surrounding landscape characteristics could be factored into siting decisions for new solar farms. Although site location is predominantly determined by available land, land use type, grid connection and a host of other factors [56], selecting land parcels with some consideration of landscape characteristics could promote positive biodiversity outcomes. For example, deploying solar farms in intensively managed landscapes, with little suitable habitat biodiversity, could be beneficial if sites are managed to provide foraging and nesting resources for invertebrates and birds. However, compositions of optimal landscapes for solar farm deployment will differ depending on the biodiversity group, or species of interest, given variation in their ecology. Moreover, solar farms could also be strategically sited to promote landscape connectivity, either by acting as stepping stones between patches of other habitats, or through expanding the hedgerow network across a landscape to promote species movement [14].

4.3. Biodiversity monitoring at solar farms

To our knowledge, the dataset used in this study is the largest solar farm biodiversity database centred on field-based assessments. Data collection at this scale was enabled by the development of a standardised monitoring approach for solar farms [26] and subsequent use at sites across the country by ecological consultancies as part of their routine monitoring work [57]. Undertaking this scale of fieldwork as part of a lone research project would be financially costly, time demanding and logistically challenging, highlighting the value of collaboration between academia, ecological consultants and industry and the benefits of applying a standardised method across many sites.

However, there are several limitations associated with this approach. Firstly, routine monitoring is typically carried out on an annual basis (or less frequently), meaning that most solar farms were only visited once. By collecting data on one day only, species which are more active or detectable at certain times of the year may not have been recorded, influencing abundance and diversity measures. Similarly, data collected as part of single visits can be heavily affected by weather and inflexible schedules mean that surveys sometimes take place in less optimal conditions, potentially impacting results. Furthermore, whilst the methods were largely standardised, survey effort differed across solar farms, in terms of the number and size of quadrats surveyed and the number of transects walked. Often this was in response to solar farm size (with more surveys being carried out at larger sites) and the number of habitats present (with more surveys being carried out with greater habitat diversity) and was also shown to influence vegetation and butterfly biodiversity results. Whilst this was accounted for in our analyses, the results highlight the challenges of applying a standardised monitoring approach to solar farms of different sizes and complexities, but this will be essential to address as solar farms continue to increase in number and size [11].

The standardised monitoring approach also largely focuses on data collection only within solar farms, but the impacts of development could be better understood if data were compared to off-site controls or other land uses. Whilst the approach recommends vegetation surveys within a control site (a field within the landowners holding managed in the same way as the solar farm prior to construction), these can be challenging to undertaken given restricted access, differences in land ownership and time constraints associated with one day surveys [26]. Instead, solar farm data could be compared to data collected through national level monitoring schemes, such as the countryside survey [58], the UK butterfly monitoring scheme [27] or the breeding bird survey [59], covering a range of taxa. This would enable greater investigation into whether patterns observed within solar farms are explained by factors such as land management actions or represent broader geographical trends. Techniques such as remote sensing could also be used to contextualise some aspects of solar farm biodiversity, such as vegetation structure and phenology, that could be assessed using LiDAR (light detection and ranging) both inside the solar farm and in the surrounding landscape [60]. However, to directly evaluate the impacts of land use change for solar farms, ecological monitoring data could be collected in a before-after-control-impact design, with the standardised approach undertaken both pre- and post-construction.

4.4. Further research

As demonstrated in this study, data collected by industry can be used to answer a plethora of research questions and increase understanding of biodiversity response to solar farms and their management. Currently, many studies focus on impacts of a single, or a few, solar farms but applying a standardised approach at more sites would enable insights into larger scale impacts. This is critical given continuing land use change for solar farms and the current lack of understanding of how impacts of these developments could be synergistic within landscapes where they are clustered. Furthermore, applying standardised methods over time (and at the same sites), will allow exploration of temporal trends. Currently, there is limited understanding of solar farm biodiversity impacts over time, but a longitudinal field study at two solar farms in Minnesota, USA, reported increases in insect abundance and diversity detected alongside increases in floral rank and species richness over five years [61]. Conducting similar studies at solar farms in other regions and ecosystem types are necessary to gain greater insight into temporal trends, which is pertinent given solar farm operational lifespans (25–40 years) [53].

Further research should also focus on the impacts of specific management actions within solar farms. The impacts of individual actions could be assessed separately, rather than grouped into broad categories, and included as variables in GLMs. This further understanding of biodiversity response to grassland management techniques (i.e. cutting or grazing), herbicide use, and the number of habitats present on site and could better inform solar farm management regimes. Detailed studies focusing on different aspects of management actions, such as experiments that vary cutting frequency, grazing densities and the timing of management actions and study biodiversity responses, would also be valuable for practitioners. However, acquiring detailed solar farm management information can be challenging and assigning management actions to broad categories allows the collection of comparable data across many sites.

Details of solar farm construction and site preparation can also be difficult to obtain but could have implications for biodiversity. During construction, disturbance and potential habitat loss could impact a range of taxa, depending on timings (i.e. during sensitive periods such as the bird breeding season) and techniques used [62]. In some instances, construction can decrease soil physical quality [63] which can hamper vegetation establishment [64]. Re-establishment methods vary but often involve the sowing of seed mixes [65] which likely influence solar farm plant communities and therefore wider biodiversity. However, most studies focus on ecological response to solar farms in the operational phase, with little evidence relating to site construction and preparation specifically [62]. As such, future research could investigate the impacts of construction and preparation methods to gain a fuller understanding of biodiversity response to solar farms.

Finally, further research could explore interactions between key explanatory variables. Given the nature of this study and the number of variables included, it was not feasible to consider interactions between them in this analysis. However, interactions between a number of the variables included may be expected, including between solar farm management and landscape characteristics, as reported in similar contexts [66]. Findings from this study could be used to guide the choice of explanatory variables in future work, resulting in models containing fewer variables and further mitigating the impacts of multicollinearity and other challenges associated with complex statistical models.

5. Conclusion

Overall, our findings indicate that a range of factors are associated with biodiversity at solar farms, with variation depending on biodiversity group and the metric assessed. Through applying a standardised monitoring approach across England and Wales, this study is the first to investigate the factors affecting multiple biodiversity groups at solar farms at a large scale. The results indicate that whilst biodiversity is linked to characteristics of the solar farm itself and the surrounding landscape context, which generally cannot be modified for existing developments, site management is a prominent driver of biodiversity and can be adapted to enhance the abundance or diversity of biodiversity groups. Solar farms managed with a biodiversity-focused strategy should be able to support or enhance plant, invertebrate and bird biodiversity, but effectiveness of management actions may be moderated by drivers that cannot be modified by management (e.g. soil type). Some solar farms may have higher baseline levels of biodiversity than others, whereas others may have greater potential to enhance biodiversity on site. Nevertheless, embedding biodiversity into the siting, designing and managing of solar farms can help to ensure positive ecological outcomes of renewable energy development.

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Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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ORCID iDs

Hollie Blaydes 0000-0002-7753-4938
Daniel Clarkson 0000-0002-2085-1684
Rachel McCrea 0000-0002-3813-5328
Christopher J Feeney 0000-0003-2175-1842
Alona Armstrong 0000-0001-8963-4621

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