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Realising co-benefits for natural capital and ecosystem services from solar parks: A co-developed, evidence-based approach

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ABSTRACT

The number of ground-mounted solar parks is increasing across the world in response to energy decarbonisation. Solar parks offer an opportunity to deliver ecosystem co-benefits but there is also a risk that their development and operation may be detrimental to ecosystems. Consequently, we created the Solar Park Impacts on Ecosystem Services (SPIES) decision-support tool (DST) to provide evidence-based insight of the impacts of different solar park management practices on ecosystem services. The SPIES DST is underpinned by 704 pieces of evidence from 457 peer-reviewed academic journal articles that assessed the impacts of land management on ecosystem services, collated through a systematic review. Application to two operational solar parks evidences the commercial relevance of the SPIES DST and its potential to enable those responsible for designing and managing solar parks to maximise the ecosystem co-benefits and minimise detrimental effects. Further, evaluation using data from nine solar parks across the south of England demonstrates the validity of the DST outcomes. With the increasing land take for renewable energy infrastructure, DSTs, such as SPIES, that promote the co-delivery of other ecosystem benefits can help to ensure that the energy transition does not swap climate change for local scale ecosystem degradation, and potentially prompt improvements in ecosystem health.

1. Introduction

Renewable energy generation has been increasing worldwide since the turn of the 21st century, and this is expected to continue as electricity supplies are decarbonised in response to global agreement on limiting the impacts of climate change [1]. Photovoltaic (PV) capacity has been growing exponentially over the past decade, consistently out-performing projections, and is predicted to become the dominant renewable energy source by 2050 [2–4]. By the end of 2016, there were 307 GW of PV installed globally with 12 GW in the UK and 57% of that ground-mounted as solar parks covering between 68 and 340 km^2 [3,5–7]. Moreover, globally, the UK has the third highest number of utility-scale solar parks, behind the USA and China [8].

The social, economic and environmental impacts of solar PV have been compared to other renewable energy technologies [e.g. Refs. [9,10]], with many comparisons focusing on land use footprint and greenhouse gas emissions [9,11,12]. However, in comparison with other electricity generation methods, solar parks have low energy densities and prompt a notable land use change [13] and thus could have important impacts on ecosystem services and natural capital. Given the increasing acknowledgement of the underpinning importance of ecosystem services and natural capital in both the scientific literature and policy documents, understanding the potential implications of solar parks is critical [14,15]. The potential for such impacts to be positive is

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Abbreviations: BRE, Building Research Establishment; DST, decision support tool; EST, Ecosystem Services Transfer; GP, Guy Parker; GPS, Global Positioning System; GW, gigawatt; MW, megawatt; PV, photovoltaic; qGISiv, Quanum Geographical Information System, version 4; SPIES, Solar Park Impacts on Ecosystem Services.

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arguably greater than for any other land use change as many solar parks are built on intensively managed agricultural land and are managed as low-intensity grasslands [16]. Further, the minimal land disturbance required during solar park operation, the anticipated 25–30 years lifetime and the ability to stipulate land management within planning consents provide excellent conditions to enhance positive ecosystem impacts and minimise negative impacts, promoting net environmental gain [17].

Despite the opportunities to improve ecosystem services and natural capital, the impacts of solar parks on ecosystems remain poorly resolved [18]. Potential environmental effects and ecological responses have been summarised, including implications for biodiversity, water, soil erosion, and air quality [19]. However, only a limited number of impacts, given the scale of the land use change, have been quantified at individual sites, including changes to the microclimate with implications for vegetation community composition, biomass and greenhouse gas release [20]. Ecosystem effects may occur onsite, for example greater invertebrate abundance has been observed at solar parks managed for biodiversity compared to agricultural alternatives [21], and off-site, for example the provision of habitat for pollinators within solar parks may benefit surrounding agriculture [22]. Further, given the wide geographical spread of solar parks, they offer a notable land area to enhance biodiversity across the UK, through contributing to landscape-level conservation [23]. For example, management of solar parks for biodiversity has been promoted as a means of addressing farmland wildlife decline concerns, through the creation of relatively secure and minimally disturbed refuges, often embedded within tracts of more intensively managed agricultural land [24].

There is scope to better incorporate scientific information into environmental policy and practice decisions, for example through the use of decision frameworks and decision support tools (DSTs), capitalising on recent advances in understanding of biodiversity and landscape-level ecosystem services [25]. DSTs for solar parks do exist, but thus far have been limited to providing guidance on the suitability of locations for solar park development [e.g. Refs. [26–33]]. The DST commonly draw on solar energy resource potential, land availability (based on current land use, topographical settings and ecological value), existence of infrastructure (i.e. road access and transmission), and any relevant legislation. For example, the Carnegie Energy and Environmental Compatibility model determines the compatibility between solar energy developments, environmental suitability and land resources in California, resolving how energy and climate change goals could be met and the suitability of existing development locations [33,34]. Whilst these spatial analysis tools provide energy stakeholders, developers, and policymakers with guidance on where to locate solar energy developments with minimal environmental and conservation impacts, they do not inform how to manage the developments to minimise ecological damage and maximise ecological co-benefits. With the increasing acknowledgement of the degraded state of the environment more broadly, there is an increased need for evidence-based tools that inform ecosystem management.

Good practice guidelines for solar park land management have been developed, for example the BRE Biodiversity Guidance for Solar Developments and Agricultural Good Practice Guidance for Solar Farms [24,35], but the guidelines are not explicitly linked to an extensive scientific evidence base given the limited quantification of the impacts of solar parks on natural capital and ecosystem services. However, the effects of land management on ecosystem services is relatively well evidenced and is likely to apply to solar parks, for example, the effects of mowing regimes on plant and insect biodiversity [36–38]. Collating and applying this evidence base to solar parks presents an opportunity to maximise environmental co-benefits and reduce any detrimental impacts of solar park development and management. Further, managing solar parks to enhance ecosystem services may avert cost and offer some agricultural revenue streams, for example co-using the land for livestock grazing or crop growth [39,40].

Given the increase in land use change for solar parks and the opportunity they offer to increase ecosystem services and natural capital, a DST that informs management of solar parks based on robust scientific evidence has the potential to promote notable ecological gains alongside much needed low carbon energy. Here we introduce the Solar Park Impacts on Ecosystem Services (SPIES) DST, which provides the first accessible, evidence-based assessment of the effects of solar park management practices on biodiversity and ecosystem services in the UK. The SPIES DST summarises the effects of solar park management practices on ecosystem services, applied both individually and in combination, and displays links between these impacts and the underlying scientific evidence in a form accessible to the public. We evaluate the SPIES DST using two commercial case studies and comparative data from a range of solar parks across England and Wales, comparing the habitats and biodiversity and pollination services change predictions with empirical data collected across the sites.

2. Methods

To ensure applicability, the SPIES DST was co-developed with a broad cross-sectoral stakeholder group, including those involved in solar park development, operation and maintenance, nature conservation bodies, land owners, the farming community and solar trade advice centres (see acknowledgements for the full list). There were five main stages to the development of the SPIES DST (Fig. 1): (1) identification of potential solar park land management actions and an appropriate ecosystem service classification; (2) a systematic literature review to collate evidence of the effects of land management actions on ecosystem service provision; (3) development of an evidence database that details the direction and scale of land management action impacts on ecosystem services and the strength of the evidence; (4) development of the SPIES DST structure and function; and (5) evaluation of the SPIES DST.

2.1. Management actions and ecosystem service classifications

A compendium of potential land management actions applicable to solar parks was determined through analysis of those within the existing Ecosystem Services Transfer (EST) Toolkit [41] and stakeholder interviews. These were then discussed at a stakeholder workshop and a final list of appropriate management actions confirmed (see Appendix Table S1). The management actions were categorised into different aspects, such as 'grazing', to enable easy navigation within the SPIES DST.

Different ecosystem service categorisations were also discussed at the stakeholder workshop and the one used by the UK National Ecosystem Assessment [42], with the addition of "maintaining habitats and biodiversity", was selected (Table S2). "Maintaining habitats and biodiversity" was added as this was frequently an environmental priority in national and local plans and was identified as a key factor by the stakeholders.

2.2. Systematic literature review

With the management actions and ecosystem services classified, a database of relevant peer-reviewed literature that provided evidence of the effects of land management actions on ecosystem services was compiled. Firstly, literature relating to land management actions relevant to solar park management was extracted from the existing EST Toolkit database [41], using the management actions identified in the stakeholder workshop (Table S1). This resulted in an EST-derived database of 125 papers. The EST database was compiled using a systematic approach in Web of Science (the most appropriate database for ecological research), searching for 'ecosystem' in combination with habitat types (e.g. 'ecosystem AND lowland agriculture') and management action terms (e.g. 'Plant/maintain wild flower/nectar seed meadows') in the titles or abstracts. Further, a search for articles for all authors of the relevant UK National Ecosystem Assessment Technical

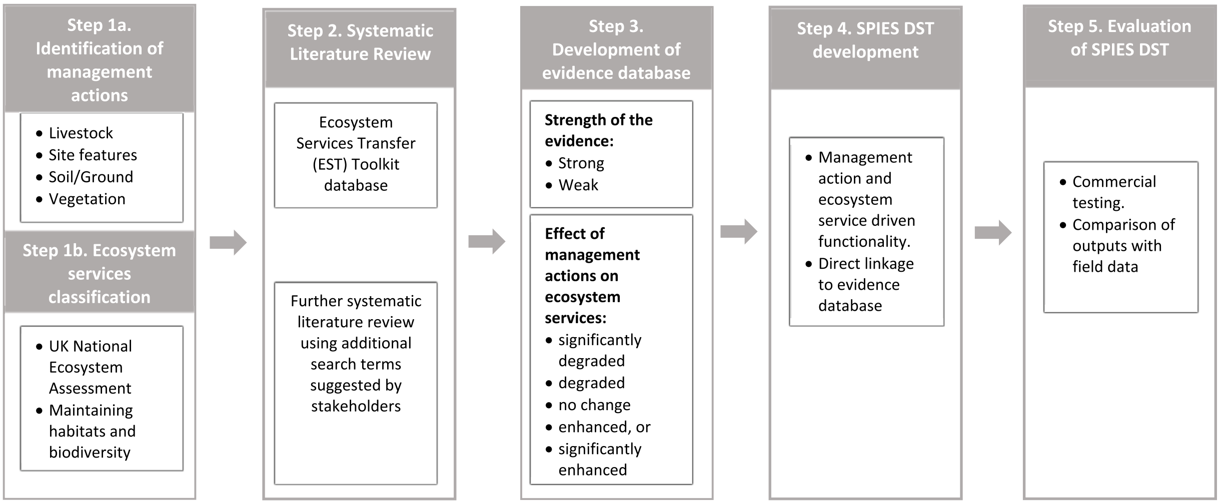

Fig. 1. Diagram of the SPIES decision support tool development workflow.

Report [42] was performed and added to the EST database. All of the articles were then assessed for relevance to the UK based on ecological and environmental factors, such as species studied, climate, topography, and soil type. For example, experiments in French lowlands were included, but Alpine slopes excluded. Then, the abstract of each article, or if inconclusive the whole article, was read to identify if it contained evidence of a management intervention effect on an ecosystem service or good. Evidence was defined as information, preferably numerical, that a management action impacted an ecosystem service, with papers that reported no change or neutral effects retained. Articles that speculated on an effect, but did not assess it within the study, were excluded. If an article demonstrated an effect on an ecosystem service, but did not use ecosystem service terminology it was included (e.g. buffer strips reducing sediment delivery to a river were categorised as effecting water quality as the association between sediment load and water quality is accepted). However, higher order effects were not included as they were too distant from that established in the article (e.g. water quality could impact fish habitats).

To ensure all literature relevant to solar park management was captured, an additional systematic review was undertaken using Web of Science, accessed December 22, 2016. All combinations of management actions and ecosystem services, as established at the stakeholder workshop, were used as search terms (see Tables S1 & S2); these search terms differed from the EST review [41]. The EST Methodology to remove irrelevant papers (described above) was used, leaving 338 additional relevant articles.

2.3. Evidence database development

In total, 704 individual pieces of evidence were extracted from the 457 articles identified during the systematic review (see Table S1 and Table S2 for the spread across management actions and ecosystem services). Six database fields were completed for each piece of evidence: article reference, abstract or summary, management action, ecosystem service, the effect of the management action on the ecosystem service, and the strength of evidence. The inclusion of the article reference enables the user to find the original article if required whilst the abstract or summary provides a brief overview without the need for users to pay for access to the articles. The management action and ecosystem service fields enable filtering of the evidence. The effect of management actions on ecosystem services provides insight into the magnitude and direction of effect, categorised as significantly degraded, degraded, neutral, enhanced, or significantly enhanced. The magnitude of effect was considered individually for each type of evidence as the frequency and diversity of data types prohibited universally appropriate categorisation. If evidence suggested a strong or substantial effect, for example, buffer strips that reduced total runoff by 33%, N loss by 44% and P loss by 50% compared to a control [43], it was categorised as “significantly enhanced” or “significantly degraded”. A suggested weak effect, or if the magnitude was not detailed, was categorised as “enhanced” or “degraded”. For example, evidence from Thomas et al. [44] for the effect of creating/maintaining beetle banks on maintaining habitats and biodiversity was graded as “enhanced” as whilst they increased habitats, it took ten years for plant diversity to reach that of field margins and it was noted that increasing their diversity further would be more beneficial for invertebrates. Evidence that suggested the management action had no effect, or where negative and positive effects cancelled each other out (e.g. carbon sequestration and methane emission on climate regulation) were categorised as neutral. Finally, evidence was categorised as weak if it was based on simulations or experimental designs tentatively relevant to UK solar parks, and the remainder, comprising relevant well-designed field studies, were graded as strong. This provides an indication of confidence in the evidence, which could be useful in informing decisions if there was conflicting evidence or low evidence counts. RRB categorised the evidence and a selection was cross-checked by PCLW and AA to ensure consistency.

2.4. Development of the SPIES DST structure and function

In response to stakeholder needs, the SPIES DST was developed with two entry points – ‘management strategies’ and ‘ecosystem services’ (Fig. 2). Throughout the SPIES DST all the tables are shaded with a colour ramp to aid visual interpretation, the strength of evidence (i.e. if the evidence was categorised as weak or strong) can be displayed to indicate the level of confidence in the outcomes, and the user can view the filtered evidence database and access the article summaries and references.

The ‘management strategies’ entry point enables the user to evaluate the likely effect of different solar park management action strategies on ecosystem service provision. Users select two alternative management strategies, each incorporating a suite of different management actions (referred to here as strategy 1 and 2), which could be two potential strategies or the current strategy and a proposed strategy. The evidence is then filtered and displayed in four tables: (1) a strategy 1 table that gives the spread of evidence relating to the first management strategy across significantly degraded, degraded, neutral, enhanced, significantly enhanced, (2) a strategy 2 table with the equivalent information for the second strategy, (3) a comparison table that quantifies the change in evidence from strategy 1 to strategy 2, and (4) a summary table displaying which ecosystem services will be enhanced, unchanged or

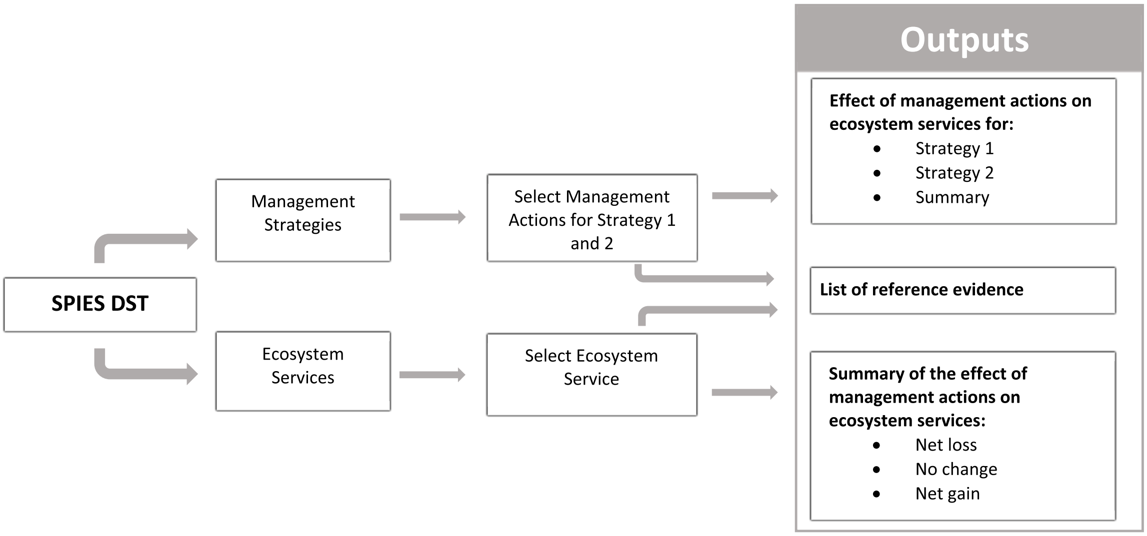

Fig. 2. Workflow of the SPIES decision support tool.

degraded by switching management practices from strategy 1 to strategy 2.

To determine if ecosystem services were degraded, unchanged or enhanced, given there was commonly a spread of data, an impact score (s) was calculated using Eq. (1) for each ecosystem service for both management strategies. The impact score was derived from the number of pieces of evidence within each effect category – significantly degraded (a), degraded (b), enhanced (c) and significantly enhanced (d):

$$s = (-1a) + (-0.5b) + (0.5c) + (1d). \tag{1}$$

The score indicates whether the overall effect of the management strategy on each ecosystem service was negative, neutral or positive. The difference between the two management strategy scores for each ecosystem service determines the difference between the two management strategies. The magnitude of the impact scores cannot be used to compare between the ecosystem services given variation in the number of pieces of evidence.

In addition to examining the change in ecosystem services between two management strategies, the effects of individual management actions on ecosystem services, and the variation in the evidence, can be examined. Here, the users select a management action and a table with the percentage of evidence for each effect category (i.e. significantly degraded, degraded, neutral, enhanced and significantly enhanced) for all ecosystem services is displayed. For example, mowing later in the year enhanced 'maintaining habitats and biodiversity' overall, with 4%, 11%, 19%, 41%, 26% of the evidence categorised as significantly degraded, degraded, no change, enhanced and significantly enhanced respectively ($n = 26$) and had a neutral effect on pollination regulation ($n = 1$).

The 'ecosystem services' entry point enables users to identify which management actions they should employ to enhance specific ecosystem services. Users select the ecosystem service(s) that they wish to enhance, the evidence is filtered and two tables are produced. The first table gives the spread of evidence for each management action across significantly negative, negative, neutral, positive, significantly positive effect categories. The second table is a summary table that lists the management activities that have a negative, no impact and a positive effect, determined by Eq (1), on ecosystem services with negative values indicating a net loss in the ecosystem service and positive values a net gain. Moreover, as for management actions, the user can also select individual ecosystem services, and a table is displayed that shows the spread of evidence between significantly negative and significantly positive.

2.5. *Evaluation of the SPIES DST*

The SPIES DST was evaluated using two approaches. Firstly, it was applied in a commercial setting to assess the functionality. Second, existing field vegetation and pollinator data were used to assess the outcomes suggested by the evidence base against that measured at existing solar parks.

To test the commercial functionality of the SPIES DST it was applied to two new solar park sites by an ecological consultant (co-author GP of Wychwood Biodiversity). The sites were selected as the site owners were interested in promoting ecosystem services and they were live projects in the ecological consultants portfolio. Firstly, the SPIES DST was used to determine the potential ecosystem service impacts of implementing a new solar park management strategy, using the 'management actions' entry point, at Southill Community Energy's Southill Solar Farm (4.5 MW capacity), Oxfordshire, UK. This was performed by GP, who had undertaken ecological assessments at the site, in consultation with Southill Solar Farm management group. The then current management strategy was selected and potential changes explored until a future management action strategy, that was suitable in light of the site characteristics, financial restrictions and management group priorities, was identified. Secondly, the SPIES DST tool was applied to NextEnergy's Emberton Solar Park, where the aim was to maximise pollination ecosystem services. Again, this was conducted by GP in collaboration with the solar park managers.

Existing field vegetation and pollinator abundance and diversity data (collated as part of an industry study) were used to evaluate the outcomes of a selection of solar park management actions on 'habitats and biodiversity' and 'pollination services' by the SPIES DST; see Montag et al. [21] for full study details. The field data were collected at nine sites, across Cambridgeshire, Cornwall, Dorset, Gloucestershire, Hampshire, Norfolk, Oxfordshire, Sussex and the Vale of Glamorgan (selected through negotiation with the ecological consultants clients) in June 2015. At each site, sampling was undertaken within the solar park and an adjacent control field that was under the same management regime (i.e. arable crop production or intensive pasture) as the solar park field prior to the construction.

Vegetation species (Poaceae family and eudicots) were assessed using 50 by 50 cm quadrats. Thirty quadrats were recorded at each site, comprising 20 quadrats within the solar park (10 quadrats were between PV array rows and 10 quadrats were directly beneath panels but these were grouped for analysis to determine the overall effect), and 10 quadrats within the control plot. The quadrat locations were selected using random points generated by qGISiv mapping software and were located on the ground using a GPS device. Abundance and species richness of butterflies and bumblebees (diurnal species of Order Lepidoptera and from Family Apidae, tribe Bombini, hereafter referred to as butterflies and bees, respectively) were surveyed using ten 100 m transects in each solar park and adjacent control site. Transects were orientated east to west and spaced evenly throughout the solar park and control fields, with one transect at the northern field boundary and one at the southern. The transects were walked at a slow pace, with all bee and butterfly species within 2.5 m of each side of the transect line recorded. Five of the sites were re-visited in late June/July due to inclement weather on the first site visits.

To verify the observed predicted changes in ‘habitats and biodiversity’ and ‘pollination services’ by the SPIES DST, we selected the appropriate SPIES management actions for each of the solar parks (Table 1). We then compared the outcomes with statistical analysis of the observed vegetation (analysed for all plants, and also eudicots and grass separately), bee and butterfly species richness data for ‘habitats and biodiversity’ and bee and butterfly abundance data for ‘pollination regulation’. Mann-Whitney and Kruskal-Wallis analyses, with Bonferroni correction, were applied to determine whether there were statistically significant differences in the median abundance and species richness of plants and pollinators between the control sites and solar parks and with the management action, respectively. The effect size was calculated as $r = \frac{Z}{\sqrt{N}}$, where Z is the Kruskal-Wallis standardised test result, with Bonferroni correction, and N the total number of samples. The standard value of r for small, medium, and large sizes was 0.1, 0.3 and 0.5, respectively. Analyses were conducted in R software [45] and SPSS [46].

3. Results: evaluation of the SPIES DST

3.1. Commercial applicability

By switching from the current management strategy at Southill Solar Farm, to the strategy identified through consultation with GP and the solar farm management group (Table 2), the SPIES DST determined that eight ecosystem services would be enhanced, seven unaffected, and one degraded, based on 389 pieces of evidence (Table 3). The amount of evidence for each management action was highly variable, ranging from just one piece up to 263 pieces. The evidence was generally strong, with the exception of water quality regulation, for which 20% of the evidence was weak suggesting some caution may be required (Table 3). However, there were fewer than ten pieces of evidence for nine of the ecosystem services (Table 3).

Application of the SPIES DST to Emberton Solar Park identified seven actions that would potentially enhance pollination ecosystem services and one management action that would be degrading (Table 4). For the management actions associated with enhanced pollination regulation, all the evidence suggested positive effects or no change, with most positive evidence for ‘Create/maintain buffer zones/field margins/set-aside’ and ‘Plant/maintain wild flower/nectar seed meadows’. The associated evidence was strong, with the exception of that for ‘connect habitats’. However, for six out of the eight management actions there were fewer than ten pieces of evidence (Table 4).

Table 1
Categorisation of solar park management by SPIES management actions.

Management actions	Site								
	2	3	4	5	6	7	8	10	11
Graze later in the year		✓		✓	✓			✓	
Plant/maintain wild flower/ nectar seed meadows				✓		✓		✓	✓
Create/maintain buffer zones/ field margins/set-aside	✓	✓	✓	✓	✓	✓	✓		

Table 2
The current and proposed management strategies for Southill Solar Farm, Oxfordshire, UK.

Category	Management action	Current	Proposed
Grazing	Graze later in the year		✓
	Replace mowing with grazing if previously mowed		✓
Habitats	Create/maintain artificial refugia		✓
	Create/maintain artificial wetlands or wet features		✓
	Create/maintain buffer zones/field margins/set-aside	✓	✓
	Install/maintain bat boxes		✓
	Install/maintain bird boxes		✓
Inputs	Reduce/cease pesticide and fertiliser use if previously used		✓
Soil	Create/maintain areas of bare ground		✓
Trees & hedges	Cut hedges in winter	✓	✓
	Maintain low hedges	✓	
Vegetation	Mow later in the year	✓	✓
	Plant/maintain hedgerows/shelterbelts		✓
	Plant/maintain wild flower/nectar seed meadows	✓	✓

3.2. Comparison with existing solar park data

Evidence within the SPIES DST suggested that all three management actions should enhance habitats and biodiversity and pollination regulation (Table 5). Most of the evidence relating to the enhancement of ‘maintaining habitats and biodiversity’ was associated with the management action of creating/maintaining buffer zones/field margins/set-aside, while most evidence relating to the enhancement of ‘pollination regulation’ was associated with plant/maintain flower/nectar seed meadows (Table 5).

Across all sites, 108 plant species comprising 27 grass species and 81 eudicots were identified. Plant, grass and eudicot species richness were higher in the solar park sites compared to the control (Fig. 3). Further, across all sites, 17 butterfly species and eight species of bees were observed during site visits, with butterfly and bee species richness higher in solar park sites compared with control sites (Fig. 3). Further plant, grass and eudicot species richness varied with management actions, all of which had a strong effect except for planting/maintaining wild flower/nectar seed meadows and creating/maintaining buffer zones/field margins/set-aside for grass richness which had a medium effect size (Table 6, Fig. 4). Overall this aligns with the SPIES DST outcome, however there was less evidence for grazing later in the year enhancing or significantly enhancing habitats and biodiversity than for creating/maintaining buffer zones/field margins/set-aside compared or planting/maintaining wild flower/nectar seed meadows (2%, 58% and 31% respectively, Table 5).

Across all solar park sites a total of 332 individuals of the 17 butterfly species and 858 individuals of the eight bee species were observed during site visits. Butterfly and bee abundances were higher in solar park sites compared with control sites (Fig. 5). Butterfly abundance was higher in solar parks where sheep grazed later in the year and in those that promoted meadows by planting or maintaining wild flower and nectar seed. Bee abundance was also higher in solar parks that promoted wild flower and nectar seed meadows compared with control sites (Fig. 6), all with a medium effect size (Table 6). These findings were in agreement with the SPIES DST outputs, which indicated a positive effect of planting/maintaining wild flower/nectar seed meadows and grazing later in the year, although there was very limited evidence for grazing later in the year (Table 5). However, the SPIES output also suggested that creating/maintaining buffer zones/field margins/set-aside would enhance pollination but this did not have a significant effect on the abundance of bees and butterflies when compared to control sites.

Table 3
The effect of changing from the current to the proposed management strategy on ecosystem services at Southill Solar Farm, Oxfordshire, UK. ⇩ indicates that overall the ecosystem service was degraded, ⇔ no change and ⇧ enhanced. The number in parentheses is the impact score (eq. (1)). The '–', '-', '0', '+' and '++' columns provide the number of pieces of evidence that suggest a significantly degraded, degraded, no change, enhanced and significantly enhanced effect, respectively. The number to the left of '→' is the number of pieces of evidence for the current strategy and to the right for the proposed strategy. N is the total number of pieces of evidence.

Ecosystem service	Net change (impact score)	Change in number of pieces of evidence relating to each effect category from current to proposed management					N	Evidence classified as weak (%)
		–	-	0	+	++		
Flood regulation	⇩ (−1)	0 → 1	0 → 1		3 → 5	1 → 1	4 → 8	0
Air quality regulation	⇔							
Biomass provision	⇔							
Educational/cultural	⇔			1 → 1			1 → 1	0
Food provision	⇔			1 → 1			1 → 1	0
Soil erosion regulation	⇔		0 → 1	0 → 4	2 → 3	2 → 2	4 → 10	0
Soil quality regulation	⇔		0 → 1		1 → 2		1 → 3	0
Spiritual or religious	⇔			1 → 1			1 → 1	0
Climate regulation	⇧ (+4)		0 → 3	0 → 2	2 → 5	1 → 3	3 → 13	0
Habitats & biodiversity	⇧ (+89)	1 → 2	4 → 10	15 → 30	106 → 161	36 → 57	162 → 263	5
Pest & disease regulation	⇧ (+7)		3 → 3	2 → 2	6 → 11	0 → 1	11 → 17	6
Pollination regulation	⇧ (+12)			1 → 2	28 → 32	11 → 15	40 → 49	0
Pollution regulation	⇧ (+1)				1 → 2		1 → 2	0
Recreation & aesthetic	⇧ (+3)				0 → 3		0 → 3	0
Water cycle support	⇧ (+3)				1 → 2	0 → 1	1 → 3	0
Water quality regulation	⇧ (+10)			1 → 1	4 → 12	1 → 2	6 → 15	20

Table 4
The management actions that degrade or enhance pollination regulation. ⇩ indicates that overall the management action had a negative effect and ⇧ a positive effect. The number in parentheses is the impact score (eq. (1)). The '-', '0', '+' and '++' columns provide the number of pieces of evidence that suggest a negative effect, no effect, a positive effect and a significant positive effect, respectively (there were no pieces of evidence that suggested significant negative effect and therefore this column was removed). *N* is the total number of pieces of evidence.

Management action	Net effect (impact score)	Frequency of evidence in different effect categories				*N*	Evidence classified as weak (%)
		–	0	+	++		
Reduce grazing intensity if previously grazed	⇩ (−1)	1				1	0
Graze later in the year	⇧ (+1)			1		1	0
Install/maintain bee hives	⇧ (+2)			2		2	0
Connect habitats	⇧ (+17)		1	3	2	6	17
Create/maintain buffers/field margins/set-aside	⇧ (+17)			11	3	14	0
Plant/maintain hedgerows/shelterbelts	⇧ (+10)		1	2	4	7	0
Plant/maintain wild flower/nectar seed meadows	⇧ (+33)			17	8	25	0
Reduce/cease pesticide and fertiliser use	⇧ (+1)			1		1	0

Table 5
The effect of management actions undertaken at the study solar parks on maintaining habitats and biodiversity and pollination regulation. The '0', '+' and '++' columns provide the number of pieces of evidence that suggest no change, enhanced and significantly enhanced effect, respectively (no evidence suggested significantly degraded, or degraded effects so '–' and '-' columns were excluded). *N* is the total number of pieces of evidence.

Management action	Ecosystem service	Frequency of evidence in different effect categories			*N*	Evidence classified as weak (%)
		0	+	++		
All	Habitats & biodiversity	12	91	27	130	2
	Pollination regulation		28	11	61	0
Grazing later in the year	Habitats & biodiversity	1	3		4	0
	Pollination regulation		1		1	0
Planting/maintaining wild flower/nectar seed meadows	Habitats & biodiversity	5	31	9	45	1
	Pollination regulation		16	8	24	0
Creating/maintaining buffer zones/field margins/set-aside	Habitats & biodiversity	6	57	18	81	3
	Pollination regulation		11	3	14	0

4. Discussion

The SPIES DST facilitates the enhancement of the energy-environment nexus at local and global scales by promoting local and landscape-level ecological enhancements with low-carbon electricity supply. It achieves this through providing an accessible, evidence-based method to inform management interventions that can enhance the biodiversity and ecosystem service co-benefits from solar parks, with a co-development approach ensuring the functionality and usability delivers to stakeholder needs. The SPIES DST complements existing DSTs, which offer solar park location guidance, by informing potential ecosystem services benefits in response to management actions. Used in combination with existing DSTs that focus on locations to mitigate environmental and ecological harm [26–28,30–32], the SPIES DST brings the ability to enhance ecosystem services and provide ecosystem co-benefits in solar park planning, development and operational stages. Further, implementing practices informed by the SPIES DST can benefit society, for example, through supporting agricultural pollination, abating pollution, and improving cultural ecosystem services such as sense of place.

The universally applicable, yet context specific interpretability of the SPIES DST is a key strength. The need for DSTs to be generic and yet

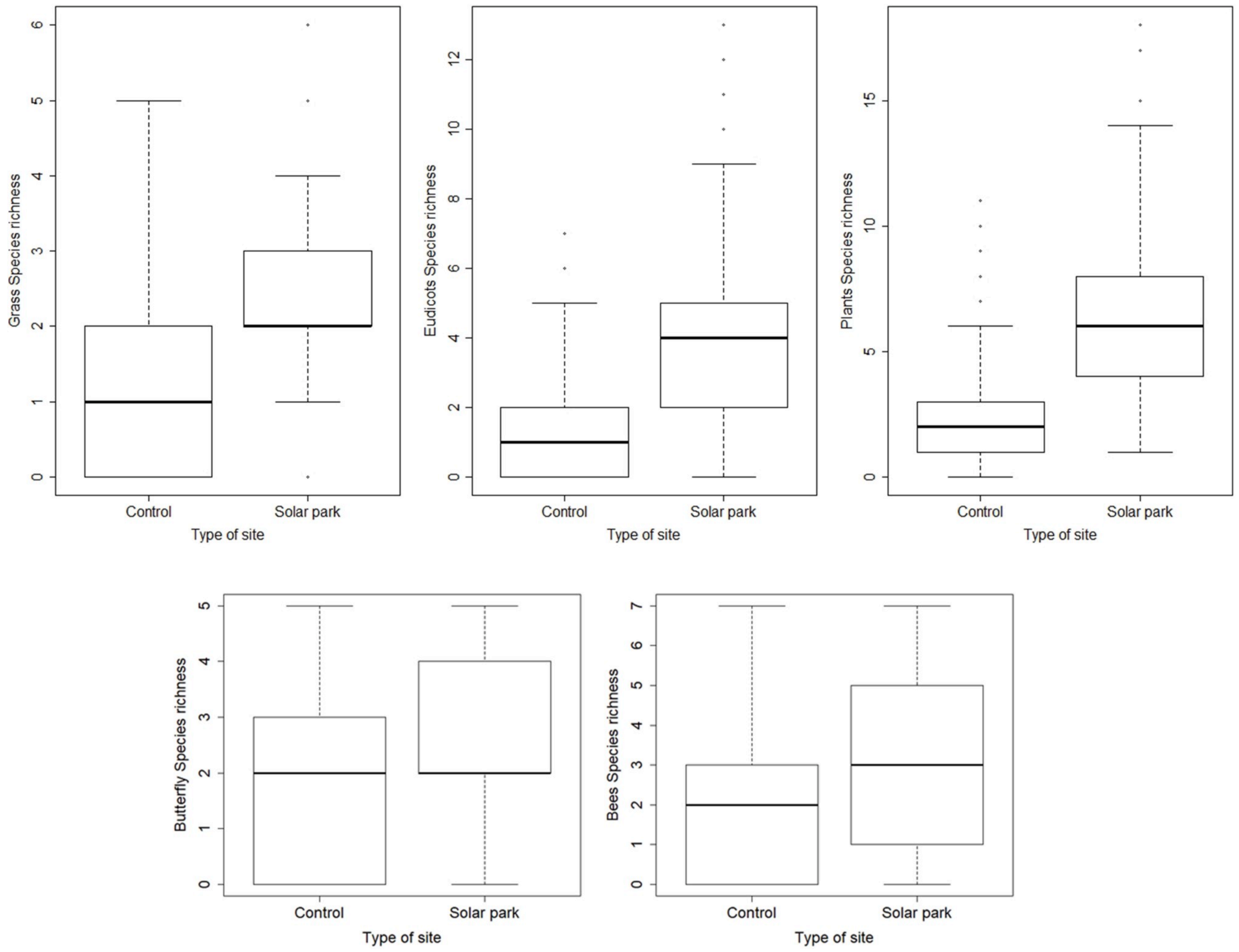

Fig. 3. Boxplots comparing plant, grass, eudicot, bee and butterfly species richness between control sites (N = 9) and solar parks (N = 9). Plant, grass, eudicot, bee and butterfly species richness was greater in solar parks compared with control sites (Plant: median = 6 vs. 2, Mann-Whitney: U = 23,289, $p < 0.001$; grass: median = 3 vs. 1, Mann-Whitney: U = 20,312.5, $p < 0.001$; eudicot: median = 4 vs. 1, Mann-Whitney: U = 23,152.5, $p < 0.001$; bee: median = 4 vs 2, Mann-Whitney: U = 211, p = 0.043; butterfly: median = 4 vs 3; U = 214, p = 0.034, respectively).

applicable to cases with specific characteristics can prohibit their use or reduce confidence in the potential outcomes resulting from their application. The SPIES DST was designed to avoid this through providing users with direct access to the underpinning evidence. Specifically, the SPIES DST does not offer any value judgement on the best ecosystem service or management actions but summarises the scientific evidence for the effects of management actions on ecosystem services. Consequently, the user can take into account the solar park specific objectives and use the DST to identify management actions specific to them, as demonstrated by the Emberton Solar Park commercial case study. Moreover, if using the 'management strategies' entry point, the effects on all ecosystem services impacts are given, and those deemed unimportant at the site can be ignored; the opportunity cost of not enhancing some ecosystem services does not impact the outcomes. For example, if it was desirable to manage a solar park for sheep grazing or food crops [47,48], any negative implications of required management actions on other ecosystem services would be delineated but they could be contextualised in the interpretation of the outcomes. Conversely, if the objective was to maximise benefits across all ecosystem services, the SPIES DST can be used to explore suitable management strategies, taking into account cost restraints and site-specific characteristics, as implemented for Southill Solar Park.

The accessibility of the evidence base enables users to analyse the outputs from the SPIES DST and interpret them with reference to local environmental and ecological contexts. Moreover, illustration of the spread of the evidence, for example varying from degraded to significantly enhanced habitats and biodiversity for the selected management strategy for Southill Solar Park (Table 3), actively encourages user contextualisation of the outcomes in light of site-specific objectives and local ecological contexts. For example, for the Southill Solar Park application one piece of the negative evidence for habitats and biodiversity was related to a negative correlation between hedgerow density and passerine abundance and species richness [49]. If the ecological enhancement aims were not focussed on birds or there were more dominant local site conditions that deterred birds, then this piece of evidence could be discounted. This affirms the criticality of the accessibility of the evidence summaries to enable users to refine the likely response at individual solar parks.

Both the Southill and Emberton Solar Park case studies highlighted the uneven spread of evidence across ecosystem services and management actions (Tables 3 and 4), underpinned by the total evidence counts across ecosystem services and management actions (Tables S1 & S2). For Southill Solar Park there was a strong bias towards habitats and biodiversity and no evidence for several ecosystem services, for example biomass materials provision. For Emberton, there was most evidence for creating or maintaining buffer zones/margins/set aside, hedgerows/shelterbelts and wildflower/nectar seed meadows and none for many management actions. This reinforces the need for an expert user to

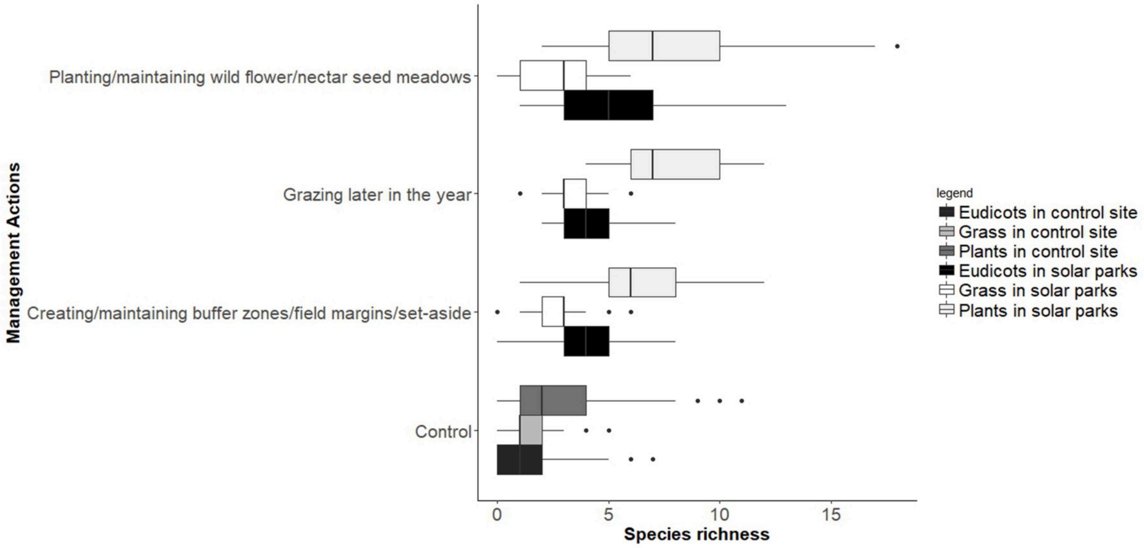

Fig. 4. Plant, grass and eudicot species richness in control sites and solar parks where management actions were applied. Plant, grass, eudicot, bee and butterfly species richness was higher in solar parks compared with control sites and varied with management actions (Plant: median = 2 and median between 6 and 7, Kruskal-Wallis: $H(3) = 120.12$, $p < 0.001$; Grass: median = 1 and median = 3, Kruskal-Wallis: $H(3) = 73.59$, $p < 0.001$; Eudicot: median = 1 and median between 4 and 5, Kruskal-Wallis: $H(3) = 115.85$, $p < 0.001$, respectively. There was no significant variation between control sites and solar park management actions for bee or butterfly species richness (pairwise comparisons with Bonferroni adjusted p-values).

Table 6
Effect size (r) of pairwise comparison, after statistically significant Kruskal-Wallis tests, between control sites and management actions applied at solar parks. The standard value of r for small, medium, and large effect sizes is 0.1, 0.3 and 0.5, respectively.

Management actions	Effect size r				
	Species richness			Abundance	
	Plant	Grass	Eudicots	Butterfly	Bee
Grazing later in the year	0.71	0.63	0.65	0.34	0.49
Planting/maintaining wild flower/nectar seed meadows	0.59	0.34	0.61	0.35	0.46
Creating/maintaining buffer zones/field margins/set-aside	0.55	0.38	0.55	0.20	0.38

interpret the findings and inform decisions about management strategies – no or limited evidence does not preclude a positive effect. However, whilst uneven, it is likely that the spread of evidence was determined by ecosystem services or management actions deemed most pivotal.

Empirical biodiversity data from solar parks enabled us to evaluate the application of the SPIES DST in the field. Comparison of the results showed that the SPIES DST outputs were broadly in agreement with the field vegetation, butterfly and bee data, which indicated higher grass and eudicot species richness and butterfly abundance in solar parks. Further, the agreement between the SPIES DST outputs and the field data demonstrates the value of a generic DST to promote positive effects, despite the known variation in ecosystem response to disturbance and management, in terms of the evidence base, categorisation of potential management actions, time since the management action occurred relative to ecosystem response, and how well the management action was performed. Some of the effect sizes determined from the field data for

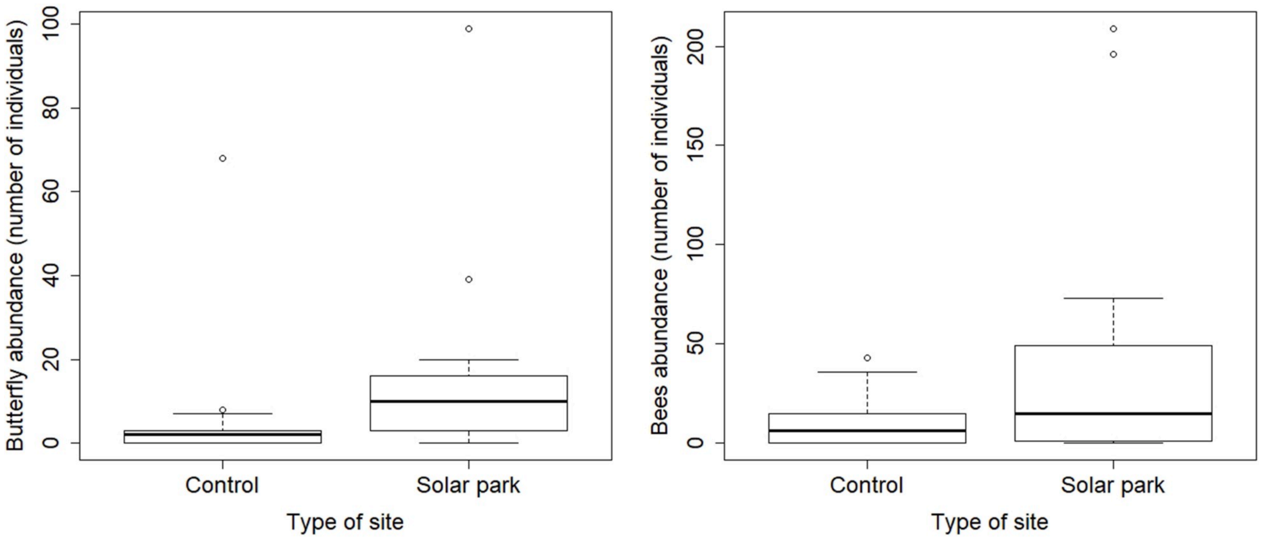

Fig. 5. Boxplots comparing butterfly and bee abundance between control sites ($N = 9$) and solar parks ($N = 9$). Butterfly and bee abundances were significantly higher in the solar park (Butterfly: median 13 vs 2, Mann-Whitney: $U = 245$, $p = 0.001$; Bee: median 37 vs 6, Mann-Whitney: $U = 234$, $p = 0.005$, respectively).

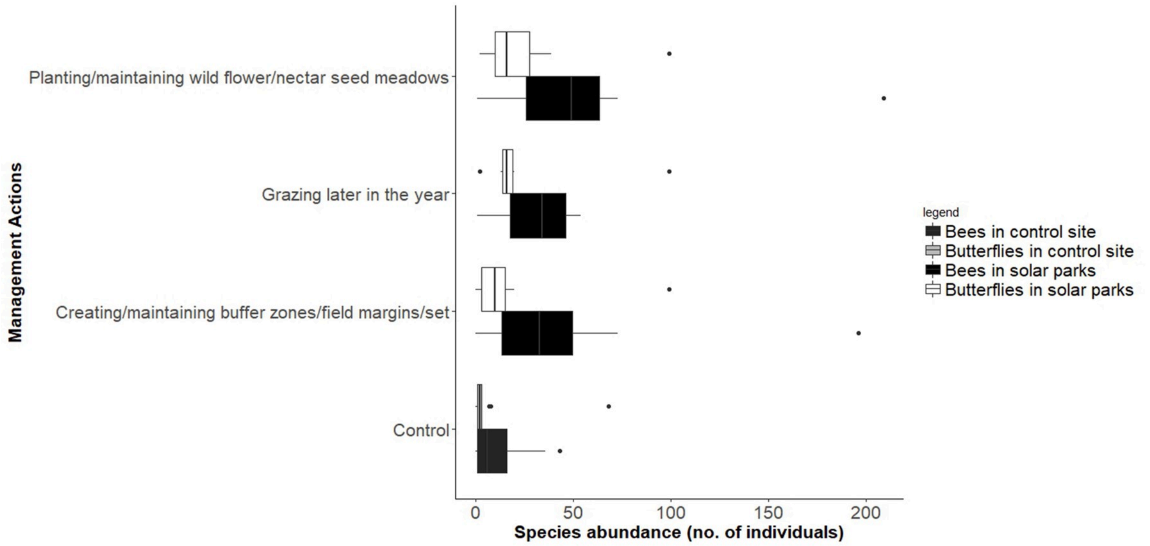

Fig. 6. Boxplot of butterfly and bee abundance in control sites and solar parks where management actions were applied. Higher butterfly abundance was associated with solar parks managed with grazing and meadows compared to control sites (Kruskal-Wallis: H(3) = 11.325, p = 0.010, for grazing median = 16; p = 0.037, effect size: r = 0.34 and for meadows median = 16; p = 0.041, effect size: r = 0. 35). Higher bee abundance was associated with solar parks managed by planting or maintaining wild flower and nectar seed meadows (p = 0.042, effect size: r = 0. 46) compared to control sites (Kruskal-Wallis: H(3) = 8.667, p = 0.034).

the management actions were not fully concordant with the evidence count. However, in terms of landscape scale management for ecosystem services, resolving the direction of change of management activities on ecosystem services is most valuable and magnitude of effect may change in response to site-specific context.

The evaluation of the SPIES DST also highlights the need for further research. The overall spread of evidence between management actions, ecosystems services and within the commercial case studies highlights the areas within which future research is required to provide a greater body of evidence to inform the effect of solar park management on ecosystem services. Specifically, there were fewer than ten pieces of evidence for air quality, biomass material provision, food provision, pollution regulation, recreation and aesthetic interactions, and spiritual or religious enrichment and water cycle support (Table S2) and 21 of the management actions effects were supported by fewer than ten pieces of evidence (Table S1). Further, well-informed management strategies would benefit from the development of measures of 'ecosystems services' as opposed to the finer scale, more specific indicators such as vegetation species richness.

5. Conclusions and policy implications

Land use change for ground-mounted solar parks has occurred at an exponential rate, and arguably offers more potential than any other land use change to deliver natural capital and ecosystem service benefits. Empirical data showing increased vegetation diversity and butterfly abundance across 11 solar parks demonstrate that these benefits are realisable. However, public and industrial policy support to capitalise on this opportunity is lacking. The SPIES DST provides a means of promoting natural capital and ecosystem service benefits at solar parks across the UK, over and above the environmental benefits related to increased low carbon energy provision. Moreover, while the evidence base and management actions in the SPIES DST are optimised for UK solar parks, these could be altered to enable applicability to other regions and other land uses. Coupled with expert knowledge of local ecosystems and the environmental and financial costs and management of existing land uses and agricultural practices, the SPIES DST could be embedded within planning and industry policies to promote land use change for solar parks that maximises net ecosystem and environmental gain.

Resources

The SPIES DST is hosted on-line at www.lancaster.ac.uk/spies. For evaluation data inquiries, please contact Guy Parker or Hannah Montag.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Guy Parker and Hannah Montag are both ecological consultants who undertake consultancy projects at solar parks. Jonathan Scurlock works for the National Farmers Union, some members of which have solar parks on their land.

CRediT authorship contribution statement

R.J. Randle-Boggis: Methodology, Investigation, Data curation, Writing - original draft. **P.C.L. White:** Conceptualization, Methodology, Investigation, Writing - original draft, Supervision, Project administration, Funding acquisition. **J. Cruz:** Methodology, Formal analysis, Investigation, Writing - review & editing. **G. Parker:** Methodology, Investigation, Data curation, Writing - review & editing. **H. Montag:** Methodology, Investigation, Data curation, Writing - review & editing. **J.M.O. Scurlock:** Writing - review & editing. **A. Armstrong:** Conceptualization, Methodology, Investigation, Writing - original draft, Supervision, Project administration, Funding acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2020.109775.

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