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Opportunities to enhance pollinator biodiversity in solar parks

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ABSTRACT

Renewable power capacity is increasing globally in response to energy decarbonisation, with solar photovoltaic (PV) projected to be the dominant renewable. A significant proportion of solar PV is deployed as ground-mounted solar parks with potential implications for the hosting ecosystem. Given their relatively rapid introduction, the impacts on land use and the local environment are poorly understood. However, if deployed and managed strategically, solar parks could offer unique opportunities to enhance the local environment and benefit biodiversity, with implications for ecosystem components such as pollinators. With a focus on north-west Europe, we systematically review the available evidence on how land management practices relevant to solar parks can enhance pollinator biodiversity. We assessed 185 articles for the quantity and agreement of evidence for 27 management interventions and assigned a confidence score to each finding. We show that a range of interventions applied to solar parks could increase their ability to enhance pollinator biodiversity. We then use our assessment to synthesise ten evidence-based recommendations on how to improve solar park management for pollinators by providing foraging and reproductive resources, undergoing considered management practices, increasing landscape heterogeneity and connectivity and providing microclimatic variation. Ensuring beneficial management of rapidly growing solar parks contributes to their wider environmental sustainability, with positive implications for both pollinator conservation and the energy sector in general.

1. Introduction

Renewable energy sources have the potential to mitigate climate change through reducing greenhouse gas emissions from fossil fuel combustion [1], but relatively little is known of the implications of the required land use change. Renewable power capacity is on the rise and predicted to expand by 50% between 2019 and 2024 [2]. Solar photovoltaic (PV) makes up almost 60% of expected growth and is projected to lead the way in the transformation of the energy sector [2,3]. Much of the solar PV capacity is deployed as ground-mounted solar parks (arrays of solar PV modules mounted on metal supports) which in 2018 made up ~70% of newly installed PV capacity globally [4]. With a total capacity of 7, 550 MW and between 1.6 and 2 ha required to generate 1 MW, solar parks occupy ~13, 749 ha in the UK and there will be increased land take for solar park infrastructure as the contribution of solar PV to electricity generation rises [5]. Solar parks have been deployed across a number of European countries, including Germany, since 2005 and began to expand in the UK in 2011, becoming increasingly common features of the landscape [6]. Despite this, the impacts on land use and the local environment are relatively unknown.

If implications for the local environment are not considered alongside solar park expansion, solar park development risks trading off climate change mitigation and local ecosystem degradation [7]. Understanding of a range of impacts of solar parks on the local environment is emerging, including changes to microclimate (air temperature, precipitation and evapotranspiration), soils (carbon cycling, soil microbial community composition and soil moisture) and vegetation (plant productivity and above ground biomass), of which the effects on biodiversity are poorly resolved [8–10]. As land use change commonly leads to habitat loss, the principal threat to biodiversity [11], increasing land take for solar parks may directly negatively affect some species through altering or degrading habitat [12]. Furthermore, habitat loss or alteration may limit species' ability to adapt to changing conditions through creating dispersal barriers to other areas of suitable habitat [12]. The limited existing evidence indicates that biodiversity has been positively and negatively affected by solar parks and associated land use change [10,13]. For example, in sensitive habitats, solar park deployment has degraded habitat through fragmentation and pollution and also led to

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the direct mortality of wildlife [14]. Moreover, solar parks under development are increasingly overlapping with conservation or protected areas acting as refuges for biodiversity [15]. However, in agricultural landscapes, which are often intensively managed and species-poor, there is potential for benefits [16]. Consequently, if deployed and managed strategically, solar parks can have minimal detrimental environmental impacts compared to other developments and may provide opportunities to enhance ecosystem function, with implications for ecosystem services such as pollination and crop production [17,18].

Pollination is a critical ecosystem service which could be impacted by land use change for solar parks [17,18]. Pollinators comprise a diverse group of animals, although a large proportion are insects with bees, both wild and managed, especially important [19]. Pollinators perform a number of services beneficial to human society, including sustaining wild plant populations, maintaining biodiversity and ecosystem stability and contributing to food security, among other functions [20]. For example, pollinators improve the production of 75% of global food crops [21]. Without pollination services, 5–8% of global crop production would be lost, valued at between $235 billion and $577 billion in 2015 [19]. However, there is growing concern over pollinator decline and widespread losses have been documented across Europe and the UK, with consequences for crop and wild plant pollination [22–24]. Using solar parks to improve pollinator populations could therefore deliver significant benefits, especially as many solar parks are situated within agricultural landscapes, and potentially contribute towards the mitigation of pollinator decline.

Much of the pollinator decline was caused by large scale habitat loss in response to the intensification of industrial scale agriculture, especially during the first half of the 20th century [25]. In addition, a range of drivers, many of which are associated with intensive agricultural practice, also contribute and include the reduction of foraging, nesting, shelter and reproductive resources when natural habitat is lost and the chronic and acute exposure to agrochemicals with a range of consequences [20,26,27]. Insecticides may pose the greatest risk to pollinators through direct mortality and a range of sub-lethal effects [28], whereas fertilisers and herbicides affect pollinator indirectly through changes to the non-cultivated flowering plant community and the foraging and reproductive resources they provide [29]. These agricultural-linked drivers act at both the local and landscape scale [30], but climate change is posing growing challenges for pollinators at the global scale [31] and pathogens, alien species and environmental pollution also pose threats [19]. In many locations, several of these drivers interact, posing perhaps the greatest threat to pollinators [19].

Solar parks offer considerable potential to mitigate the causes of decline in pollinator populations but there is currently limited scientific understanding, especially in light of the projected growth of solar [2,3]. Many of the measures identified to promote pollinator conservation and recovery, including reversing trends in agricultural intensification, maintaining natural habitat within the landscape matrix and creating or retaining microhabitats important for insects during climatic events [19,32] could be employed at solar parks. Creating suitable habitat on solar parks, which are commonly located amongst intensively managed agricultural land, could offer refuges for pollinators in landscapes where much habitat has been lost, whilst also increasing landscape heterogeneity and connectivity. Furthermore, considering pollinators and biodiversity may help to ensure the wider environmental sustainability of such facilities and help meet planning policy criteria, statutory requirements and environmental policy targets, for example, those stated by the UK National Policy Planning Framework [33], the 25 Year Environment Plan for the UK [34] and the global Sustainable Development Goals [35]. Consequently, this paper aims to review the evidence that solar parks can enhance pollinator biodiversity. This is achieved by systematically searching and screening the literature for articles documenting impacts of interventions on pollinator populations and extracting evidence from relevant literature. Findings are then synthesised in light of solar park conditions to produce ten evidence-based management recommendations.

2. Methods

A quick scoping review (QSR) based on guidelines by Collins et al. [36] was undertaken to provide a rapid, cost-effective assessment of peer-reviewed scientific literature to answer the primary question “what are the opportunities for solar parks to enhance pollinator biodiversity?”. The key steps were: protocol development, literature search, results screening and evidence extraction and are detailed below. Moreover, subsequent statistical analysis of the balance of the evidence and the assignment of confidence levels to the evidence, which are not part of the Collins et al. [36] protocol, are described.

2.1. Protocol development

Developing a protocol separates QSRs from less structured reviews, in that the methodology is clearly predetermined [36]. The first part of protocol development is establishing the scope of the primary question to provide clear limits. In this case, the geographic scope was restricted to north-west Europe. In terms of pollinator groups, the scope was limited to bees, butterflies and hoverflies. Bees are considered the most important contributors to global pollination, visiting more than 90% of the leading crop types [21] and included bumblebees, other wild bee species and managed honeybees (*Apis mellifera*). Hoverflies were included as they are one of the key pollinators after bees, valuable in both agricultural and natural systems [37]. Although playing a comparatively minor role in crop pollination in temperate regions, butterflies were also included as they are generally well studied, are an iconic component of biodiversity, and have been used as indicators of change for many insect groups for which data are lacking [38,39]. Whilst other insects, including other flies, beetles, moths, wasps and ants also contribute to pollination, they are less effective in Europe and were therefore excluded [40].

The second step in protocol development involved identifying the Population, Intervention, Control and Outcome (PICO) elements in the primary question. The Population is the subject of study and defined here as solar parks. However, as there is limited existing scientific evidence from solar parks, the Population included habitats that solar parks are managed as or the land use they replaced, such as grassland, meadow, agricultural or arable land (Table 1). The Interventions, or the factors to consider regarding the potential of solar parks to support pollinator populations, included management actions, the impact of solar park infrastructure and landscape connectivity (Table 1). The Comparator, or the control with no intervention, referred to areas or habitats without the interventions that impact pollinators and in this case they were the same as the Population (Table 1). Lastly, the Outcome was defined as the impact of the Interventions, referring to pollinator population response, for example, a change in abundance or diversity (Table 1).

The PICO elements were used to develop a search strategy using three search strings created based on Population and Control, Intervention and Outcome keywords. Keywords were generated through identifying popular relevant words and phrases found in published literature and through expert insight from both researchers and industry. Key words were then combined with Boolean and wildcard operators to form search strings (Table 1).

2.2. Literature search and results screening

Search strings were combined and an advanced search was undertaken in the Web of Science core collection, to provide a robust peer-reviewed body of results. All articles published 1945–2019 were considered if they were in English. Results from the search were downloaded on November 14, 2019 and were screened to reduce the

Table 1
Search strings based on keywords relating to PICO elements derived from the primary question, "what are the opportunities for solar parks to enhance pollinator biodiversity?", used in the QSR. Boolean operators were used to combine keywords, where AND ensured results contain all keywords and OR ensured each result contained at least one of the listed keywords. The asterisks wildcard operator specified zero or more of any alphanumeric character, as in pollinat* located pollinator, pollinators or pollinate. Keywords enclosed within double quote characters returned only results that contain the phrase as was typed. Each string began with TS to ensure the title, abstract and keywords of each result was searched.

PICO element	Search string
Population, Control	TS = (grass* OR farm* OR crop* OR agricultur* OR arable OR horticultur* OR pasture* OR meadow* OR "solar park" OR "solar farm" OR "solar panel" OR "solar array" OR "utility scale solar" OR photovoltaic OR brownfield)
Intervention	TS = (flower* OR wildflower* OR floral OR vegetation OR nectar OR pollen OR foodplant* OR resource* OR forage OR structure OR nest* OR hive* OR graz* OR mow* OR cut* OR sow* OR manage* OR maintain* OR plant* OR agrienvironment* OR agri-environment* OR fertil* OR herbicide* OR insecticide* OR pesticide* OR agrochemical* OR treatment* OR shad* OR climate* OR temperature* OR precipitat* OR radiation* OR moisture* OR humidity* OR wind* OR shelter* OR connect* OR fragment* OR movement* OR dispers* OR corridor* OR metapopulation* OR landscape)
Outcome	TS = (("bumblebee*" OR "honeybee*" OR "bee" OR "bees" OR "wild bee*" OR butterfl* OR hoverfl* OR pollinat*) AND (rich* OR abundan* OR divers* OR response* OR number* OR conserv* OR biodivers* OR habitat*))

returns to relevant evidence. A three phase screening approach was used, whereby the first phase involved reading only the title and marking articles as "relevant", "uncertain" or "irrelevant" and discarding the "irrelevant" articles. In the second phase, the abstracts were read and "irrelevant" articles were discarded. In the third, and final, phase the full article was read and all "relevant" articles were classified into five themes based on factors known to impact pollinators and are relevant to solar parks: (1) foraging resources, (2) nesting, breeding and reproductive resources, (3) site management, (4) landscape and connectivity and (5) climate.

2.3. Evidence extraction

An evidence database was created, comprising references, pollinator groups, themes, sub-themes, interventions and the impact of the intervention on pollinators. Each piece of evidence was recorded within each of the relevant themes: (1) foraging resources, (2) nesting, breeding and reproductive resources, (3) site management, (4) landscape and connectivity and (5) climate. Within each theme, evidence was recorded under interventions (such as "summer grazing" or "sheep grazing") and evidence across different, but related, interventions were grouped together to form sub-themes (such as "grazing"). When defining the sub-themes, it was ensured that the direction of the evidence was aligned. For example, under the sub-theme "grazing", positive evidence for the intervention "no summer grazing" was realigned to negative impacts of "summer grazing". Pollinators were classified into the following groups where possible: "bumblebee", "bee" (any other wild bee species), "honeybee", "butterfly" and "hoverfly". If the pollinator group was not specified or multiple groups were analysed together the group "mixed pollinator" was used. The impacts of interventions on pollinators were categorised as "negative", "neutral" or "positive" and included any effect on pollinator populations or the ability of pollinators to provide pollination services. Multiple pieces of evidence were extracted from a single article where results related to more than one pollinator group or if multiple interventions affected pollinators. Meta-analyses were included, with the overall findings extracted as evidence, rather than results from individual articles considered in the analysis. No weighting was given to the evidence due to the potential to incorporate uncertainties and time constraints given the rapid nature of the review.

2.4. Analysis

To test if the distribution of evidence for each sub-theme was evenly distributed or if there was a trend, Chi-square goodness of fit tests were used, comparing the distribution of observed evidence across negative, neutral and positive impacts and an expected equal distribution. Chi-square goodness of fit tests were performed only on sub-themes which had more than 15 pieces of evidence, as this ensured that the expected frequency was always five or above, meeting the tests assumptions [41]. Any P values less than 0.05 were deemed statistically significant.

After the evidence had been analysed and interpreted, the discussion was supplemented with peer reviewed grey literature, such as the IPBES report on Pollinators, Pollination and Food Production [19], and additional journal articles in order to ensure contextualisation in the full extent of current knowledge where required. Grey literature and additional journal articles were not included in the evidence base and are not listed in summary tables.

2.5. Recommendations

Based on our analysis and input from a number of key stakeholders we developed recommendations for solar park management and a confidence level was assigned to each recommendation. Confidence levels, based on the four-box model used by the IPBES report on Pollinators, Pollination and Food Production [19] and other IPBES reports, was first applied to each sub-theme. Sub-themes were classified as "well established", "established but incomplete", "unresolved" or "inconclusive" based on the quantity and level of agreement of evidence, determined by quantitative thresholds based on qualitative descriptions of each classification from the IPBES [19] (Table 2). Management recommendations were based on the evidence within one or multiple sub-themes and assigned a confidence level based on the confidence levels of the relevant sub-themes. Where multiple sub-themes were included in one recommendation and were assigned different confidence levels, the level assigned to the majority of sub-themes within the recommendation was used. Where this was not possible, the confidence level assigned to the sub-theme in which the recommendation drew most from was used.

Table 2
Confidence levels assigned to sub-themes describing the impact of a group of related interventions on pollinator populations. Confidence levels are based on the four-box model used by the IPBES [19] and the quantitative thresholds for the quantity of evidence and the level of agreement were based on the specific evidence database used in this review, but related to the qualitative descriptions in IPBES [19].

Confidence level	Qualitative description	Quantity of evidence	Level of agreement
Well established	There is a comprehensive meta-analysis or other synthesis or multiple independent studies that agree.	$n \geq 15$	$\geq 69\%$
Established but incomplete	There is general agreement, although only a limited number of studies exist; there is no comprehensive synthesis, and/or the studies that exist address the question imprecisely.	$6 \leq n \leq 14$	$\geq 59\%$
Unresolved	Multiple independent studies exist but their conclusions do not agree.	$n \geq 6$	$\leq 58\%$
Inconclusive	There is limited evidence and a recognition of major knowledge gaps.	$n \leq 5$	n/a

3. Results and discussion

3.1. Overview

The literature search returned 6981 articles and 185 were deemed relevant after screening (Fig. 1). Of the relevant articles, comparatively large numbers addressed foraging resources ($n = 90$) and landscape and connectivity ($n = 81$). Articles assessing the impact of management practices were also numerous ($n = 59$). In comparison, fewer articles addressed nesting, breeding and reproductive resources ($n = 27$) and climate ($n = 16$).

From the 185 relevant articles, 472 pieces of evidence were extracted, with the distribution between themes following the trend observed in the number of articles sorted into each theme (Table 3). Evidence counts also varied between sub-themes (Table 4), with the breakdown of evidence displayed in Tables A – E (Appendices). Moreover, evidence counts varied across pollinator groups, with most evidence for bumblebees and butterflies and less for other wild bee species, honeybees or hoverflies (Table 3). Sixty-eight pieces of evidence related to mixed pollinators, where articles did not separate out pollinator groups (Table 3).

Out of the 27 sub-themes there were sufficient data ($n > 15$) to test the relationship between the interventions and impact on pollinators for nine sub-themes (Table 4). For seven sub-themes there were significantly higher positive evidence counts compared to expected counts, specifically the presence of flowering plants, season-long access to resources, sown vegetation, taller or structurally diverse vegetation, organic farming, increasingly semi-natural or heterogeneous landscape and proximity and connectivity to semi-natural habitat ($P < 0.05$, Table 4). In contrast, agrochemical application had a higher negative evidence count compared to expected counts ($P < 0.05$, Table 4) and no significant difference between observed and expected evidence counts was recorded for grazing ($P > 0.05$, Table 4). The full results of Chi-square goodness of fit tests are shown in Table F (Appendices). Moreover, the evidence for the vast majority of sub-themes were categorised as either well established ($n = 7$, Fig. 2), established but incomplete ($n = 9$, Fig. 2) or inconclusive ($n = 9$, Fig. 2), whereas fewer sub-themes were classified as unresolved ($n = 2$, Fig. 2). In the following sections, we discuss the findings for each of the sub-themes under the broader themes of (1) foraging resources, (2) nesting, breeding and reproductive resources, (3) site management, (4) landscape and connectivity and (5) climate.

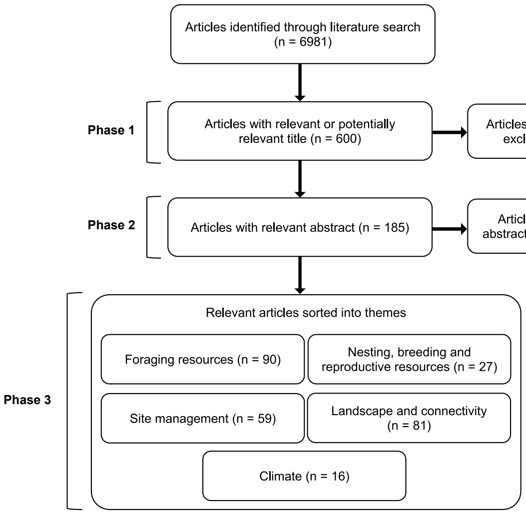

Fig. 1. Flow diagram of the literature search and three phase screening process, including the number of articles downloaded, screened and included in each of the main themes. Articles were categorised under multiple themes where relevant.

3.2. Foraging resources

Foraging resources are one of the most important factors affecting pollinator populations [42]. Although some hoverflies use non-floral resources, most insect pollinators rely on floral resources for nutrition and hence foraging resources here refers to flowering plants [43]. The presence of flowering plants has a beneficial impact on pollinators ($P < 0.01$, Table 4), attributable to floral abundance, floral richness, functional diversity, forage quality and if the species were native (Table A).

Approximately half of the foraging resource evidence focused on floral abundance, typically relating to the number of individual flowers, inflorescences (a group or cluster of flowers on a stem) or the cover of flowers bearing a pollen or nectar reward (Table A). Positive evidence made up 79% of the evidence count and was recorded across pollinator groups, with most reporting positive relationships between floral resource abundance and bumblebee [44–55], bee [49,55–57], butterfly [48,52,53,57–62], hoverfly [48,51,56,57,63–65] and mixed pollinator [44,58,66–70] abundance, density or species richness (Table A). There was limited evidence for honeybees, with two pieces of evidence reporting positive relationships between floral abundance and honeybee abundance [44,66]. The neutral and negative impacts of floral abundance on pollinators [54,63,65,70–75] reported differential impacts depending on pollinator and flowering plant species, indicating species-specific preferences where pollinators can be selective with flower use and hence a diverse range of foraging resources is beneficial [76]. For example, the abundance of old man's beard (*Clematis vitalba*) negatively affected the distribution of ringlet (*Aphantopus hyperantus*) and meadow brown (*Maniola jurtina*) butterflies, but positively affected gatekeeper (*Pyronia tithonus*) distribution [71].

Just under half of the forage resource evidence discussed the impact of floral species richness on pollinators, of which 93% was positive (Table A). The majority established increases in bumblebee [49,55,73,77–82], bee [49,55,78,83], butterfly [60,73,81,82,84–88], hoverfly [64,89,90] and mixed pollinator [67,76,91–95] abundance or species richness with floral diversity. The increase in pollinators with floral diversity is commonly attributed to increased heterogeneity, allowing more species to co-exist through niche partitioning [96]. However, certain plant species may be of more general insect conservation value, although specific flowering plant species may be necessary to support more specialist pollinators [97]. For example, there is evidence suggesting that the impact of increased floral diversity saturates after nine species and that pollinators may only use a subset of species [78]. Honeybees presented with high flowering plant diversity utilised just 11% of plant genera, with all colonies studied using the same core set of species [98]. Similarly, wild bees and hoverflies used only 15% of plant species and 4 species supported 80% of pollinator visits [95]. Consequently, whilst diversity may be beneficial to an extent, the presence of key species may support the majority of pollinators.

Higher quality forage also had positive impacts on pollinators, although the evidence was limited to six pieces. Moreover, the definition of quality varied, including amino acid composition of pollen [50,99], nectar quality based on total sugar per inflorescence [46] and floral composition and age of wildflower strips [63]. There was insufficient evidence of the impacts of forage quality, functional diversity and also native species ($n = 6$, 2 and 5 respectively, Table A) to provide robust insight. However, the results indicate that higher quality forage and native species benefit pollinators as 67% and 60% of evidence respectively was positive (Table A). Positive [98,100] and neutral [100,101] impacts of native species were recorded, although the results mirror the wider literature where limited direct evidence for the benefits of native plant species exists. Instead, there is a focus on the negative impacts of alien plant species and how they can outcompete native plant species, change native plant-pollinator interactions and risk pollinator health if they are nutritionally poor [19]. In summary, although evidence is limited, native plant species may be beneficial in order to avoid negative impacts of alien species on pollinators.

Table 3

Counts of evidence extracted from 185 articles relating to the impacts of interventions affecting pollinator populations. Pollinators were categorised into 6 groups: “bumblebee”, “bee” (any other wild bee species), “honeybee”, “butterfly”, “hoverfly” and “mixed pollinator” (if the pollinator group was not specified or multiple groups were analysed collectively).

Theme	Pollinator group						Total
	Bumblebee	Bee	Honeybee	Butterfly	Hoverfly	Mixed pollinator	
Foraging resources	58	17	10	30	19	23	157
Nesting, breeding and reproductive resources	20	5	0	5	2	6	38
Site management	27	9	7	46	6	17	112
Landscape and connectivity	42	17	7	40	23	19	148
Climate	3	0	0	12	0	2	17
Total	150	48	24	133	50	67	472

Hedgerows and wooded areas are also important sources of foraging resources ($n < 15$, Table 4). Although there were only ten pieces of evidence it suggests that butterflies were enhanced in field boundaries containing hedgerows [87], whereas those without hedgerows were negatively correlated with butterfly species richness [102]. This could be partially attributable to the higher resource density given the mix of woody and herbaceous flowering plant species [103]. Indeed, herbaceous species at the base of hedgerows were considered to be particularly important for hoverflies [104]. However, it is not just the presence of hedgerow that makes a difference, but the quality. More than twice as many bumblebees were observed on good quality hedgerows compared to poor quality hedgerows, where good quality was defined as hedgerows containing at least three woody plant species and those which were continuous and unbroken [104]. In addition to providing foraging resources, hedgerows support breeding pollinators [105,106], act as structural elements affecting pollinator movement [107,108] and provide shelter and a range of microclimates for pollinators [61,71].

As well as the amount of foraging resource, the availability throughout the season is important to provide nutrition to pollinators throughout the year ($P < 0.01$, Table 4). Beneficial effects of season-long access to resources, eliminating seasonal periods of nutritional deficit, were predominantly reported for bumblebees [55,80,109–112], bees [55,113,114] and honeybees [115,116]. Dependent on floral resources, strong temporal fluctuations can occur with potential detrimental impacts on pollinators. For example, farmland nectar supplies can change throughout the season and one article reported peaks in May and July and periods of lower availability in March, June, August and September on four farms in the UK [112]. There is evidence that late-season resources are more important than early-season resources as all evidence recorded for continuous or late-season resources was positive, whereas 60% of evidence was positive for early-season resources (Table A). This evidence is reinforced by observations that two thirds of pollinators have peak flight observations during the late summer when floral resources primarily take the form of herbs [91]. However, as flowering herbs are now scarcer and more patchily distributed than in the past, the availability of late season resources is increasingly important for pollinators [91].

Given the decline in foraging resources and pollinators, areas are actively managed for them, with a common approach of sowing nectar and pollen producing plant species. Such sown areas have beneficial impacts on pollinators ($P < 0.01$, Table 4) and generally support a greater abundance or diversity of pollinators than forage established through other methods, but also compared to grass-based treatments, other non-crop vegetation and cropland [54,81,117–127]. Benefits of sowing to reproduction were also documented, where a measure of bumblebee reproduction (an index of total biomass of bumblebee sexuals) was higher on sown forage patches compared to conventionally managed control areas after controlling for floral density [128]. Although responses of different bumblebee species vary according to plant species sown, the results suggested that targeted mixtures can enhance reproduction [128]. Sowing may therefore be most effective because of the ability to dictate species composition of the plant community, and through purposefully including a diverse range of plant species, sown forage is able to support a broad range of pollinators.

Whilst sowing provides greater benefits and allows greater control of the resources provided, allowing the natural regeneration of vegetation may also positively impact pollinators ($n < 15$, Table 4). For example, 88% of insect diversity and 82% of volume was recorded on naturally regenerated resources compared to purposely sown resources on farmland [124]. In some cases the reported positive impacts of natural regeneration may be confounded by study design, reflecting the benefits relative to cropped areas rather than the establishment method [54,129]. Furthermore, evidence reported that natural regeneration was an ineffective establishment method for butterfly abundance on field margins [130] and naturally regenerated areas supported a range of undesirable weed species [54,130]. However, evidence was scarce ($n = 4$, Table 4) and additional research is required to draw robust insight.

3.3. Nesting, breeding and reproductive resources

Whilst foraging resources are generally considered to be among the primary factors affecting pollinator populations, nesting, breeding and reproductive resources are also important (Table 4). However, foraging resources remain beneficial in the context of reproduction ($n < 15$, Table 4). Although there were only eight pieces of evidence, positive effects of foraging resources on nest density, survival or construction were documented [79,106,114,127,131,132] and a high local ratio of foraging habitat to number of nests was suggested to reduce competition [133]. Proximity to foraging resources has been investigated, but the evidence was scarce and no clear trend was observed ($n < 15$, Table 4). As bees are central place foragers, returning to the same site in between foraging trips, it may be expected that nesting and foraging resources in close proximity would beneficial. However, evidence suggested that the benefit of nearby resources differs among species, partially dependent on variation in foraging ranges [134–137].

The presence of larval resources, both food plant and habitat, for butterflies and hoverflies is also beneficial ($n < 15$, Table 4). All evidence recorded for larval resources reported a positive impact on butterflies and hoverflies, although there is limited evidence despite the critical importance of larval resources for completing species’ lifecycles. Butterflies often require specific plant species to lay their eggs on and on which larvae subsequently feed. Evidence for butterflies showed that larval food plants were a variable of major importance in butterfly habitat [138] and greater numbers of butterflies were recorded in habitats where the larval food plant was present [61,84]. A study on Brown hair streak butterflies (*Thecla betulae* L.) reported that the amount of young food plant (mostly blackthorn; *Prunus spinosa* L.) was relevant in explaining observed egg densities in an agricultural landscape [105]. Relying on a broader range of resources, hoverfly larvae requirements are highly variable, depending on specific macro and microhabitats [64]. However, the evidence recorded for larval habitat reported beneficial impacts and hoverflies were associated with suitable larval habitat at local and landscape scales [64,90].

As pollinators often require specific reproductive resources, a range

Table 4

The impacts of sub-themes on pollinators categorised as negative, neutral or positive based on evidence extracted from 185 articles within the foraging resources, nesting, breeding and reproductive resources, site management, landscape and connectivity and climate themes. Cells shaded darker red or green indicate there is a statistically significantly higher negative or positive evidence count respectively compared to expected counts ($P < 0.05$) and cells shaded dark grey represent no significant difference ($P > 0.05$) according to Chi-square goodness of fit tests. Cells shaded paler red, grey or green indicate a negative, neutral or positive trend respectively, suggested by evidence counts where n was too low to carry out statistical analyses ($n < 15$).

Theme	Sub-theme	Total	- (%)	0 (%)	+ (%)
Foraging resources	Presence of flowering plants	110	2	17	**81**
	Presence of hedgerow	10	0	30	70
	Season-long access to resources	16	6	6	**88**
	Sown vegetation	17	0	0	**100**
	Naturally established vegetation	4	25	0	75
Nesting, breeding and reproductive resources	Availability of floral resources	8	0	13	88
	Proximity to resources	6	0	50	50
	Presence of larval resources	6	0	0	100
	Specific habitat features	14	0	7	93
	Nest site availability	4	0	25	75
Site management	Grazing	15	53	13	33
	Cutting	10	90	0	10
	Removal of cut material	4	50	0	50
	Mowing	3	100	0	0
	Taller or structurally diverse vegetation	22	0	18	**82**
	Agrochemical application	39	**72**	15	13
	Low intensity hedgerow management	4	0	0	100
	Organic farming	15	13	7	**80**
Landscape and connectivity	Increasingly semi-natural or heterogeneous landscape	106	15	16	**69**
	Organic farming in the landscape	4	0	0	100
	Linear features in the landscape	13	15	15	69
	Proximity and connectivity to semi-natural habitat	22	5	36	**59**
	Large habitat area	3	0	0	100
Climate	Warmer microclimate	2	0	0	100
	Shelter	6	0	17	83
	Microclimatic variation	3	0	0	100
	Climate warming	6	83	17	0

of habitat features are beneficial ($n < 15$, Table 4). Positive impacts of habitat features were attributable to tussocky vegetation, sparse vegetation, woodland edge, hedgerow, field margin, open terrain, sandy soil, sloped ground, and banks or ditches, although evidence for each was limited (Table B). Limited evidence for each feature represents species-specific reproductive requirements and evidence predominantly reported beneficial impacts on bumblebees [106,135,139–141], other wild bee species [133], and mixed pollinators [70,142]. For example, interspecific variation in preferred habitat type was documented for seven UK bumblebee species, where *Bombus terrestris*, *B. lapidarius* and *B. lucorum* preferred banks or ditches and *B. pascuorum*, *B. hortorum* and *B. ruderarius* benefitted from tussocky vegetation [139].

A range of habitat features may boost nest site availability for a diversity of species and hence benefit pollinator populations ($n < 15$, Table 4). Nest sites can be natural or artificial, where natural nest sites for bees commonly comprise of undisturbed soil patches, hollow stems,

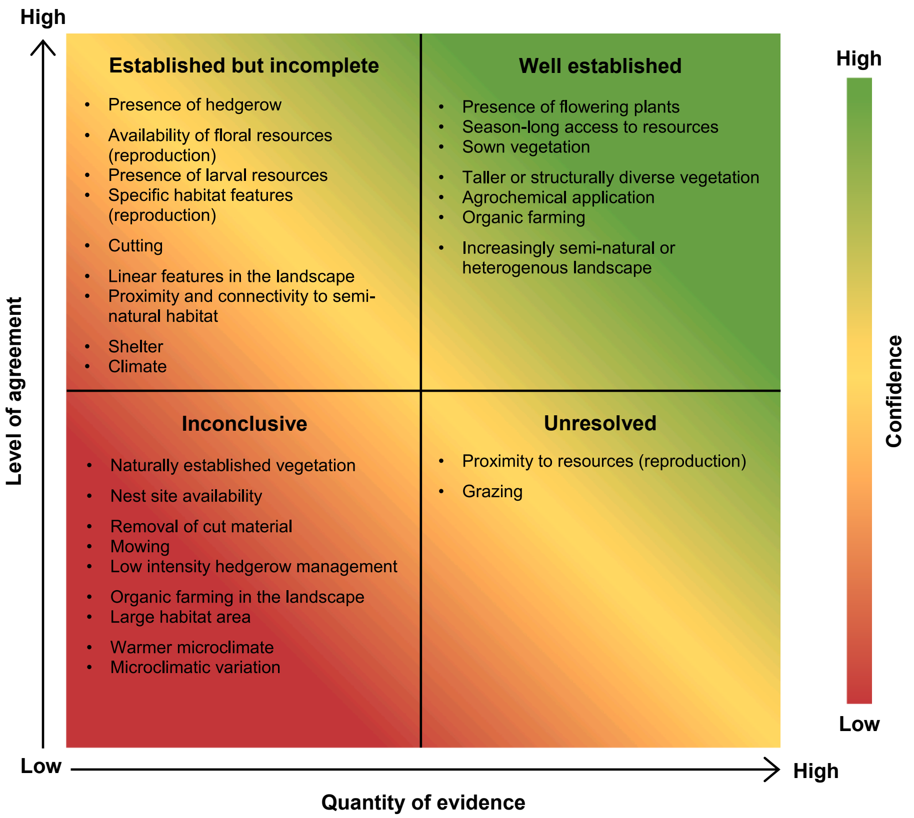

Fig. 2. The confidence levels assigned to 27 sub-themes made up of interventions that affect pollinators (Table 4) based on evidence extracted from 185 articles. Confidence increases towards the top-right corner as suggested by the shading and is based on the four box model used by IPBES [19]. Well established – there is a comprehensive meta-analysis or other synthesis or multiple independent studies that agree; Established but incomplete – there is general agreement, although only a limited number of studies exist; there is no comprehensive synthesis, and/or the studies that exist address the question imprecisely; Unresolved – multiple independent studies exist but their conclusions do not agree; Inconclusive – there is limited evidence and a recognition of major knowledge gaps.

shrubs, trees or dead wood [19]. Evidence for natural nest availability was scarce ($n = 2$, Table B), but suggested that increases in availability boosted red mason bee (*Osmia bicornis*) populations [143] and that availability is a critical factor affecting bumblebee and other wild bee species diversity more broadly [144]. Where natural nest sites are limited, artificial domiciles have been proposed, however, evidence of their effects is scarce and inconclusive ($n = 2$, Table B). For example, it was documented that artificial trap nests promoted cavity nesting bees, with brood cells increasing three-fold [144], but artificial nest boxes for bumblebees were found to be largely unsuccessful and achieved low uptake rates [145]. Additional research is therefore required to draw further conclusions on the impact of natural and artificial nest sites on pollinators.

3.4. Site management

To ensure that resources are suitable for pollinators, management is often required. A broad range of management practices can be undertaken, including grazing, as livestock selectively consume vegetation, enrich the soil through faeces and compact the soil by trampling, consequently affecting the plant community and pollinator resources [19]. Evidence suggests that grazing has no impact on pollinators ($P > 0.05$, Table 4), but this is due to the positive and negative effects of different grazing regimes counteracting one another (Table C). For example, beneficial effects of low intensity grazing (low frequency or low density of livestock) on abundance or richness were reported for bees [146], butterflies [138,146,147] and mixed pollinators [148]. In contrast, grazing at particular times of the year, such as during the summer, can have negative effects, with implications for the abundance and richness of bumblebees [57,149], other wild bees, butterflies and hoverflies [57]. Summer grazing rest periods extend the time period for flower development and increase floral resource availability [57] and therefore whilst inappropriately-timed or intensive regimes can be detrimental to pollinators, careful grazing management be beneficial.

Intensity and timing of management is also important for vegetation cutting, which had negative impacts on pollinators ($n < 15$, Table 4). Intensity refers to the frequency of cutting and it was suggested that two sward cuts per year (compared to a single cut or no cuts) resulted in a decrease in mixed pollinator species richness [82] whilst decreasing cutting frequency benefitted butterflies [81]. As with grazing, cutting during the summer was suggested to negatively impact pollinators due to the reduction in resources at crucial times [53] and benefits of summer rest periods were reported across pollinator groups [57,121]. Following a cut, material is either removed or left in situ and this can impact pollinators indirectly through changes in the plant community, where leaving material in situ acts as a physical barrier to light that alters plant competition [53]. However, there was insufficient evidence of the impacts of removal of cut material to provide robust insight of the impact on pollinators ($n < 15$, Table 4). This was also the case for mowing ($n < 15$, Table 4), but trends appeared similar to those of grazing and cutting, suggesting low intensity regimes and summer rest periods benefit pollinators [102,150,151].

Practices such as grazing, cutting and mowing impact pollinators indirectly through changes in vegetation structure; taller or structurally diverse vegetation have a positive impact on pollinators ($P < 0.01$, Table 4). Structurally diverse vegetation was associated with greater bumblebee and butterfly abundance, richness or diversity [81,152], whereas the benefits of tall vegetation were predominantly associated with butterflies, with most evidence reporting relationships between vegetation height and butterfly abundance or richness [52,60,73,86,146,152]. Taller vegetation is likely to be a feature of habitats managed less intensively, or could indicate increased biomass and vegetation complexity. Less evidence was recorded for other pollinator groups other than butterflies, although correlations between vegetation height and bumblebee [52] and hoverfly [70] species richness were documented and taller flowers generally attracted more insect visitors [153,154].

Agrochemicals have a negative impact on pollinators, attributable to the effects of fertilisers, herbicides and insecticides ($P < 0.01$, Table 4). Two thirds of the agrochemical evidence focused on insecticides, with 81% reporting negative impacts (Table C). Evidence established decreases in bee [148,155], honeybee [155], butterfly [156–158], hoverfly [155] and mixed pollinator [69,159–161] abundance, richness or density with insecticide use, but also reported a range of sub-lethal or lethal effects on pollinators. Impacts on pollinator reproduction included reduced colony growth in bumblebees [69,77,162] reduced nesting in solitary bees [69] and honeybee colony losses across England and Wales [163]. Other evidence focused on pollinator behaviour and performance, reporting changed patterns in foraging behaviour [162], altered sensory responses and memory [164] and decreased flight distance and duration [165] in response to insecticide exposure.

Negative impacts of fertilisers and herbicides on pollinators were also documented (Table C). For example, declines in bee abundance and richness were reported with fertiliser use [82,148,160], vegetation of fertilised soils were found to be unimportant for bumblebees [166] and stopping fertilisation was suggested to be beneficial for butterflies [81,167]. Fertiliser application commonly reduces floral diversity due to competitive exclusion and therefore reduces the diversity of resources available to pollinators [168]. Commercial use of herbicides can also diminish pollinator resources, with declines in butterfly abundance documented [121,158]. In contrast, some evidence reported positive impacts of fertiliser and herbicide use on pollinators. For example, benefits to nettle-feeding peacock (*Aglais io*) and small tortoiseshell (*Aglais urticae*) butterflies were documented, as fertiliser application increased nitrogen content in their food plant (stinging nettle; *Urtica dioica*), resulting in higher survival rates, shorter larval periods and heavier pupae in both species [169]. However, effects of fertiliser and herbicide use may be indicative of the impacts of changes in land use rather than agrochemical use [148].

Low intensity hedgerow management also had positive impacts on pollinators, although the evidence was limited to four pieces ($n < 15$, Table 4). Benefits were reported where hedgerows were cut less frequently, cut in winter instead of autumn, cut incrementally (where the cutter bar is raised by 10 cm each time the hedgerow is cut) [170] and where hedgerows were not managed at all [150]. However, as evidence was scarce additional research is required for further insight.

In addition to management of particular habitat features, management at the farm scale is important, with organic farming having a positive impact on pollinators ($P < 0.01$, Table 4). The evidence reported benefits of organic farming to bumblebees [109], honeybees [116], butterflies [109,171–174], hoverflies [175] and mixed pollinators [92,176,177]. Benefits are attributable to organic farms generally having greater habitat heterogeneity, reduced agrochemical use and conserve more natural vegetation than conventional farms, retaining more resources for pollinators [178].

Due to the nature of the evidence extraction method, management practices have been considered in isolation, although in reality the combination of management actions is important. Yet, there is limited evidence and articles investigating multiple management actions are scarce, with one returned in the literature search, suggesting that bumblebee and butterfly abundance and diversity differed according to combinations of fertiliser application, cutting, grazing and the sowing of different seed mixtures [81]. Consequently, the results offer an insight into the impacts of certain management practices on pollinators, but to gain a more complete understanding the entire management regime should be considered.

3.5. *Landscape and connectivity*

When providing resources and managing habitats for pollinators it is important to consider larger spatial scales, surrounding land uses and connectivity. There is evidence that increasingly semi-natural or heterogeneous landscapes have a positive impact on pollinators ($P < 0.01$, Table 4), where heterogeneous landscapes are composed of a greater diversity of land uses or higher proportions of semi-natural habitat. Landscape scale typically referred to a radius of 250 m–5 km surrounding a pollinator habitat or resource and increases in species richness or abundance with increasingly semi-natural or heterogeneous landscapes were documented for bumblebees [48,51,55,73,110,126,148,179,180], other wild bees [148,179,181–184], butterflies [60,102,151,174,183,185–191], hoverflies [51,64,65,70,74,184,188,192] and mixed pollinators [67,68,93,175,177]. Increasing cover of semi-natural habitat in the landscape results in an increase in critical foraging and reproductive resources for pollinators and a diversity of habitats can mean that pollinators have to travel less far to reach specific resources provided only by certain habitat types [179]. Different semi-natural habitats in the landscape differ in value to pollinators depending on species-specific preferences, explaining the neutral and negative evidence. Moreover, neutral and negative impacts of increasing semi-natural or heterogenous landscapes may be attributable to the differences in habitat quality across different study areas.

Other semi-natural landscape characteristics, such as linear elements, also had a positive impact on pollinators ($n < 15$, Table 4) and included ditches, edge habitats and roads (Table D). Evidence for the impact of ditches was scarce and specific to species that use them as a source of foraging and reproductive resources [135], but edge habitats were valuable to a wider range of pollinators. For example, positive impacts of edge habitats, such as field margins and hedgerows, were documented for bumblebees [80], butterflies [70,193], hoverflies [192] and mixed pollinators [70,194]. Evidence of positive impacts was also recorded for roads in the landscape [70,193], although this was limited and negative impacts were also documented [70,80]. The contrasting evidence is explained by the benefits of the foraging resources offered by road verges and suboptimal management regimes and direct mortality from traffic [80].

Linear elements in the landscape also act as semi-natural pollinator corridors, facilitating movement and enhancing landscape connectivity, which is important for pollinators ($P < 0.01$, Table 4). Non-cultivated linear elements are often the only remaining connections between areas of semi-natural habitat in agricultural landscapes and evidence specifically reported benefits of field margins and hedgerows for pollinator movement [107,108,195,196]. Movement between suitable habitats decreases the likelihood of population extinction through reduced gene flow, inbreeding depression and the increased susceptibility to environmental perturbations [197]. The ability to move between habitats differs between species depending on ecological traits and hence the proximity to other semi-natural habitat has an impact on pollinators [73]. Evidence documented positive impacts of proximity to semi-natural habitat on the abundance, density or richness of bumblebees [73,198], other wild bee species [56], butterflies [73,198], hoverflies [56] and mixed pollinators [199,200]. Species' ability to move further or differences in the permeability of landscape matrices across articles may explain the evidence documenting no impact of proximity to semi-natural habitat [56,66,105,198,200].

Whilst the evidence suggested that semi-natural, rather than agricultural, landscapes benefit pollinators, the type of agriculture can have an impact. Organic farming in the landscape had a positive impact on pollinators, although this was supported by only four pieces of evidence ($n < 15$, Table 4). Enhanced bee and butterfly species richness was documented with increased organic cropping in the landscape [49,62] and increases in pollinator abundance and richness were reported at the regional scale in areas dominated by organic farming [92]. However, organic farming is typically less productive than conventional farming and can require a greater area of land to produce equivalent yields [201]. If additional semi-natural habitat is required to be brought into production to compensate, then organic farming may be overall costly to pollinators at the landscape scale, although this was not considered by the evidence. Additional evidence is therefore required to gain further insight into the impact of the type of agriculture at the landscape scale on pollinators. Similarly, there was insufficient evidence of the impacts of habitat area to provide robust insight ($n < 15$, Table 4).

3.6. *Climate*

In addition to biotic and landscape factors, abiotic factors, including climate, also impact pollinators at macro and micro scales. Insect pollinators are ectothermic and hence are strongly influenced by the microclimate that they experience [202]. Warm microclimates and shelter benefit pollinators, although there were only two and six pieces of evidence respectively ($n < 15$, Table 4). Almost all of the evidence focused on butterflies and although limited, supports well-known ideas that north-western European butterfly species are often dependent on a warm and protected microclimate. Specifically, insolation was a variable of major importance in linear habitats [138] and influenced butterfly distribution [71]. The importance of specific habitat types for the shelter that they provide was also documented, including tall vegetation [203], green lanes [59], shrubs, hedgerows and woodland [61,71] which are sought out by butterflies when conditions in more open, exposed habitats become unsuitable [61]. However, evidence also reported that a variety of microclimates is beneficial for pollinators, although evidence was scarce ($n < 15$, Table 4). Habitats offering variation in vegetation structure or topography provide a range of thermal conditions for pollinators that can be exploited according to shifts in climate [204,205] and hence a variety of microclimates could act as a refuge for pollinators from climate warming [206].

Climate warming has a negative impact on pollinators and the evidence documented declines in wild bee or butterfly abundance, diversity or reproduction with higher temperatures [99,149,207,208], although there were only six pieces of evidence ($n < 15$, Table 4). Limited evidence was recorded, despite the plethora of pollinator response to climate warming research, because many articles examining the impacts of climate warming on pollinators focus on larger spatial scales than habitats managed as solar parks and hence key words were not present in the majority of articles titles, keywords or abstracts (Table 1). Nevertheless, the effects of climate warming will impact pollinators in this context and affect all organisational levels, from the individual, to population genetics, to species-level shifts and changes at the community level [27]. Impacts have been documented already, whereby the ranges of plants and pollinators have moved, abundance has altered and phenology has shifted in response to climate warming over the last few decades [19]. In addition, indirect impacts of climate warming on pollinators, such as those associated with impacts on preferred plant species or habitats pollinators rely on, have been documented [19]. Models indicate that climate warming will continue to impact pollinators in the future and one piece of evidence predicted decreases in butterfly diversity under future climate change scenarios [209]. However, the impacts of climate warming on pollinators may not be fully apparent for decades due to the delayed response times of ecological systems [19].

4. Evidence-based recommendations

Here, using the findings of the QSR, we present ten evidence-based management recommendations centred around the five main themes: (1) foraging resources, (2) nesting, breeding and reproductive resources, (3) site management, (4) landscape and connectivity and (5) climate (Fig. 3). The recommendations are based directly on the evidence, align with industry biodiversity guidelines [16] and are grounded in solar park management practice, acknowledging the restrictions of solar park operation and maintenance needs. Whilst the recent nature of land use change for solar parks and limited assessments preclude strong evidence of the long-term impacts on pollinators, early evidence suggests enhancements are feasible. For example, a greater diversity of bumblebees and butterflies were observed on solar parks managed for biodiversity across eleven sites in the UK [210].

Solar park management strategies must incorporate potential implications for site operation. It is recognised that ideal management practices, such as repeat visits to sites to manage vegetation differentially dependent on location within a park, may not always be possible due to cost. Furthermore, the cost implications of the recommendations may either prohibit or limit the scale of application. Where cost is limiting, application to small areas or around the solar park margins can still deliver valuable ecosystem benefits [211]. Further, site characteristics may make them more or less suitable for management actions to enhance pollinators and if resources are limited, it may be preferable to focus efforts on fewer sites. Finally, whilst confidence in the underpinning evidence for almost all of the recommendations are “well established” or “established but incomplete”, expert local advice about solar park management should be sought to tailor implementation, as each site is unique. Information, for example regarding appropriate seed mixes, about the most suitable management for pollinators at a local level can be sought from local ecologists (e.g. Association of Local Government Ecologists, academics, and NGOs such as the Bumblebee Conservation Trust, Butterfly Conservation, Plantlife or Hedgelink).

Fig. 3. Illustration depicting the potential for solar parks to enhance pollinator biodiversity through (1) providing foraging resources, (2) providing nesting, breeding and reproductive resources, (3) undertaking suitable management practices, (4) increasing semi-natural habitat in the landscape and promoting connectivity and (5) generating microclimatic variation on solar parks.

4.1. *Foraging resources*

Recommendation 1: Provide a diverse mix of key flowering plant species *(well established)*.

Solar parks should be managed to provide a diverse mix of pollinator flowering plant species; foraging resources are essential for pollinators and diversity is of benefit for wild bees, butterflies and hoverflies (Table A). Rather than maximising floral diversity, it is preferable to provide a number of key plant species, preferably of local provenance, and selected on a site-by-site basis suited to local growing conditions and target pollinator communities (pollinator species can be specific in the floral resources they require).

Given that the footprint of solar parks is around 5% with solar panels generally raised 1–2.5 m above the ground there is significant opportunity to provide floral resources within solar parks [16]. Although, as solar panels typically over-sail 25–40% of the park, altering the microclimate, plant communities and productivity may vary spatially [8,16,210,211]. To have the greatest influence over the floral resources provided and to create a plant community targeted at a specific pollinator community, sowing is the most effective establishment method (Table A). The solar park could be entirely re-seeded with a mix containing a diverse range of flowering plant species, or where this is not possible, strips of floral resources sown in certain places would be beneficial. Solar park margins are the most appropriate location for wildflower strips, where vegetation can grow taller without the need for frequent management to prevent solar panel shading. Periodic re-seeding every few years may also be required to maintain plant biodiversity, although over time it is likely that additional species will colonise naturally.

Recommendation 2: Plant or maintain hedgerows at the site boundary *(established but incomplete*).

Installing, or maintaining if already present, hedgerows at the site boundary of a solar park provides a multitude of benefits to pollinators in addition to the co-benefit of visual screening, a common requirement of planning applications. Hedgerows are an important source of floral resources for pollinators, attributable to the mixture of woody and herbaceous plant species (Table A). Hedgerows also support breeding pollinators, enhance pollinator movement and provide shelter and favourable microclimates. New and existing hedgerows should also be carefully managed, with evidence suggesting that low intensity practices (e.g. incremental or less frequent cutting) and winter management yields the greatest benefits to pollinators (Table C).

Recommendation 3: Ensure season-long access to foraging resources *(well established*).

Flowering plants and hedgerows should be planned and managed to ensure season-long access to foraging resources, as this is important for pollinators (Table A). Seed mixes should include plant species that flower at different points throughout the season to ensure continuous resource availability and to complement hedgerow species where applicable. Evidence suggested that late season resources are especially important to pollinators (Table A) and therefore establishing late-flowering species on solar parks will be particularly beneficial and help to eliminate periods of nutritional deficit.

4.2. Nesting, breeding and reproductive resources

Recommendation 4: Provide a range of nesting, breeding and reproductive resources *(established but incomplete*).

Nesting, breeding and reproductive resources are important for pollinators and hence solar parks should provide a diverse range of resources for target pollinator communities. In comparison to floral resources the implications are poorly resolved and no studies have addressed such resources in a solar park context. However, the evidence suggests that creating suitable natural habitat for nesting, breeding and reproduction is more effective at boosting nest site availability or breeding habitat than providing artificial domiciles (Table B). Natural habitat is also associated with other benefits, including the provision of floral resources, which may be beneficial when coupled with nesting, breeding and reproductive resources (Table B). Indeed, the evidence specifically described the benefits of features such as tussocky vegetation, sparse vegetation and banks or ditches for pollinator nesting, breeding and reproduction (Table B) and hence management actions to provide such features should be undertaken where possible.

Rather than specific habitat features, some pollinators rely on particular plant species on which to lay their eggs and these preferred plant species could be included in seed mixes or planted. However, where such plants are established should be carefully considered as pollinators can be specific not only about the plant species, but the conditions in which the plant itself grows. For example, female butterflies often depend upon highly specific conditions for egg-laying, relying on particular microclimates. Such resources may be best established in solar park margins, where vegetation is often managed less intensively, to prevent the destruction of eggs and larvae. Refraining from cutting some areas of vegetation in the margins annually would also aid pollinator larvae or adults overwintering in this habitat.

4.3. Site management

Recommendation 5: Graze, cut or mow at low intensity and late in the season *(established but incomplete*).

Grazing, cutting or mowing should be low intensity and undertaken later in the season, ensuring that pollinator foraging resources are available throughout the summer and providing the opportunity for forbs to flower and set seed (Table C). However, it is critical to solar park electricity productivity that vegetation does not shade the panels. Consequently, where this occurs, narrow strips (<1 m) in front of the south facing panel edge should be cut or mown as required.

Sheep are the most common and arguably the most suitable grazers on solar parks, as cattle or horses are able to dislodge mounting systems and pigs or goats can cause cable damage [6]. However, compared to other grazers, sheep graze the vegetation very low. Consequently, deploying sheep late in the season is very important and if summer grazing is necessary, should be undertaken at low densities (Table C). Moreover, there is some evidence that well managed spring and winter grazing, but not summer grazing, can increase plant diversity on solar parks [212]. Where cutting or mowing is undertaken, a similar low intensity regime with a summer rest period will be most beneficial (Table C).

Recommendation 6: Create or maintain variation in vegetation structure *(well established*).

Grazing, cutting and mowing regimes should aim to create heterogeneity in the vegetation within the solar park, as structurally diverse or taller vegetation has a positive impact on pollinators (Table C). Excluding areas from grazing, cutting or mowing management would enhance structure and create areas of taller vegetation. The evidence suggested that taller vegetation benefits butterflies in particular, although species-specific preferences may mean that creating patches of vegetation of different heights may support a wider range of species. Within a solar park, strip mowing to prevent panel shading would create areas of shorter vegetation, increasing heterogeneity in vegetation structure and height across the solar park.

Recommendation 7: Minimise the use of agrochemicals *(well established*).

Minimising agrochemical use on solar parks brings benefits to pollinators as well as reducing management costs. Agrochemicals negatively impact pollinators (Table C) and whilst solar parks may provide a refuge from fertilisers and insecticides, herbicides are used at some sites and can diminish pollinator floral resources. A survey across UK solar parks reported non-selective herbicide use at some solar parks, resulting in the eradication of broadleaved plants and hence pollinator foraging and reproductive resources [213]. Ideally, the use of herbicides at solar parks should be minimised; even selective herbicide used to target injurious weeds or invasive species can eliminate non-target species. If not possible to avoid herbicide use, techniques to control undesirable species such as spot spraying, weed wiping or mechanical removal are preferable to spraying [213].

4.4. Landscape and connectivity

Recommendation 8: Target management for pollinators on solar parks located in homogenous and intensive agricultural-dominated landscapes *(well established*).

Solar parks offering pollinator resources will likely have the greatest impact in resource-depleted landscapes and thus pollinator management strategies on solar parks located in predominantly intensive agricultural or homogenous landscapes should be prioritised (Table D). Considered site management could enable solar parks to act as sizeable patches of semi-natural habitat in the landscape, providing foraging and reproductive resources for pollinators, as well as shelter and microclimatic variation. Moreover, there may also be benefits for surrounding crops through boosting pollination services [17,18].

Recommendation 9: Promote connectivity to semi-natural habitat *(established but incomplete)*.

Connectivity between solar parks and other semi-natural habitats should be enhanced through the installation or maintenance of semi-natural linear features (e.g. hedgerows, wildflower strips) as they can act as pollinator corridors, improving connectivity and facilitating pollinator movement (Table D). This will enable solar parks to act as stepping stones across the landscape for pollinators, connecting otherwise isolated habitat patches and populations [214]. Consequently, features such as hedgerows should be installed or maintained at site boundaries and where possible, actions outside of the boundary should be considered. For example, further hedgerows could be installed or margins in surrounding fields could be left uncultivated and seeded with flowering plant species used by pollinators.

4.5. Climate

Recommendation 10: Generate a range of microclimates *(inconclusive)*.

Microclimatic variation should be generated on solar parks to provide a range of thermal conditions for pollinators and although solar park infrastructure already provides microclimatic niches, this can be enhanced through considered management of natural features [8]. For example, features such as tall vegetation or hedgerows can provide warmer microclimates and shelter that benefit some pollinators (Table E).

5. Conclusion

As solar PV capacity rises there will be increased land take for ground-mounted solar parks and to ensure optimal ecosystem outcomes associated with this land use change, the local environment and biodiversity must be considered. Solar parks have considerable potential to enhance pollinator biodiversity through mitigating some of the major drivers of pollinator decline. Whilst the areas are relatively small compared with dominant land uses, such as agriculture, solar parks offer areas of land for enhancement with different geometries (i.e. squarer compared to conservation strips around arable fields), provide opportunities for the creation of different habitats and minimise the impacts of agricultural edge effects (e.g. spraying). Moreover, they are often located in agricultural landscapes where action to reduce pollinator biodiversity decline is most needed.

Our review suggests enhancement of pollinator biodiversity is achievable through undertaking considered management of solar parks to provide pollinator foraging and reproductive resources, enhance landscape heterogeneity and connectivity and generate microclimatic variation. Management recommendations based directly on the evidence could therefore be used to inform optimal solar park management, where the overarching outcomes are applicable to the UK and north-west Europe but also to other temperate regions outside of these. Applying such recommendations could ensure solar parks contribute to the reversal of pollinator biodiversity decline, especially as land use for solar increases. However, current key knowledge gaps exist around how solar parks are currently managed and this information would be useful in shaping optimal management regimes. Furthermore, knowledge gaps exist where the impact of interventions on pollinators were “inconclusive” or “unresolved” and hence future research effort is required to better understand the impacts of certain practices on pollinator biodiversity. Monitoring of both the habitat established and pollinator biodiversity in response to management practices on solar parks is also critical to quantify the effectiveness of interventions, especially in the longer term. Collaboration between industry, policy and researchers is therefore required to enhance the wider environmental sustainability of solar parks and ensure that the decarbonisation of the energy sector incorporates environmental benefits, minimising the trade-off between climate change mitigation and local biodiversity.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A

Raw evidence counts extracted from relevant articles returned in the literature search within the foraging resources theme (n = 90). Each piece of evidence was categorised as “negative”, “neutral” or “positive” depending on the impact on pollinator populations. Shading represents the quantity of evidence recorded for each intervention, where darker shades represent a higher count. Specifically, no shading represents a count of 0, the lightest shade represents a count of 1, the light shade represents counts of 2–5, the dark shade represents counts of 6–20 and the darkest shade represents counts of 21 or higher [215,216].

Sub-theme	Intervention	Total	-	0	+	References
Presence of flowering plants	Abundance	56	1	11	44	[44-75, 138, 181]
	Richness	41	0	3	38	[49, 55, 60, 64, 67, 73, 74, 76-95, 115, 166, 215]
	Functional diversity	2	1	1	0	[153, 216]
	Forage quality	6	0	2	4	[46, 50, 63, 99]
	Native species	5	0	2	3	[98, 100, 101]
Presence of hedgerow	Presence of hedgerow	5	0	0	5	[87, 102, 103]
	Presence of understory flowers	4	0	3	1	[104]
	High quality hedgerow	1	0	0	1	[104]
Season-long access to resources	Early season resources	5	1	1	3	[55, 80, 112, 113]
	Late season resources	8	0	0	8	[80, 91, 109-113]
	Continuous resources	3	0	0	3	[109, 115, 116]
Sown vegetation	Sown vegetation	17	0	0	17	[54, 81, 117-128, 140]
Naturally established vegetation	Naturally established vegetation	4	1	0	3	[54, 124, 129, 130]

Table B
Raw evidence counts extracted from relevant articles returned in the literature search within the nesting, breeding and reproductive resources theme (n = 27). Each piece of evidence was categorised as "negative", "neutral" or "positive" depending on the impact on pollinator populations. Shading represents the quantity of evidence recorded for each intervention, where darker shades represent a higher count. Specifically, no shading represents a count of 0, the lightest shade represents a count of 1, the light shade represents counts of 2–5, the dark shade represents counts of 6–20 and the darkest shade represents counts of 21 or higher [217].

Sub-theme	Intervention	Total	-	0	+	References
Availability of floral resources	Availability of floral resources	8	0	1	7	[79, 106, 114, 127, 131-133, 217]
Proximity to resources	Proximity to floral resources	4	0	2	2	[135-137]
	Proximity to semi-natural habitat	2	0	1	1	[134]
Presence of larval resources	Presence of larval food plant	4	0	0	4	[61, 84, 105, 138]
	Presence of larval habitat	2	0	0	2	[64, 90]
Specific habitat features	Tussocky vegetation	2	0	0	2	[139, 141]
	Sparse vegetation	1	0	0	1	[142]
	Woodland edge	1	0	0	1	[141]
	Hedgerow	3	0	1	2	[105, 106, 140]
	Field margin	2	0	0	2	[133, 140]
	Open terrain	1	0	0	1	[141]
	Sloped ground	1	0	0	1	[142]
	Sandy soil	1	0	0	1	[70]
	Banks/ditches	2	0	0	2	[135, 139]
Nest site availability	Natural nest sites	2	0	0	2	[143, 144]
	Artificial domiciles	2	0	1	1	[113, 145]

Table C

Raw evidence counts extracted from relevant articles returned in the literature search within the site management theme (n = 59). Each piece of evidence was categorised as “negative”, “neutral” or “positive” depending on the impact on pollinator populations. Shading represents the quantity of evidence recorded for each intervention, where darker shades represent a higher count. Specifically, no shading represents a count of 0, the lightest shade represents a count of 1, the light shade represents counts of 2–5, the dark shade represents counts of 6–20 and the darkest shade represents counts of 21 or higher [218–221].

Sub-theme	Intervention	Total	-	0	+	References
Grazing	Grazing	3	2	1	0	[81, 82, 207]
	Low intensity grazing	5	0	0	5	[138, 146-148]
	Summer grazing	5	5	0	0	[57, 149]
	Grazing by sheep	1	1	0	0	[86]
	Grazing by traditional or commercial livestock breeds	1	0	1	0	[147]
Cutting	Frequent cutting	2	2	0	0	[81, 82]
	Cutting in summer	8	7	0	1	[53, 54, 121]
Removal of cut material	Removal of cut material	4	2	0	2	[53]
Mowing	Frequent mowing	2	2	0	0	[150, 151]
	Mowing in summer	1	1	0	0	[102]
Taller or structurally diverse vegetation	Heterogeneous sward structure	5	0	0	5	[81, 82, 140, 152]
	Tall vegetation	15	0	4	11	[52, 60, 70, 73, 86, 88, 146, 151-154]
	Mid-late successional vegetation	2	0	0	2	[166, 218]
Agrochemical application	Fertiliser	9	5	2	2	[81, 82, 148, 160, 166, 167, 169]
	Herbicide	4	2	0	2	[117, 121, 148, 158]
	Insecticide	26	21	4	1	[69, 77, 148, 155-165, 219-221]
Low intensity hedgerow management	Cutting in winter	1	0	0	1	[170]
	Reduced cutting frequency	1	0	0	1	[170]
	Incremental cutting	1	0	0	1	[170]
	Unmanaged hedgerow	1	0	0	1	[150]
Organic farming	Organic farming	15	2	1	12	[65, 92, 94, 109, 116, 171-177]

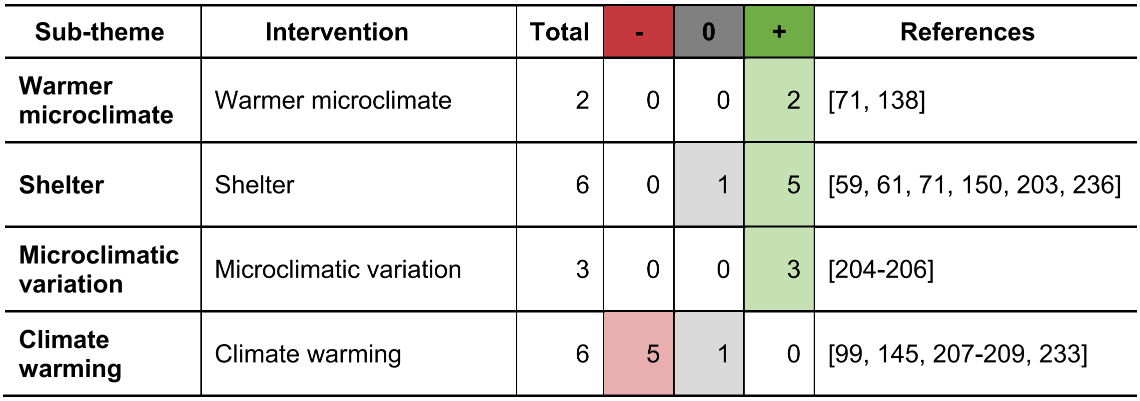
Table D

Raw evidence counts extracted from relevant articles returned in the literature search within the landscape and connectivity theme (n = 81). Each piece of evidence was categorised as "negative", "neutral" or "positive" depending on the impact on pollinator populations. Shading represents the quantity of evidence recorded for each intervention, where darker shades represent a higher count. Specifically, no shading represents a count of 0, the lightest shade represents a count of 1, the light shade represents counts of 2–5, the dark shade represents counts of 6–20 and the darkest shade represents counts of 21 or higher [222–235].

Sub-theme	Intervention	Total	-	0	+	References
Semi-natural or heterogeneous landscape	Semi-natural or heterogeneous landscape	74	9	13	52	[48, 50, 51, 55, 60, 63-65, 67, 68, 70, 73, 74, 88, 93, 102, 104, 109, 110, 120, 126, 135, 148, 151, 160, 174, 175, 177, 179-192, 196, 198, 208, 222-225]
	Less agricultural or homogenous landscape	32	7	4	21	[47, 48, 63, 66, 69, 128, 135, 151, 160, 172, 173, 185, 187, 192, 194, 224, 226-233]
Organic farming in the landscape	Organic farming in the landscape	4	0	0	4	[49, 62, 92]
Linear features in the landscape	Roads	4	2	0	2	[70, 80, 193]
	Edge habitat	8	0	2	6	[70, 80, 192-194]
	Ditches	1	0	0	1	[135]
Proximity and connectivity to semi-natural habitat	Semi-natural corridors	5	0	1	4	[107, 108, 195, 196, 234]
	Connected habitats	3	1	1	1	[235]
	Proximity to semi-natural habitat	14	0	6	8	[56, 66, 73, 105, 193, 198-200]
Large habitat area	Large habitat area	3	0	0	3	[60, 64, 190]

Table E

Raw evidence counts extracted from relevant articles returned in the literature search within the climate theme (n = 16). Each piece of evidence was categorised as "negative", "neutral" or "positive" depending on the impact on pollinator populations. Shading represents the quantity of evidence recorded for each intervention, where darker shades represent a higher count. Specifically, no shading represents a count of 0, the lightest shade represents a count of 1, the light shade represents counts of 2–5, the dark shade represents counts of 6–20 and the darkest shade represents counts of 21 or higher [236].



Sub-theme	Intervention	Total	-	0	+	References
Warmer microclimate	Warmer microclimate	2	0	0	2	[71, 138]
Shelter	Shelter	6	0	1	5	[59, 61, 71, 150, 203, 236]
Microclimatic variation	Microclimatic variation	3	0	0	3	[204-206]
Climate warming	Climate warming	6	5	1	0	[99, 145, 207-209, 233]

Table F
The results of Chi-square goodness-of-fit tests undertaken on interventions affecting pollinators made up of evidence categorised as having a negative, neutral or positive impact. Grey shading indicates that evidence counts were not high enough for analysis to be performed.

Theme	Sub-theme	X^2	df	p
Foraging resources	Presence of flowering plants	115.98	2	<0.001
	Presence of hedgerow			
	Season-long access to resources	21.13	2	<0.001
	Sown vegetation	34.00	2	<0.001
	Naturally established vegetation			
Nesting, breeding and reproductive resources	Availability of floral resources			
	Proximity to resources			
	Presence of larval resources			
	Specific habitat features			
	Nest site availability			
Site management	Grazing	3.60	2	0.17
	Cutting			
	Removal of cut material			
	Mowing			
	Taller or structurally diverse vegetation	24.36	2	<0.001
	Agrochemical application	26.00	2	<0.001
	Low intensity hedgerow management			
	Organic farming	14.80	2	<0.001
Landscape and connectivity	Semi-natural or heterogeneous landscape	60.25	2	<0.001
	Organic farming in the landscape			
	Linear features in the landscape			
	Proximity and connectivity to semi-natural habitat	9.91	2	0.007
	Large habitat area			
Climate	Warmer microclimate			
	Shelter			
	Microclimatic variation			
	Climate warming			

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