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Research article

The location of solar farms within England's ecological landscape: Implications for biodiversity conservation

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ABSTRACT

A global energy transition to using sustainable renewable sources is being driven by global agreements. Simultaneously there is a call for increased biodiversity conservation. This creates a green-green dilemma, where the expansion of renewables could lead to the demise of biodiversity if not carefully assessed, managed and monitored. Recognition of the dilemma is central to the development of Sustainable Development Goals. It is therefore important to understand whether renewable energy sources such as solar farms are being sited in areas where they have minimal impact on biodiversity. If solar farms were sited with minimal impacts on biodiversity, we hypothesised that they would be less likely to be sited close to ecologically sensitive areas than near random points. We used Geographic Information System methods to explore the density of solar photovoltaic (PV) farms in England and assessed their siting relative to sensitive ecological features, including priority habitat types, designated sites, and land conservation initiatives. We compared the area of 25 sensitive ecological features around solar farms and random points across three spatial scales (100 m, 1000 m, and 6000 m radius scales). Solar farms were distributed throughout England, with the highest concentration in South West England. Solar sites were primarily surrounded by habitats with anthropogenic influences, such as agricultural and urban settings. Priority habitats, such as woodland, grassland, wetland and heathland, were more extensive around random points across spatial scales (except for woodland at the largest scale). Most designated sites were significantly more extensive around random points. We conclude that, under current planning regulations, solar sites in England are being placed appropriately with regard to sensitive ecological habitats, and are often sited in areas already impacted by farming and development. Adaptive planning should be implemented to ensure that the evolving research around biodiversity and solar farms is incorporated into decision making, and monitoring is completed across the lifespan of solar farms to assess impacts and effective mitigation.

1. Introduction

A global energy transition is underway. This is being driven politically, particularly within Europe which is heavily reliant on energy sources provided from other countries (European Commission, 2022), and also due to a focus on energy sustainability (Siddi, 2023). Renewable energy sources continue to be under ever increasing pressure to meet global power demands and drive the reduction in carbon dioxide output to reduce the pace of climate change, particularly given the goals set by the Paris Agreement 2015 (agreed at the 21st Climate Conference of the Parties (COP21)). However other regulations, such as the

Kunming-Montreal Global Biodiversity Framework, agreed at the Conference on Biological Diversity in 2022 (Biodiversity COP 15), are simultaneously requiring the restoration of global biodiversity. This interface creates potential green-green dilemmas, by which achieving climate targets through renewable energy sources may have detrimental impacts on biodiversity (Dulluri and Raç, 2019; Voigt et al., 2024).

There is a growing awareness regarding potentially negative effects of renewable energy sources. Solar power, wind turbines, hydro-electric power, tidal, geothermal and bioenergy can all cause biodiversity loss (Gasparatos et al., 2017), and threaten globally important biodiversity areas (Rehbein et al., 2020). Green-green dilemmas are central to

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Sustainable Development Goals (SDGs) set by the UN to address global environmental and societal challenges in that they identify the need to produce green energy in ways that are sustainable environmentally (Işık et al., 2024). SDGs are affected by environmental, social and governance (ESG) principles, and leveraging industries to adopt cleaner and more efficient technologies is important providing that environmental degradation is mitigated (Işık et al., 2024).

To date there has been a strong focus on the impact of wind turbine developments on biodiversity. The conclusions from such studies are that the legislation around biodiversity protection is not 'overly strict', stakeholder communication is poor and the implementation of the mitigation hierarchy is weak (Köppel et al., 2014; Straka et al., 2020; Voigt et al., 2019). Although the siting of solar technology has been studied in relation to infrastructure and geographic features (e.g., Her-nik et al., 2019; Palmer et al., 2019), it has received limited attention regarding its effects on biodiversity and ecosystems until recently (Gómez-Catasús et al., 2024; Lafitte et al., 2023; Tinsley et al., 2023; Tölgyesi et al., 2023). Severe potential impacts on wildlife have been identified for 'large-scale solar projects', and these can occur from construction, through to maintenance and operation, and include associated infrastructure requirements (Gorman et al., 2023; Pizzo, 2011). Solar development can lead to habitat loss and fragmentation (Smallwood, 2022), microclimate alteration (Armstrong et al., 2016), and changes in animal behaviour (Barré et al., 2024; Chock et al., 2021), all of which are likely to affect ecological function at solar farm sites and the surrounding areas (Pizzo, 2011).

Careful planning of renewable energies to avoid conflicts between green energy and biodiversity is required, for example siting wind turbines away from 'ecologically sensitive areas' is already recognised as an important measure to limit negative impacts on biodiversity (Johnson and Stephens, 2011; Mulualet, 2016; Voigt et al., 2024). However this is not always achieved (Barré et al., 2022; Rehbein et al., 2020), and can be a particular challenge for countries like Greece where 28% of the country is within the Natura2000 network (Doukas et al., 2020). Thus pressure is falling upon governments and investors to demand environmental standards which manage green-green dilemmas (Voigt et al., 2024), particularly where ambitious growth strategies are in place.

In 2023, solar photovoltaics (PV) represented half of the total new renewable capacity in the UK (Department for Energy Security & Net Zero, 2024a), and targets for solar power to increase five-fold by 2035 are in place (HM Government, 2022). Solar energy is considered the most abundant and fundamental of all the renewable energy sources (Chel and Kaushik, 2011; Jones et al., 2015). Due to the development of solar technology, government renewable energy policies and the provision of subsidies, solar PV development has expanded 402-fold in England over the last two decades to reach 14,086 MW in 2022, a similar energy capacity to that provided by onshore wind (14,581 MW, 2022; Jones et al., 2014; Department for Business Energy & Industrial Strategy, 2022). The expansion and need for solar energy are occurring globally (Haegel et al., 2023).

It is therefore important that the placement of solar sites within the ecological landscape should be considered carefully, and opportunities to make biodiversity improvements to previously degraded land are optimised. Minimising the impacts of solar farms on biodiversity follows a similar mitigation hierarchy to that recognised for wind farms (Bennun et al., 2021). The first stage in the mitigation hierarchy involves the planning phase, implementing careful siting of facilities so they have minimal impacts on biodiversity. Sites that could potentially have negative impacts, or which are in protected areas should be avoided. At present in England the National Planning Policy Framework states that Sites of Special Scientific Interest (SSSI), Special Protection Areas (SPA), Special Areas of Conservation (SAC), and Ramsar sites (internationally important wetlands), as well as wildlife rich habitat and ecological networks should be 'identified, mapped and safeguarded' as part of the planning process (Department for Levelling Up Housing & Communities Ministry of Housing & Communities & Local Government, 2023).

The onus on sensitive planning around biodiversity is increasing, with investment companies and financiers paying closer attention to asset portfolios since the establishment of the 'Taskforce for Nature-related Financial Disclosures' and their associated recommendations which have developed from the Biodiversity COP15 (TNFD, 2023). As such the drive to meet solar expansion targets, whilst ensuring developments are attractive to investors by being sensitive to biodiversity is now recognised as important and fundamental to SDGs.

Palmer et al. (2019) state that government policy on site-suitability for large scale solar developments in the United Kingdom (UK) is equivocal. Although siting solar farms on ecologically sensitive areas is not banned, planning permission is still unlikely to be granted. A recent UK government review (Rankl, 2024) states that farms with a generating capacity <50 MW need planning permission from the local planning authority (LPA), while larger installations (>50 MW, large-scale solar farms) need consent from the Secretary of State for Energy Security and Net Zero. Large-scale solar farms need to meet the 'exceptional circumstances' test for development in protected areas (e.g. National Parks and National Landscapes), and areas that might affect areas protected under The Conservation of Habitats and Species Regulations (2017) (SAC and SPA) and government policy (Ramsar sites (internationally important wetlands)). 'Significant effects' on protected areas must be avoided or mitigated by LPAs, and if this is not possible, the LPA must refuse planning consent unless there are 'imperative reasons of overriding public interest'. Modifications of the guidelines above exist under the devolved governments in Wales, Scotland, and Northern Ireland. About 67% of planning applications for solar farms with >1 MW capacity submitted to LPAs were approved between 2010 and 2023 (Rankl, 2024).

Environmentally Protected Areas have been considered in relation to the siting of offshore (e.g. Spiropoulou et al., 2015) and onshore wind farms (e.g. Hajto et al., 2017). In contrast studies on the siting of solar farms in relation to ecologically sensitive areas have been lacking with some notable exceptions (Ascensão et al., 2023; Evans et al., 2023; Hermoso et al., 2023; Rehbein et al., 2020). Several studies have used Geographic Information System (GIS) methods to identify locations for siting solar farms, though ecological impacts are rarely considered in depth (Giamalaki and Tsoutsos, 2019). Palmer et al. (2019) used site-suitability analyses to understand the future scope of large-scale solar developments in the United Kingdom (UK). They considered land use, solar energy resource and electrical grid constraints. Palmer et al. (2019) concluded that, despite planning permission and grid constraints limiting land available for solar developments by up to 97%, sufficient land was still available to meet the government's Future Energy Scenarios. However, Palmer et al. (2019) considered only a very limited number of environmental features, including National Parks, woodland (defined broadly) and moorland as environmentally sensitive areas. The analyses presented in our study investigate ecologically sensitive areas in greater breadth and depth, so more informed evidence on environmental impacts can be reached to understand whether current planning regulations in England have resulted in careful siting of solar farms from an ecological perspective.

We aim to fill some knowledge gaps regarding how solar farms are sited in relation to environmentally sensitive areas. Our methods are potentially transferable to other geographic areas and are of global relevance given the rapid development of solar farms worldwide. We quantify the density of solar farms in England and assess whether solar farms are strategically sited in ways that are not detrimental to biodiversity over a range of spatial scales. We tested the null hypothesis that solar farm developments are not being placed on sensitive areas within the ecological landscape. If the null hypothesis is upheld, we can conclude that solar farms have generally been sited in areas where impacts on biodiversity are limited. Sensitive siting would result in the areas covered by features that promote biodiversity (e.g. priority habitats, designated sites, and land conservation initiatives) being less extensive around solar farms compared with around random locations at

a range of spatial scales, and we tested if this was indeed the case.

2. Material and methods

2.1. Data source and refinement

The dataset used to map solar farm locations within the UK was downloaded in January 2024 (Department for Energy Security & Net Zero, 2024b) (Supplementary Table S1). This is a quarterly updated source of information incorporating all British renewable energy, produced by the UK Government. The data were refined to include only ground-based solar sites. Using a precautionary approach, we included sites labelled as: Ground (1972), Ground & Roof (6), Floating (3), and blank (14). Any data labelled only as Roof were removed. The data were further filtered to include all sites which were operational, under construction and proposed. Any sites with refused or withdrawn planning permission and those outside of England were removed given that different planning guidance may apply in devolved regions. This provided a final dataset of 1995 solar farm sites. The same number of random points was generated using the QGIS random point tool (QGIS Development Team, 2024) within England for direct comparison with the solar farm dataset allowing us to test if solar farms are found in proximity to larger areas of sensitive ecological features than around sites identified randomly.

2.2. Solar farm density

To better visualize where solar farms are located in England, we created a heatmap of solar sites using QGIS with the final 1995 sites. We applied the Kernel Density Estimation tool to the dataset to calculate the density of sites with a 50 km radius, thus creating a scaled heat map. A pixel size of 1000 was selected to provide a clear resolution at a country-wide scale.

2.3. Sensitive ecological features

Sensitive ecological feature types were mapped and included (i) the Land Cover Map 2021, (ii) the Priority Habitat Inventory, (iii) statutory and other designated sites (Ramsar sites, Sites of Special Scientific Interest (SSSI), Special Areas of Conservation (SAC) and Special Protection Areas (SPA) and Local Nature Reserves (NNR), National Parks (NP), National Landscapes (NL)) and (iv) land conservation initiatives (Nature Improvement Areas Countryside and Environmental Stewardship Schemes (CSS and ESS)) (see Supplementary Table S1 for data sources). Three buffer sizes (100 m, 1000 m, and 6000 m radii) were created around each solar farm and each random point. The buffer sizes were determined to account for both direct and indirect impacts of solar farms on biodiversity which may extend beyond the area they occupy (Niebuhr et al., 2022). The solar farm data point was used as the central grid reference of the solar farm. We provide below a description of each sensitive ecological feature analysed at the three spatial scales.

2.3.1. Land cover and priority habitats

The Land Cover Map was developed by Centre for Ecology and Hydrology (Morton et al., 2022) and is compiled from “satellite images and digital cartography and provides land cover information for the entire UK”. The map is based on the UK Biodiversity Action Plan’s Broad Habitats classifications. Priority Habitats are defined in the Biodiversity Action Plan to “cover a wide range of semi-natural habitat types, and were those that were identified as being the most threatened and requiring conservation action” (Joint Nature Conservation Committee, 2024). Understanding whether solar farms are installed in proximity to these habitats could help interpret the potential for a solar farm to have negative impacts on surrounding biodiversity and ecological processes. Given the large number of different habitat types included in the Land Cover Map and Priority Habitat database, it was necessary to group

these where possible for analysis (Supplementary Table S2). We therefore combined habitats considered to be similar, as guided by the Phase 1 Habitat groupings (Joint Nature Conservation Committee, 2016). The polygons from these datasets were clipped to the 100 m buffer to provide an indication of the ecological habitats within each solar farm established or proposed. The 1000 m and 6000 m buffers were also used to determine the habitats present in the wider landscape.

2.3.2. Designated sites

Designated sites are areas of land legally protected to safeguard their importance for nature conservation, geology, and/or public interest. There are a variety of types of designated sites in the UK which are of global, European, national, and local interest. We selected the following designated sites. At the global level, Ramsar sites are areas of wetland with particular importance as wildfowl habitat and are internationally listed under the Ramsar Convention, 1971; United Nations Educational Scientific and Cultural Organisation 1971). At the European level, Special Areas of Conservation (SAC) are protected under the Conservation of Habitats and Species Regulations (2017) as an area within the European Union that best represents the range and diversity of the habitats and species listed in the Habitats Directive (92/43/EEC). Special Protection Areas (SPA) are areas designated across Europe for the conservation of wild birds (under Directive 79/409/EEC). Nationally, Sites of Special Scientific Interest (SSSI) provide statutory protection for the best examples of the UK’s fauna and flora, as well as geological or physio-geographical features, and underpin other national and international nature conservation designations. National Parks are areas designated to ensure the enhancement and conservation of wildlife, natural beauty and cultural heritage. National Landscapes (previously named Areas of Outstanding Natural Beauty (AONB)) are areas outside National Parks which are preserved due to their natural beauty. At the local level, Local Nature Reserves (LNR) are a statutory designation and are protected for their wildlife (or geological) features which are of local special interest.

2.3.3. Land conservation initiatives

Nature Improvement Areas (NIA) are areas where partnerships are in place to enhance the natural environment, providing a joined-up approach to biodiversity and farming to improve ecosystem functions and services. Environmental Stewardship Schemes (ESS) and Countryside Stewardship Schemes (CSS) were also mapped. The CSS ended in 2020 and was superseded by ESS, though it was retained in our analyses given its former significance. ESS are agri-environment management schemes, of which one of the main objectives is to conserve biodiversity in farmland. The schemes are graded with the management measures increasing in benefit from Entry Level to Higher Level, and consider the quality of the habitat present within the management parcel that are favourably managed for biodiversity (e.g. field margins, hedgerow quality, intensification of farming practice). The extraction of the areas under land conservation initiatives provided an indication of how favourable the ecological conditions at the solar farm sites were likely to be, as well as those in the surrounding area.

2.4. Statistical analysis

Statistical analyses were conducted using R 4.3.2 (R Development Core Team, 2023). We compared the amount of each sensitive ecological feature between solar farms and random points at different spatial scales using a series of two-sample permutation tests with 999,999 Monte Carlo replications (function permTS, ‘perm’ package) (Fay and Shaw, 2010). We opted for the two-sample permutation test because it does not assume a specific distribution of the data, which was heterogeneous in our dataset, thus allowing to perform the comparisons in a single analytical framework. Due to the large number of tests performed (75 tests conducted), we applied a Bonferroni correction to the *p*-value to protect against inflation of type I errors. To estimate the mean

differences and associated 95% confidence intervals in the amounts of ecologically sensitive areas between solar and random points, we then performed bootstrap resampling with 999 iterations on the dataset.

3. Results

3.1. Solar farm density in England

The highest density of solar farms is in South West England with 572 of the 1995 sites (29%), predominantly in Devon, Cornwall and Somerset (133, 108, and 104, respectively) (Fig. 1, Supplementary Table S3). South East England holds the second highest number of sites, while the East of England has the third highest number (349 and 327, respectively).

3.2. Sensitive ecological features

Overall, the sensitive feature types found in significantly higher areas around solar farms were human manipulated low-level habitats (LCMGroup2) at all buffer distances, and developed habitat (LCMGroup6) at 100m and 6000m (not significant at 1000 m). Coastal habitats (PHGroup5) at 6000m were also identified as significantly higher around solar sites (Fig. 2). This suggests that solar farms are being sited in proximity to these habitat types, more so than if they were randomly placed.

Several sensitive features were also identified to not be significantly different around solar sites compared to control points. This included woodland (LCMGroup3 & PHGroup3) at 6000m, marine and coastal sensitivities (LCM Group 5 and Ramsar sites at 1000 m and 6000 m, PHGroup5 at 100 m and 1000 m), Natural exposures (LCMGroup 7 at all

buffer distances, and PHGroup6 at 100 m and 1000 m). Nature Reserves, Nature Improvement Areas and Countryside Stewardship Schemes were also not significantly different at all distances, as well as Environmental Stewardship schemes (Higher and Organic Entry Level plus Higher Level). These results show that solar sites are located within or near to these area as much as if randomly placed. All other sensitive features had significantly higher areas recorded around random points (Fig. 2). We explore the similarities and differences in more depth below.

3.2.1. Land cover and priority habitats

Of the land cover habitat groups within 100 m of solar sites, there is a significantly higher area of human-manipulated low-level habitats and developed areas compared with random points (Table 1). In fact, at all distances these are the only two LCM habitat groups which are found at a significantly higher area around solar farm sites compared to random points. These trends remained significant except for developed habitats at 1000 m where no significant difference occurred. All the other habitat types were significantly larger in area around random points at 100 m scale except for natural exposures. At 1000 m, there was on average more natural-low-level vegetation, woodland and wetland around random points compared with around solar farms. These differences remained except for woodland at 6000 m. Hence overall, human-manipulated and developed habitats were larger in area close to solar farms, while more natural and ecologically sensitive habitats were more extensive around random points.

Of the priority habitat groups (Table 2), all are found in higher areas at the random points compared to around solar farms, except for coastal habitats which were significantly higher in area around solar sites, but only at the 6000m buffer zone. No differences in priority woodland were apparent at 6000m, as found in the analysis reported for the similar

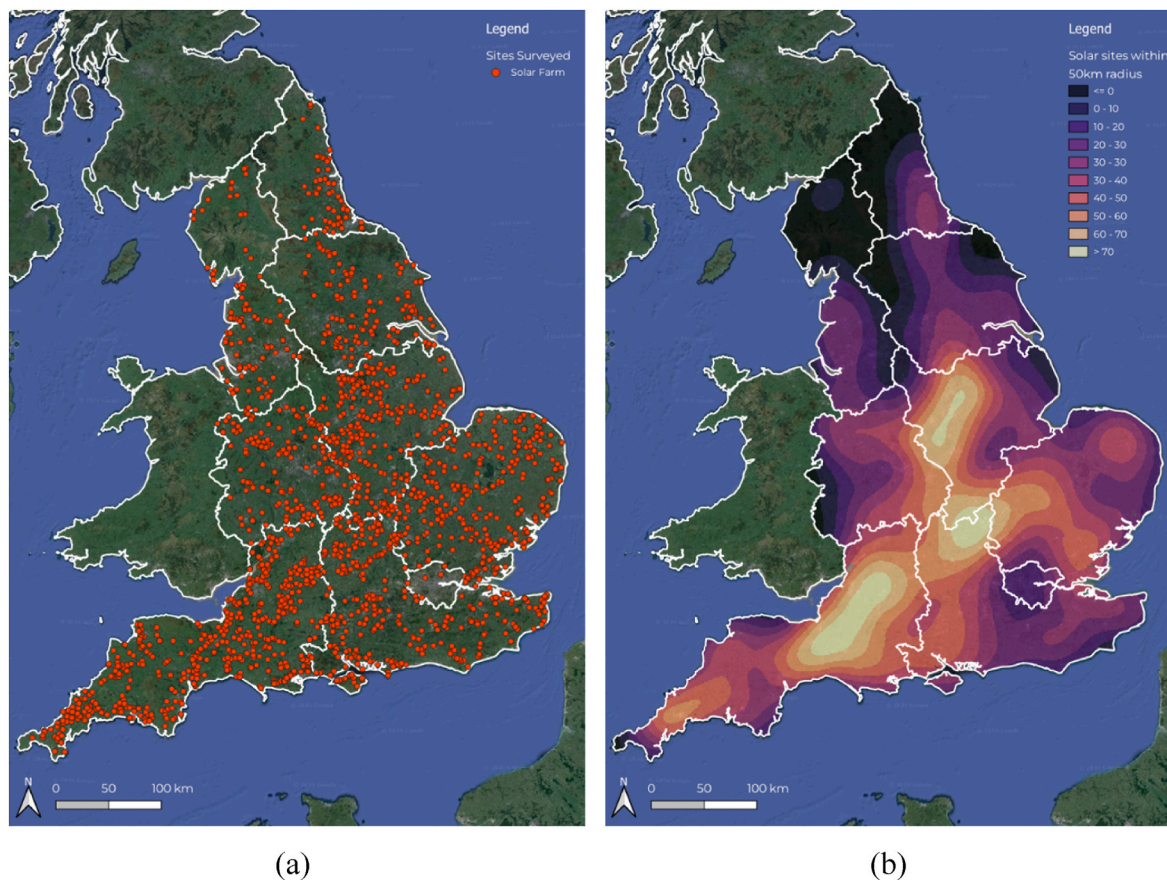


Fig. 1. (a) The distribution of the 1995 ground-mounted solar farms across recognised regions in England used for this study and (b) the density of the 1995 solar farms in England. Solar farms are distributed throughout much of England, with the highest density (572 sites) located in South West England.

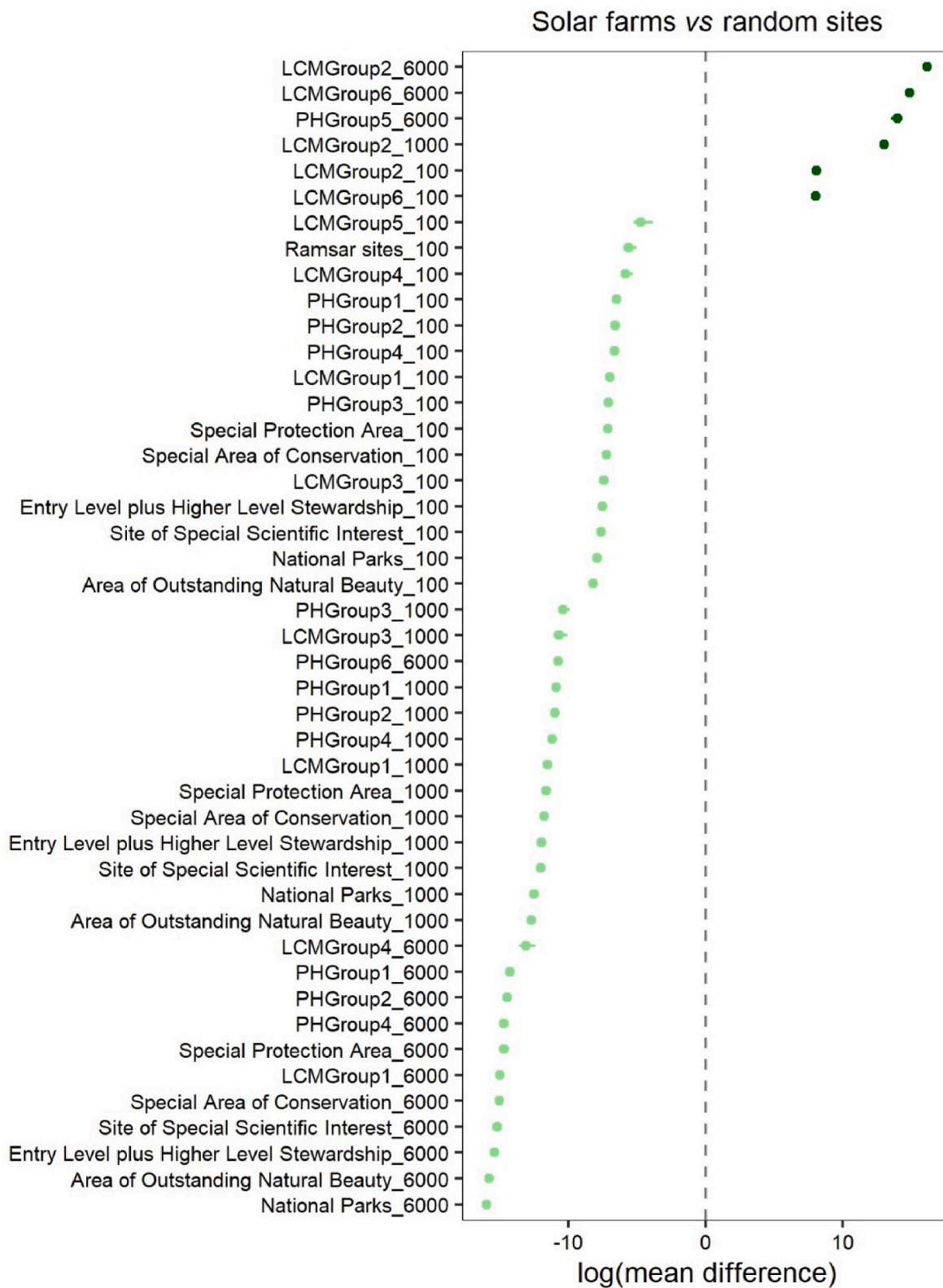


Fig. 2. Mean differences and associated 95% confidence intervals in sensitive areas amounts at different spatial scales between solar farms and random points obtained with the bootstrap resampling method (999 iterations). Data were log-transformed. Only the variables for which their areas are significantly greater or lower on solar farms compared to random points are shown. Negative values (light green points) indicate that the amounts of a given variable at a given scale are significantly lower in the vicinity of solar farms compared to random points. See Tables for definitions of acronyms. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1Mean area (m²) of Land Cover Map Habitats groups within a 100m, 1000m and 6000m buffer radius of solar farms and random points in England.

Land Cover Map habitat group	Buffer size (m)	Mean size (m ²) of sensitive area in proximity to solar farm ± SD	Mean size (m ²) of sensitive area in proximity to random point ± SD	p-value	Corrected p-value (75 tests)
LCMGroup1: Natural Low-level vegetation	100	426.346 ± 2982.334	1527.192 ± 6131.661	***	***
	1000	57,609.161 ± 217,883.390	158,125.709 ± 496,288.402	***	***
	6000	2,806,075.393 ± 6,592,164.542	6,116,175.358 ± 14,174,995.613	***	***
LCMGroup2: Human manipulated low-level habitats	100	21,326.003 ± 11,400.969	18,187.845 ± 13,554.609	***	***
	1000	2,273,644.400 ± 794,762.314	1,821,599.957 ± 1,094,779.181	***	***
	6000	74,956,314.388 ± 24,478,843.587	64,536,578.637 ± 34,217,478.661	***	***
LCMGroup3: Woodland	100	1069.541 ± 3531.439	2723.305 ± 6937.064	***	***
	1000	215,100.580 ± 260,953.411	259,179.649 ± 371,961.392	***	*
	6000	9,175,921.587 ± 7,110,377.023	9,050,726.269 ± 8,190,672.926	.	NS
LCMGroup4: Wetland	100	133.245 ± 1334.630	485.147 ± 3344.698	***	***
	1000	28,196.743 ± 98,592.324	47,391.043 ± 240,248.489	***	.
	6000	1,225,496.634 ± 2,337,909.962	1,726,790.788 ± 5,944,371.756	***	***
LCMGroup5: Marine	100	4.946 ± 210.534	120.680 ± 1689.827	***	***
	1000	12,122.480 ± 88,301.188	19,093.192 ± 148,637.403	*	NS
	6000	1,580,348.474 ± 5,293,509.010	1,118,226.971 ± 5,054,435.253	**	NS
LCMGroup6: Developed	100	6466.513 ± 9594.952	3450.908 ± 8390.384	***	***
	1000	354,493.265 ± 490,416.278	335,722.680 ± 588,476.321	NS	NS
	6000	14,306,535.296 ± 12,165,922.454	11,390,414.085 ± 14,104,397.735	***	***
LCMGroup7: Natural Exposures	100	79.702 ± 1430.139	45.207 ± 929.216	NS	NS
	1000	7003.497 ± 75,185.881	5644.230 ± 59,690.689	NS	NS
	6000	285,609.678 ± 1,651,788.511	196,013.307 ± 1,121,572.194	.	NS

Group1: Acid grassland, Calcareous grassland, Neutral grassland, Heather grassland, Heather. **Group 2:** Improved grassland, Arable and horticulture. **Group 3:** Deciduous woodland (broadleaved mixed and yew woodland), Coniferous woodland. **Group 4:** Fen, marsh and swamp, Freshwater (standing open water and canals/ rivers and streams), Bog. **Group 5:** Littoral sediment, Saltmarsh, Saltwater, Supralittoral sediment. **Group 6:** Urban, Suburban. **Group 7:** Inland rock, Supralittoral rock, Littoral rock.

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, · $p < 0.10$, NS: $p \geq 0.10$.

Table 2Mean area (m²) of Priority Habitats groups within a 100m, 1000m and 6000m buffer radius of solar farms and random points in England.

Priority habitat group	Buffer size (m)	Mean size (m ²) of sensitive area in proximity to solar farm ± SD	Mean size (m ²) of sensitive area in proximity to random point ± SD	p-value	Corrected p-value (75 tests)
PHGroup1: Grassland habitats	100	63.807 ± 977.186	725.07 ± 3886.98	***	***
	1000	23,587.161 ± 86,926.611	78,360.083 ± 254,100.892	***	***
	6000	1,304,251.991 ± 2,269,728.773	2,899,745.075 ± 6,051,164.247	***	***
PHGroup2: Heathland	100	14.208 ± 406.477	755.827 ± 4346.88	***	***
	1000	8261.038 ± 68,399.982	69,876.275 ± 317,487.276	***	***
	6000	509,701.554 ± 1,923,780.959	2,444,734.703 ± 7,146,450.009	***	***
PHGroup3: Woodland	100	806.282 ± 2637.425	1982.68 ± 5423.770	***	***
	1000	150,105.054 ± 170,075.207	184,013.801 ± 235,202.713	***	***
	6000	6,231,615.409 ± 3,934,174.485	6,503,412.249 ± 4,956,164.437	.	NS
PHGroup4: Wetland	100	2.216 ± 66.295	784.109 ± 4535.475	***	***
	1000	4111.392 ± 41,633.862	78,036.369 ± 383,573.533	***	***
	6000	325,699.04 ± 1,623,697.936	2,789,268.7 ± 10,094,615.516	***	***
PHGroup5: Coastal	100	525.061 ± 3293.349	504.617 ± 3318.006	NS	NS
	1000	86,395.601 ± 323,192.645	61,078.423 ± 246,541.060	**	NS
	6000	3,490,565.104 ± 7,723,895.835	2,333,163.807 ± 6,176,942.892	***	***
PHGroup6: Natural Exposures	100	1.451 ± 64.813	17.910 ± 491.577	NS	NS
	1000	739.431 ± 12,004.575	1024.970 ± 13,720.949	NS	NS
	6000	739.431 ± 12,004.575	46,899.355 ± 230,103.545	***	***

PHGroup1: Calaminarian grassland, Good quality semi-improved grassland, Lowland calcareous grassland, Lowland dry acid grassland, Lowland meadows, Grass moorland, Purple moor grass and rush pastures, Upland calcareous grassland, Upland hay meadows. **PHGroup2:** Fragmented heath, Lowland heathland, Upland heathland, Mountain heath & willow scrub. **PHGroup3:** Deciduous woodland, Traditional orchard. **PHGroup4:** Blanket bog, Lowland fens, Lowland raised bog, Reedbeds, Upland flushes, fens & swamps. **PHGroup5:** Coastal and floodplain grazing marsh, Coastal saltmarsh, Coastal sand dunes, Coastal vegetated shingle, Mudflats, Saline lagoons. **PHGroup6:** Maritime cliff and slope, Limestone pavements.

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, · $p < 0.10$, NS: $p \geq 0.10$.

habitat group in Table 1. Of note, the woodland analysis for priority habitat groups reported in Table 2 comprised deciduous woodland and traditional orchards and not coniferous woodland which is typically planted. The findings suggest that in general, priority habitats are more extensive around random points compared with around solar farms.

Not all land cover and priority habitats were found around solar sites (Supplementary Tables S4 and S5). At 100 m, land cover habitats including bog, saltwater, supralittoral rock, supralittoral sediment, and littoral rock were not found around solar sites. Of the priority habitats calaminarian grassland (grassland rich in heavy metals), purple moor grass and rush pastures, upland calcareous grassland, upland hay

meadows, fragmented heath, upland heathland, mountain heath & willow scrub, blanket bog, lowland raised bog, reedbeds, upland flushes, fens and swamps, coastal saltmarsh, coastal sand dunes, coastal vegetated shingle, saline lagoons and limestone pavements were never recorded at 100 m around solar sites, with fragmented heath, mountain heath and willow scrub, and limestone pavements also not found at 1000 m, and only mountain heath and willow scrub not found at 6000 m. All land cover and priority habitats were identified around random points, with the exception of limestone pavements and mountain heath and willow scrub at 100 m.

3.2.2. Designated sites

All designated sites were found in a higher area around the random points, compared to the solar sites (Table 3). This difference was not significant for Ramsar sites at 1000 m and 6000 m, and also for Local Nature Reserves at all buffer distances. This suggests that solar sites are as likely to be placed close to Ramsar sites and Local Nature Reserve sites if randomly placed. Otherwise, the results are consistent with solar farms not being placed in areas that contain large areas of designated habitats.

3.2.3. Land conservation initiatives

Regarding the partnership schemes assessed (Table 4) there was no significant difference at any buffer size when assessing Nature Improvement Areas, suggesting that solar farms are as likely to be located within these areas as if they were randomly placed. Countryside Stewardship Schemes were always found at a higher average area around random points compared to solar sites; however, this was not found to be significant once the *p*-values had been corrected for multiple comparisons. Similarly, the Environmental Stewardship Schemes were consistently found in a higher mean area around random point. There was a significant difference at 100 m, 1000 m, and 6000 m for Entry Level plus Higher Level schemes, with the areas always being higher at random points. Higher Level and Organic Entry Level plus Higher Level was not found to differ significantly at any buffer distance, suggesting that solar farms are as likely to be placed within or near these areas if they were sited randomly. The results suggest that solar farms are often not placed close to areas where some important Environmental Stewardship Schemes are implemented.

4. Discussion

Overall, our findings contribute to the ongoing dialogue on reconciling sustainable energy development with biodiversity conservation, in line with global efforts towards the Sustainable Development Goals (SDGs) (Işık et al., 2024). Careful planning procedures that account for the protection of key wildlife habitats and which have little impact on protected areas are vital if green-green dilemmas are to result in win-wins scenarios whereby sustainable energy output is increased while biodiversity loss is minimised. Although the planning process in England appears to result in solar farms being placed sensitively in an ecological context, it is important to realise that the impacts are non-zero (e.g. some protected areas and key habitats are in close

proximity to solar farms). Moreover, the findings may not be applicable globally: five percent (146) of photovoltaic facilities overlapped with protected areas and seven percent (201) with Key Biodiversity Areas in a global review, with major concerns for current and protected developments in South and Southeast Asia, areas of high biodiversity value (Rehbein et al., 2020). Minimising the siting of solar installations in protected areas is of global significance.

Our work is novel in that it considers the effects of scale on the extent of sensitive features around solar farms. Although most features showed similar effects across the scales studied, there were some scale-dependent effects for example with some key woodland habitats being similar in extent to values around random points at the largest scale studied (6000m). This highlights the importance of studying scale-dependent effects on any adverse effects that solar farms may have on biodiversity, and whether the effects are limited to the farm, or are transferable at larger scales beyond the farm boundaries. Following these general points, we now discuss the findings at the national scale.

4.1. Distribution of solar farms in England

The three counties with the most solar sites installed were all in South West England. This aligns with plans for the ‘Great South West’ to be a clean energy powerhouse for the UK, with ambitions to provide up to 11% of the UK’s 2035 low carbon electricity capacity, with solar sites already contributing 1.2 GW capacity (Great South West, 2023). Palmer et al. (2019) assumed that solar farms should receive at least 1050 kWh/m²/year with their analysis showing the highest numbers of solar farms in the south of England, closely matching the predicted relatively high solar resources in this region. Rankl (2024) showed that about 28% of all solar farms in the UK were in South West England, consistent with the findings reported here. However, many large scale (>50 MW) solar farms are now planned to be sited farther north, especially in the Midlands (Rankl, 2024).

4.2. Habitat types found within and around solar farms

Overall, our findings suggest that solar sites are being placed sensitively in relation to particularly sensitive ecological habitats, and that there is a steer to place solar farms on those habitats already impacted anthropogenically for farming and development. Generating solar energy at solar farms on low grade land, or from panels placed on buildings may have minimal impacts for biodiversity, but such sites may be in

Table 3
Mean areas (m²) of Designated Sites within a 100m, 1000m and 6000m buffer radius of solar farms and random points in England.

Designated Site	Buffer size (m)	Mean size (m ²) of sensitive area in proximity to solar farm ± SD	Mean size (m ²) of sensitive area in proximity to random point ± SD	<i>p</i> -value	Corrected <i>p</i> -value (75 tests)
Area of Outstanding Natural Beauty (National Landscapes)	100	1007.619 ± 5399.418	4719.516 ± 11,058.206	***	***
	1000	125,273.807 ± 534,311.823	465,332.221 ± 1,053,989.267	***	***
	6000	8,608,110.197 ± 18,899,447.463	16,017,916.270 ± 31,122,108.385	***	***
Ramsar sites	100	5.989 ± 234.242	281.249 ± 2719.007	***	***
	1000	15,520.315 ± 104,148.762	32,218.364 ± 228,876.159	**	NS
	6000	1,857,851.021 ± 5,575,122.782	1,700,105.090 ± 6,879,054.343	NS	NS
Site of Special Scientific Interest (SSSI)	100	55.881 ± 957.029	2160.064 ± 7493.757	***	***
	1000	47,677.067 ± 164,077.679	216,415.201 ± 616,621.918	***	***
	6000	4,209,543.160 ± 6,897,606.634	8,170,530.603 ± 15,299,155.052	***	***
Special Area of Conservation (SAC)	100	2.314 ± 60.599	1382.192 ± 6124.746	***	***
	1000	17,157.148 ± 109,723.234	146,508.611 ± 545,059.073	***	***
	6000	2,481,750.921 ± 6,650,454.738	59,06,871.858 ± 14,542,643.553	***	***
Special Protection Area (SPA)	100	6.136 ± 234.312	1286.975 ± 5990.614	***	***
	1000	23,429.641 ± 137,462.315	137,652.121 ± 543,036.116	***	***
	6000	3,417,438.530 ± 9,243,085.589	5,915,153.436 ± 15,296,255.228	***	***
Local Nature Reserves	100	27.329 ± 594.463	140.013 ± 1751.713	**	NS
	1000	98,56.547 ± 56,526.335	12,608.760 ± 81,437.880	NS	NS
	6000	377,462.575 ± 737,161.937	324,014.687 ± 767,089.114	*	NS
National Parks	100	96.080 ± 1577.789	2856.633 ± 8931.182	***	***
	1000	13,972.670 ± 152,137.341	286,361.715 ± 870,791.403	***	***
	6000	1,810,179.43 ± 8,059,452.423	10,506,436.174 ± 28,208,675.696	***	***

****p* < 0.001, ***p* < 0.01, **p* < 0.05, · *p* < 0.10, NS: *p* ≥ 0.10

Table 4

Mean areas (m²) of Partnership/Stewardship Schemes within a 100m, 1000m and 6000m buffer radius of solar farms and random points in England.

Partnership/Stewardship Scheme	Buffer size (m)	Mean size (m ²) of sensitive area in proximity to solar farm ± SD	Mean size (m ²) of sensitive area in proximity to random point ± SD	p-value	Corrected p-value (75 tests)
Nature Improvement Areas	100	1103.946 ± 5666.608	1148.885 ± 5752.289	NS	NS
	1000	111,895.530 ± 537,135.245	115,452.929 ± 533,342.213	NS	NS
	6000	4,054,350.495 ± 15,781,309.72	4,069,243.919 ± 15,224,028.114	NS	NS
Countryside Stewardship Schemes (CSS)	100	291.682 ± 2731.089	244.22 ± 2409.768	NS	NS
	1000	28,255.883 ± 139,061.803	31,885.398 ± 166,614.301	NS	NS
	6000	1,012,958.240 ± 1,503,043.014	1,181,757.943 ± 2,115,684.401	**	NS
Environmental Stewardship Scheme (ESS)					
Entry Level plus Higher Level	100	1070.244 ± 4925.112	2927.213 ± 8368.448	***	***
Higher Level	100	20.634 ± 613.017	154.93 ± 2005.086	**	NS
Organic Entry Level plus Higher Level	100	49.176 ± 1131.015	126.521 ± 1889.273	NS	NS
Entry Level plus Higher Level	1000	138,977.308 ± 361,979.758	301,608.409 ± 626,245.998	***	***
Higher Level	1000	9744.527 ± 59,738.598	12,729.482 ± 119,664.906	NS	NS
Organic Entry Level plus Higher Level	1000	5436.010 ± 57,955.36	9264.682 ± 93,951.634	NS	NS
Entry Level plus Higher Level	6000	5,790,398.506 ± 5,819,502.458	10,584,856.977 ± 13,753,816.436	***	***
Higher Level	6000	447,724.877 ± 1,125,393.651	527,612.887 ± 2,577,996.703	NS	NS
Organic Entry Level plus Higher Level	6000	322,004.686 ± 1,099,868.965	391,398.914 ± 1,354,784.900	.	NS

****p* < 0.001, ***p* < 0.01, **p* < 0.05, · *p* < 0.10, NS: *p* ≥ 0.10.

short supply (Tölgyesi et al., 2023) or targeted for housing development.

Solar farms in England are more commonly located in areas already influenced by anthropogenic activities, such as urban and agricultural settings. Whilst it is encouraging that solar sites are tending to avoid habitats which are more ecologically sensitive, it should be noted that the mean area of human manipulated low level habitats (improved grassland, arable and horticulture) was 230% higher than the developed habitats (urban and suburban). This suggests that there is a high burden on the agricultural landscape. PV generating capacity grew by 41% between 2009 and 2018, with most solar farms sited on cropland, arid lands and grassland globally, with siting on agricultural land dominant in Europe (Kruitwagen et al., 2021).

The ecological importance of the habitat types which comprise the human manipulated low level habitats category should not be underestimated. Where appropriate land practices are in place agricultural land can classify under Annex I habitat types (a defining feature of SAC designations under the Habitats Directive), particularly where low intensity grazing and mowing are applied (Halada et al., 2011). Further, in the UK some bird species show increased abundance in arable habitats (Robinson et al., 2001). In Italy farmland meadow habitats have been highlighted for improving biodiversity in agricultural landscapes (De Simone et al., 2017), and in Canada farmland mosaic habitats are important for conserving native plant species (Freemark et al., 2002). As such, the implications of installing solar sites in the agricultural landscape for biodiversity should not be underestimated. The ecological improvement of existing and planned sites (e.g. attracting pollinators) through the concept of ecovoltinism is also important (Gómez-Catasús et al., 2024; Tölgyesi et al., 2023).

Coastal priority habitats were found in a significantly higher area and LCM marine habitats had no significant difference and at 6000m around solar farms. This is probably because most sites are in South West England where the larger buffer sizes include coastline (Fig. 1). While there is unlikely to be any direct impact on marine life from onshore solar sites, the indirect impacts on marine sea birds for example should be considered. Marine seabirds perch on off-shore solar farms, as do seals (Vlaswinkel et al., 2023) but risk disorientation. Collision of migratory species and water birds when solar sites are placed on land close to the coast requires further investigation (Grippio et al., 2015).

At the 6000 m buffer scale priority woodland habitat occupied similar areas around solar sites and random points. The potential impacts on priority woodland might therefore need further consideration at a landscape scale. Woodland habitat is known to be important for bats (Bouhey et al., 2011; Fuentes-Montemayor et al., 2013; Walsh and

Harris, 1996), as well as other species and ecological processes, particularly in an agricultural setting.

4.3. Proximity of solar farms to designated sites

Significantly higher areas of designated site types around random points compared with solar sites data at 100 m (except for Local Nature Reserves), suggests that solar sites are being placed to avoid designated areas, aligning with the National Planning Policy Framework which dissuades causing harm to designated sites which are important for biodiversity (Department for Levelling Up et al., 2023). This finding is consistent across spatial scales, except for Ramsar sites, where no differences occurred in comparisons at 1000 m and 6000 m.

Finding no significant difference between the area of Local Nature Reserves surrounding solar sites and random points at any buffer distance suggests that solar farms are as likely to be placed in these sites as if randomly allocated. This calls into question whether local biodiversity is being valued as highly locally as at internationally designated sites.

We conclude that solar sites are being placed sensitively to designated sites compared to the random points, but solar farms are occasionally placed within designated sites (areas recorded at 100 m), and the implications for transient wildlife at 1000 m and 6000 m need to be understood. Gray et al. (2016) identified that while there is an importance of designated site protection global biodiversity, these areas do not “consistently benefit species with small ranges or increase the variety of ecological niches”. It may be that because local authorities both own Local Nature Reserves and house the planning departments which approve the applications for solar farms, there is a potential conflict of interest which requires addressing to ensure biodiversity at a local level is maintained.

There is an ongoing debate about whether protected areas reduce threats to biodiversity, and standardised review protocols (Pulido-Chadid et al., 2023) and methods of data collection (Lisón et al., 2017) are needed. Nevertheless, protected areas reduce rates of biodiversity loss compared with unprotected areas, though benefits are highest where socio-economic conditions are favourable for wildlife conservation (Geldmann et al., 2013). The effectiveness of Protected Areas (SSSIs, SACs, SPAs, Ramsar Sites, National Nature Reserves and LNRs) in Britain for the conservation of pollinators and predators was assessed by Cooke et al. (2023). They found that although protected areas had 155 more species on average than unprotected areas, declines in occupancy of around 27% were found in both protected and unprotected areas. Hence, although protected areas can show higher levels of

species occupancy, action is necessary to mitigate rates of biodiversity loss in them (Cooke et al., 2023).

4.4. Integration of solar farms into environmental stewardship

Our results indicate that solar farms are not being incorporated into Nature Improvement Areas and Countryside Stewardship Schemes any more than if randomly placed. The same is true for Environmental Stewardship schemes, and at all buffers sizes there is one scheme type (Entry Level plus Higher Level) significantly smaller around solar farms than around the random points. Landowners inclined to set up land conservation initiatives might favour also incorporating a renewable energy source, such as solar farms, particularly due to the additional grants and subsidies available such as environmental credits for carbon sequestration and biodiversity improvements (Nordberg et al., 2021). However, in the UK, land owners and businesses are being steered financially toward rooftop solar panning (Rural Payments Agency, 2024).

Environmental Stewardship Schemes can have important benefits for wildlife. Targeted agri-environmental schemes promote farmland biodiversity including insect pollinators (Image et al., 2022; Wood et al., 2015) and birds (Bright et al., 2015). Specifically, hedgerow trimming is discouraged under some ESSs such as High-Level Stewardship, and untrimmed hedgerows can increase bat activity and species richness (Froidevaux et al., 2019a) as well as increasing the abundance of moths (Froidevaux et al., 2019b). Non-target species may also benefit from agri-environmental schemes designed for the conservation of circl buntings (*Emberiza circlus* L.) (MacDonald et al., 2012a) corncrake (*Crex crex*) (Wilkinson et al., 2012), and stone curlew (*Burhinus oedipnemus*) (MacDonald et al., 2012b).

4.5. Implications for conservation

Although we highlight a general trend for the sensitive siting of solar farms in the UK, there is further work necessary to limit the potential negative impacts of these developments on biodiversity, both at a local level, and with regard to transient species.

A renewable energy planning strategy based on a site-by-site basis may not be fit to manage the potential wider impacts on biodiversity, and a co-ordinated approach to account for conflicts between renewables and biodiversity over larger spatial scales should be applied (Carvalho et al., 2024; Gorman et al., 2023; Köppel et al., 2014; Rehbein et al., 2020). This co-ordination is particularly relevant as governments accelerate both their climate and biodiversity action strategies simultaneously. Gorman et al. (2023) proposed applying a “Right Action, Right Place” framework, particularly for solar sites, to limit their development to only the built environment in Ireland. Once these broader strategies provide the first step in the mitigation hierarchy, i.e. to avoid sensitive areas, a focus on individual site impacts can take place.

Once ‘no-go zones’ have been established, the further stages of the mitigation hierarchy can be applied to a site-based applications. A key way to manage impact is through site design to reduce the area of a site impacted, for example by applying innovative artificial intelligence (AI), the Internet of Things (IoT) and tracking technology to make panels more efficient (Mohammad and Mahjabeen, 2023; Patel et al., 2021; Shapsough et al., 2021). Further to this, restoring the biodiversity at solar farms should be incorporated into the operational design (Blaydes et al., 2022; Nordberg et al., 2021; Randle-Boggis et al., 2020). This should also be considered at decommissioning; however, there is a proposal in the UK to facilitate repowering of solar farms at the end of life, so the complete restoration of sites for biodiversity may be challenging (Rankl, 2024).

Finally, compensation and offsetting of impacts may become important. The Environment Act being passed in the UK legally enforces the application for Biodiversity Net Gain assessments with a focus on

improving habitat biodiversity (Department for Environment Food & Rural Affairs, 2024). Other offsetting ideas are also being developed around a land tax in Finland, to manage the green-green dilemma between biodiversity at wind farms, based on the quantity and quality of habitat displaced (Rinne, 2022). These methods can be deployed at solar sites, to enhance the areas of developed and human-manipulated low-level habitats, into Priority Habitat types, through sensitive farming techniques, such as grazing and mowing.

Looking ahead, ‘adaptive planning’ with regard to renewable expansion should be applied (Kato and Ahern, 2008). At present, renewable development must progress with a series of unknowns with regard to biodiversity impacts. As such there is a requirement for stringent monitoring to ensure the correct decisions continue to be made despite the current limited conclusions on the best biodiversity mitigation at solar farms (Kato and Ahern, 2008; Köppel et al., 2014). In the UK, guidance exists regarding standardised monitoring of a variety of aspects of biodiversity at solar farms, including categorising site management and Biodiversity Net Gain assessments, as well as species-specific assessments (Solar Energy UK, 2022). For adaptive planning to work, there is a key element of stakeholders, professionals and researchers combining their functions to support the decision-making process (Kato and Ahern, 2008; Mulvaney, 2014; Straka et al., 2020). Future uncertainties such as changes in climate and economic policy, the risk of pandemic and conflict need to be considered also.

In conclusion, we found that solar farms are generally being sited in England in ways that are sympathetic to the conservation of important habitats and protected areas at a range of spatial scales, suggesting that current planning regulations are being adhered to and are effective. Although the siting of solar farms may often be appropriate, it is crucial to assess their potential impact on biodiversity through long-term on-site monitoring.

CRediT authorship contribution statement

Elizabeth Tinsley: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Jérémy S.P. Froidevaux:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Gareth Jones:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

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Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2024.123372>.

Data availability

The data are available on Zenodo (<https://doi.org/10.5281/zenodo.14067796>).

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