Global assessment of solar park impacts on ecosystem services

GLOBAL ASSESSMENT OF SOLAR PARK IMPACTS ON ECOSYSTEM SERVICES

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Abstract

Global solar photovoltaic capacity is growing exponentially, and it is projected to become the dominant renewable energy source by 2050. A significant proportion of photovoltaic capacity is deployed as ground-mounted solar parks (SPs), incurring significant land use change, with implications for hosting ecosystems. Despite the rapid deployment of SPs, understanding of their environmental impacts and consequences for ecosystem services (ES) remains poor. Here, we use a systematic literature review to identify environmental impacts of SPs and derive implications for ES, beyond the benefits that SPs confer over other means of electricity generation. We found 622 pieces of evidence from 167 articles demonstrating a wide range of both positive and negative impacts of SPs on ES, with responses varying with climate, ecosystem type and SP life cycle phase. Dominant positive outcomes included enhanced soil quality regulation in dry climates, and enhanced water cycle support, soil erosion regulation and pollination regulation during the operational phase. Conversely, savanna and grassland ecosystems and the construction phase were more commonly associated with negative outcomes. Further, negative climate regulation outcomes tended to occur in desert ecosystems. Crucially, we highlight significant knowledge gaps, with ≤ 20 pieces of evidence for half of all ES, including vital services such as pollination regulation, likely to be impacted by SP land use change. The outcomes of this review could inform site location and management decisions which maximise ecosystem co-benefits and avoid detrimental impacts, providing valuable insight for emerging environmental policies. Ultimately, understanding of the impact of SPs on ES could aid an energy system transition that mitigates the climate and ecological crises.

Highlights

- Evidence from 167 articles highlights the impacts of solar parks on ES
- Impacts vary with solar park location, life cycle phase and management decisions
- Climate regulation may be degraded in desert and semi-desert ecosystems, whilst soil quality regulation may be degraded in temperate climates but enhanced in dry regions
- Negative impacts on habitats and biodiversity during construction but scope to enhance a range of ES during solar park operation, including water cycle support, soil erosion regulation and pollination regulation
- Knowledge gaps for a range of ES, including air and water quality and pollution regulation
- Evidence-based recommendations for stakeholders across the solar park life cycle

Word count: [10622]

Keywords: Solar farms, renewable energy, photovoltaics, biodiversity, natural capital, land use change

1.0 INTRODUCTION

Climate change mitigation has prompted the rapid rise of renewable energy in recent years. Of the existing renewable energy technologies, photovoltaic (PV) solar power has the greatest potential power generation across the world [1]. Indeed, the capacity of PV panels for electricity generation has seen exponential growth in the past decade, with 1412 GW of PV installed globally by 2023 and predictions indicating that by 2050 it will become the dominant renewable energy source [2, 3]. Due to their relatively high capacity and economies of scale compared with smaller building mounted systems [4], utility-scale PV solar parks (hereafter referred to as SPs) account for much of global PV installation and are predicted to represent almost two-thirds of global PV capacity by the middle of this century [5, 6].

The growth of SPs will result in significant land use change, with average land use requirements ranging from 1.6 ha MW^{-1} in the UK [7] to 2.8 ha MW^{-1} in the US [8]. SPs have often been considered 'benign' in terms of their environmental impact [9] which is reflected in the relatively sparse evidence base compared to other renewables [10]. Decarbonisation of energy systems through SP development has well-established benefits for ecosystems through climate change mitigation [2, 11]. Despite this, land use change for SPs may have notable ecosystem impacts: previous studies have observed changes to the microclimate, such as altered temperatures, albedo, photosynthetically active radiation (PAR), humidity, and wind speed and direction in and around SPs [12-18]; biodiversity impacts including direct mortality of wildlife, habitat loss and altered vegetation community composition [12, 19-22]; and the potential for integration with agriculture in so-called 'agrivoltaic' systems [23-28]. The ecosystem consequences of SPs are likely to vary with SP life cycle phase, climate zone, and ecosystem type, with the response varying through time. Moreover, during the operational phase, solar farm management practices, such as implementation of agrivoltaics, wildflower planting, soil amendments, mowing and grazing regime and pesticide use [10, 29, 30] will be strong determinant of ecological outcomes. However, there is a distinct lack of research which synthesises the global environmental and ecosystem service (ES) impacts of SPs and accounts for the influence of such factors.

Together with contributing to understanding of the health of our ecosystems, knowledge of SP impacts on the environment could help to avoid or mitigate negative ecological impacts and maximise co-benefits [10]. This is particularly pertinent considering the decline in the capacity of global ecosystems to provide ES, much of which is caused by land use change [31, 32]. Specifically, this understanding may be used to directly inform decision support tools [10] and thus SP location, design and management decisions. Notably, this could provide much needed insight to apprise energy, climate change and nature policies and frameworks. At a global scale, this could include the UN Sustainable Development Goals [33] and Kunming-Montreal Global Biodiversity Framework [34], whilst also being relevant to national energy strategies and mandatory planning requirements such as Biodiversity Net Gain [35] within the UK.

Given the decline in global ecosystems, the rate of SP expansion and associated land take, it is essential that we rapidly advance our understanding of the ecological impacts. For the first time, this paper synthesises the environmental impacts of SPs on a global scale, underpinned by a systematic review, and links the impacts to ES categories. Within this we investigate the influence of climate zone, ecosystem type and the life cycle phase of the SP and outline good practice guidance for industry. Through identifying these nuances and knowledge gaps, we aim to both inform site-specific SP design and management and to direct future research efforts, but comparison with other technologies and climate change effects are beyond our scope.

2.0 METHODOLOGY

To answer the primary question "what are the ES impacts of SPs?", a quick scoping review (QSR) of peer-reviewed publications was undertaken, following U.K. Department for Environment, Food and Rural Affairs (DEFRA) guidelines [36]. The review comprised four key steps - scope definition, literature search, results screening, and evidence database development - each of which is detailed below.

2.1 Scope definition

The literature search scope was defined using the PICO approach [36], identifying the Population, Intervention, Control and Outcome elements. The population, the subject of the study, was defined as SPs. Given the global scope of the review, no geographic restrictions were selected (Appendix: Table 1). To ensure all potential environmental impacts were captured, regardless of previous land use or specific interventions during construction and operation of the SP, no interventions or controls were specified. The outcome was defined as any aspects of the environment that may be affected by SPs, for example pollination, species diversity and land use change (Appendix: Table 1). The population and outcome keywords were selected through identifying relevant words and phrases in the published literature, and expert insight, reflecting varying terminology across nations (Appendix: Table 1). The keywords were combined with Boolean and wildcard operators to form the final search strings (Appendix: Table 1). Evidence relating to carbon emissions reduction associated with transition to SPs from other forms of electricity generation was considered outside the scope of this review, as this has been assessed previously [37] and is concomitant on the carbon intensity of the grid. For example, wind power may have a higher carbon intensity than solar and fossil-fuel forms of electricity generation in certain contexts, such as development on peatlands [38].

2.2 Literature search and results screening

An advanced search of peer-reviewed scientific articles was undertaken in the Web of Science™ core collection on 11/12/2020 using the search strings and subsequently updated on 24/10/2023 using the same protocol. All articles published in English between 1945 – 2023 were included, and irrelevant science categories excluded (e.g., thermodynamics, nuclear physics). A three-phase screening approach was used to exclude articles outside of the scope of the study (Appendix, figure 1). The first phase involved reading the title and discarding irrelevant articles. In the second phase, abstracts were read, and unrelated articles discarded. In the third phase the full article was read, and evidence extracted from all relevant articles. Multiple pieces of evidence were extracted from an article where results related to more than one ES, property or process known to impact an ES. Evidence for Concentrated Solar Power (CSP), roof mounted and floating solar was excluded.

2.3 Evidence database development

The lead author created an evidence database comprising the following fields for each piece of evidence: article reference, a brief summary of the evidence, ES impacted, impact direction, evidence quality, study location, ecosystem type, climate zone, study design type, solar panel life cycle phase. A subset of 10% of the total evidence was cross validated by the co-authors.

Evidence from SPs was categorised according to which of the 16 ES (using ES categories used in a SP management tool [10]) it could potentially impact (Appendix: Table 2). If the paper mentioned a specific ES this was recorded, however most papers did not provide direct measurements of ES. In these cases, the evidence was linked to the primary ES the ecosystem property or process assessed was most likely to impact, although this may not be a direct measure of an ES. For example, Guerin et al., [19] recorded the deaths of 20 animals during SP construction in Australia, which was linked to degradation of the ES defined as “maintaining habitats and biodiversity”.

The impact direction was categorised as positive, neutral, negative, or uncertain. Positive and negative impacts were defined as enhancement and degradation of the ES, respectively. A neutral impact indicated no impact, or if two processes cancelled each other out e.g., observed decreases in surface albedo, but increases in effective albedo [17] indicating a neutral impact on the climate regulation ES. Uncertain impacts were those for which there was no scientific consensus of the impact on an ES, or where the impact of the evidence was inconclusive or taken from conceptual framework papers highlighting potential impacts.

Each piece of evidence was classified as either strong or weak. Evidence was considered strong if it was empirical data derived from lab or field measurements, derived from well-established concepts, or followed an established methodology. In contrast, evidence was classed as weak if it was speculative, expert opinion, based on anecdotal evidence or was unverified modelling.

The location of the evidence was classified to country level. Ecosystem type was categorised as one of the seven terrestrial biomes as per the IUCN’s Global Ecosystem Typology 2.0 [39] with urban (e.g., built-up areas, car parks) and agricultural categories replacing the intensive land-use biome (Appendix: Table 3). Ecosystem types were inferred through the articles themselves (if given) or by locating the site on the IUCN Global Ecosystem Typology map [39]. Climate type was defined as tropical, dry, temperate, continental, or polar following the simplified Köppen Climate Classification system and was taken from the paper where available or identified using the updated Köppen-Geiger climate map [40]. If evidence was summarised from multiple countries, ecosystem types, climate zones, lab experiments or perspective papers, “not applicable” was recorded. Study design type was categorised as original research (e.g., empirical data), opinion/meta-analysis/conceptual frameworks, or reviews of empirical data, with the latter excluded from further analysis. Finally, the SP life cycle phase the evidence pertained to was categorised as construction, operation (including management) or decommissioning (including recycling and disposal).

2.4 Evidence analysis

Chi-square goodness of fit tests were conducted to establish if the evidence allocated to each ES was biased towards positive or negative impacts (neutral and uncertain impacts, summarised in section 3.2 were excluded from analysis given the focus on change and low evidence numbers) and strong or weak quality. The Chi-square tests were only performed on ES where the number of pieces of evidence ≥ 10 to ensure a critical assumption of the Chi-square test was not violated [41]. P values ≤ 0.05 were deemed statistically significant. The distribution of evidence across the positive and negative impact categories was assessed for each ES by climate type, ecosystem type, location, evidence type and life cycle phase.

To summarise the understanding of the impact of SPs, each ES was classified based on the quantity and quality (% strong) of evidence following an adaptation of the IPBES four-box model [32]. Specifically, “well established” was both high quantity and high quality, “established but incomplete” was high quality but lower quantity, “unresolved” was high quantity but lower quality and “inconclusive” was both low quantity and low quality. Impact direction (significantly enhanced – significantly degraded) was calculated for each ES using positive, negative and neutral data on a sliding scale of 1 to -1 (with 1 being 100% positive and -1 being 100% negative) and indicated with text shading.

Following evidence analysis and interpretation, the discussion was supplemented where relevant with peer reviewed grey literature and journal articles, to establish context within the current evidence base. However, these additional sources were not subjected to analysis.

3.0 RESULTS AND DISCUSSION

3.1 General trends

We identified 194 journal articles, which together provided 849 pieces of evidence of how SPs impact ES, with 116 classified as neutral and 111 uncertain. In total there were 622 pieces of evidence evenly distributed between positive (n = 306) and negative (n = 316) impacts (X^2 = 0.16, p = 0.69). Counts of articles published per year were unevenly distributed across the time period of 2009 – 2023 (X^2 181.32, $p < 0.001$, Table 1, Appendix: Figure 2). Generally, more of the evidence associated with negative ES impacts was considered strong (X^2 = 25.63, $p < 0.001$), derived from empirical or quantitative methods, whilst evidence linked to positive ES impacts was evenly distributed between strong and weak quality (X^2= 0.01, p = 0.91). Significant trends emerged when contextualising the ES through location, climate zone, ecosystem type and life cycle phase, which are discussed below. A fuller description of both positive and negative effects is included in Section 3.2.

The evidence was unevenly distributed across ES (X^2 = 839.61, p = < 0.001; Table 1), with most related to the impacts on maintaining habitats and biodiversity (25%), food provision (21%), climate regulation (14%) and soil quality regulation (10%). Out of all ES, only maintenance of habitats and biodiversity was generally degraded at SPs (X^2 = 8.01, $p < 0.001$), whilst water cycle support, soil erosion regulation and pollination regulation were generally enhanced (X^2 = 5.23, p = 0.02; X^2 = 9.78, $p < 0.001$; X^2 = 7.20, $p < 0.001$, Table 1). Understanding of just four ES - maintaining habitats and biodiversity, food provision, climate regulation and soil quality regulation - was considered well-established due to the relatively high quantity and quality (figure 2), whilst understanding of water cycle support, biomass materials provision, soil erosion regulation and recreation and aesthetic interactions was considered established but incomplete, with lower quantity but high quality (figure 1). Evidence was inconclusive (low quantity and quality) for the remaining ES (figure 2). Of these, some are unlikely to be notably impacted by SPs, specifically flood regulation, air quality regulation and educational and cultural interactions. However, others for which SP land use change could be highly influential were underrepresented; for example, pollination regulation comprised just 3% of evidence, despite the potential for significant impacts [42] and important links to human wellbeing through maintenance of wild plant reproduction, biodiversity, ecosystem stability and crop yields [43, 44].

The evidence was unevenly distributed between nations (X^2 = 1504.57, $p < 0.001$; Table 1) and did not match the deployment trends (figure 1). Almost one third of evidence (27%) for which location could be identified was from the USA (Table 1), followed by China (19%), Italy (8%) and France (8%). Whilst the USA and China feature in the top 10 rankings of installed PV capacity [45], China has over three-times more installed PV capacity than the USA, and there is limited evidence for Japan, Germany and India despite having the 3rd, 4th, and 5th highest installed PV capacities globally [45]. Moreover, data on the siting location i.e., building mounted, ground mounted or floating, is not available for all countries and thus it is not possible to infer the global impacts of SPs on ES.

Similarly, the evidence was unevenly distributed between climate zones ($X^2 = 127.33$, $p < 0.001$), with the majority (36%) derived from temperate climates. This reflects the large proportion of current PV solar capacity installed in temperate areas of Europe, China and the USA (Table 1). This was followed by dry (29%) and continental climates (12%). Significantly more evidence was associated with negative impacts on soil quality regulation in temperate climates ($X^2 = 10.71$, $p < 0.001$, Table 2). Conversely, water cycle support and pollination regulation were enhanced in temperate climates ($X^2 = 6.25$, $p = 0.01$, $X^2 = 4.45$, $p = 0.03$, Table 2), whilst soil quality regulation was enhanced in dry climates ($X^2 = 6.37$, $p = 0.01$, Table 2).

Evidence was identified from a wide range of broad global ecosystem types, including agricultural, savanna and grassland, deserts and semi-deserts, alpine and urban areas, yet was unevenly distributed ($X^2 = 558.58$, $p < 0.001$). Most evidence, where ecosystem type could be identified, was from agricultural ecosystems (35%), partly attributable to the significant increase in research on agrivoltaics in recent years [46]. Significantly more evidence linked to soil erosion regulation and water cycle support in agricultural ecosystems was associated with positive impacts ($p < 0.05$, Table 2). Conversely, relatively little evidence (16%) was identified from desert and semi-desert ecosystems, although significant proportions of PV capacity in arid areas of China and the USA [45]. Despite this, climate regulation, a key ES intrinsically linked with many other ES, was generally degraded at SPs in desert and semi-desert ecosystems ($X^2 = 5.26$, $p = 0.02$, Table 2). Moreover, evidence from savanna and grassland ecosystems was dominated by negative ES impacts ($X^2 = 12.74$, $p < 0.001$, Table 1), with the majority categorised as strong quality ($X^2 = 10.53$, $p < 0.001$, Table 1). These include potential for negative outcomes associated with a range of ES, such as climate regulation, soil quality regulation and maintaining habitats and biodiversity. [12, 47-49]. These outcomes highlight the importance of considering the wide-ranging potential implications for ES when developing SPs in these ecosystems.

In terms of life cycle stage, the review identified significant knowledge gaps on evidence specific to the construction and decommissioning phases, with the overwhelming majority of evidence (78%) relating to the operational phase ($X^2 = 953.96$, $p < 0.001$, Table 1). Overall, the operational phase has significant scope for ES enhancement ($X^2 = 6.92$, $p < 0.01$, Table 1). Principally, three ES - pollination regulation, soil erosion regulation and water cycle support – were found to be enhanced in the operational phase ($X^2 = 7.12$, $pp = 0.01$, $X^2 = 8.91$, $p < 0.001$, $X^2 = 7.41$, $p < 0.01$, Table 2). Despite the lack of evidence specific to SP construction, this phase has the potential to be the most damaging to ES, with significantly more evidence associated with negative ES impacts overall ($X^2 = 53.93$, $p < 0.001$, Table 1), including impacts on maintaining habitats and biodiversity [20, 48, 50-53], pest and disease regulation [54, 55] and soil quality regulation [19, 56]. However, more of the construction phase evidence linked to negative impacts was considered weak ($X^2 = 7.67$, $p = 0.01$, Table 1), as there is limited empirical research. Specifically, maintaining habitats and biodiversity was degraded during the construction phase ($X^2 = 29.88$, $p < 0.001$, Table 2), largely due to the initial habitat loss. Notably, there is currently very limited evidence on the impacts of decommissioning (< 1%; Table 1) given the lifetime of SPs and their relatively recent deployment, yet many SPs will be nearing end of life by the early 2030s [6]. Consequently, there is a critical need for empirical data which quantify the impacts of SP construction and decommissioning to ensure improved understanding and aid mitigation of potential negative impacts throughout the SP life cycle.

Finally, although outside the scope of this review, SPs significantly reduce GHG emissions compared to fossil fuel electricity generation, and thus mitigate global climate change [2, 57-59]. Further, the negative impacts of fossil fuel sources of electricity generation (and associated mining and hydraulic fracturing) are well-established e.g. air and water pollution, wildlife mortality and habitat degradation

264 [60-63]. Alongside exacerbation of climate change, these impacts can have wide-ranging implications
265 for a range of ES at global and local scales.

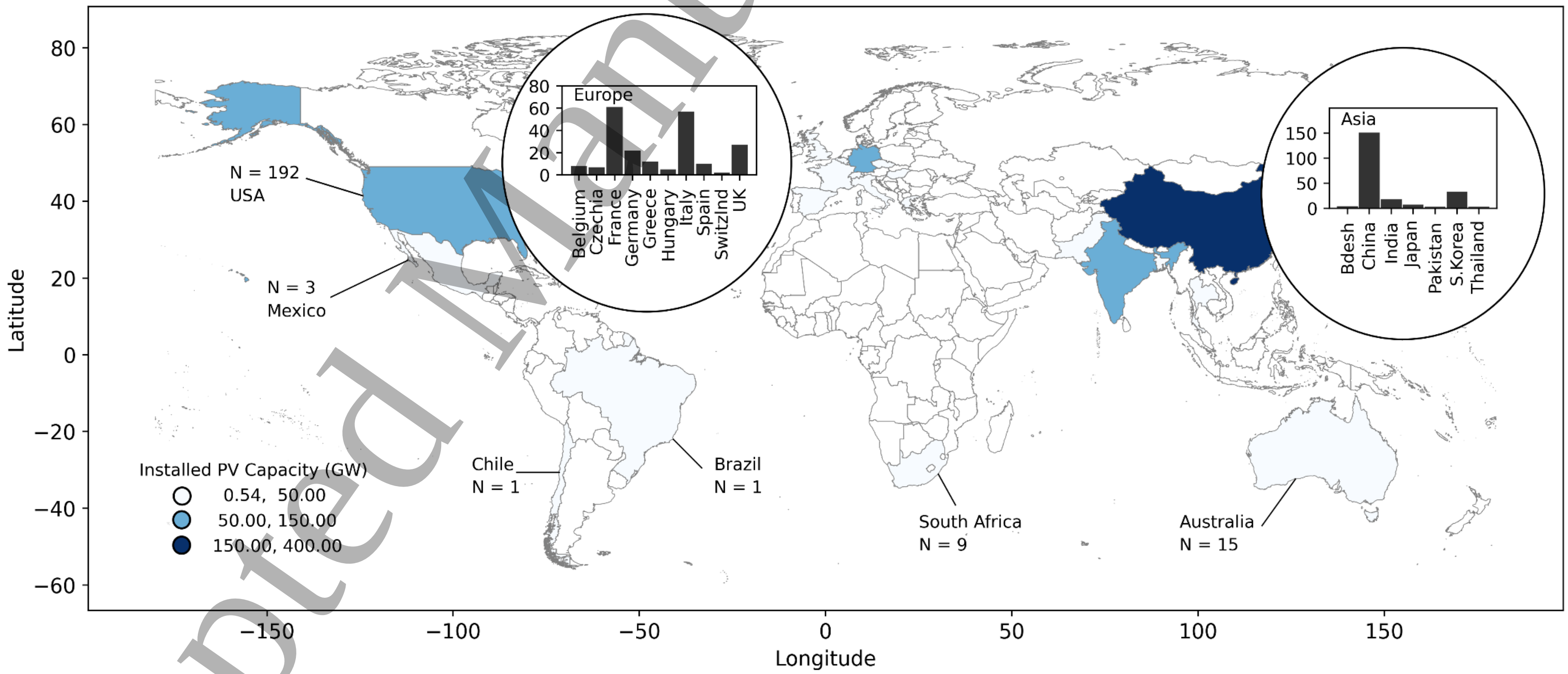

Figure 1: Global distribution of evidence extracted during the review and linked to positive, negative or neutral impacts on 16 ecosystem services. Installed PV capacity (GW) for corresponding countries is indicated through shading. N = total evidence per country. Bar plots show the number of pieces of evidence per country for continents where evidence was extracted from multiple countries. Country abbreviations: Switzland = Switzerland, Bdesh = Bangladesh, S. Korea = South Korea.

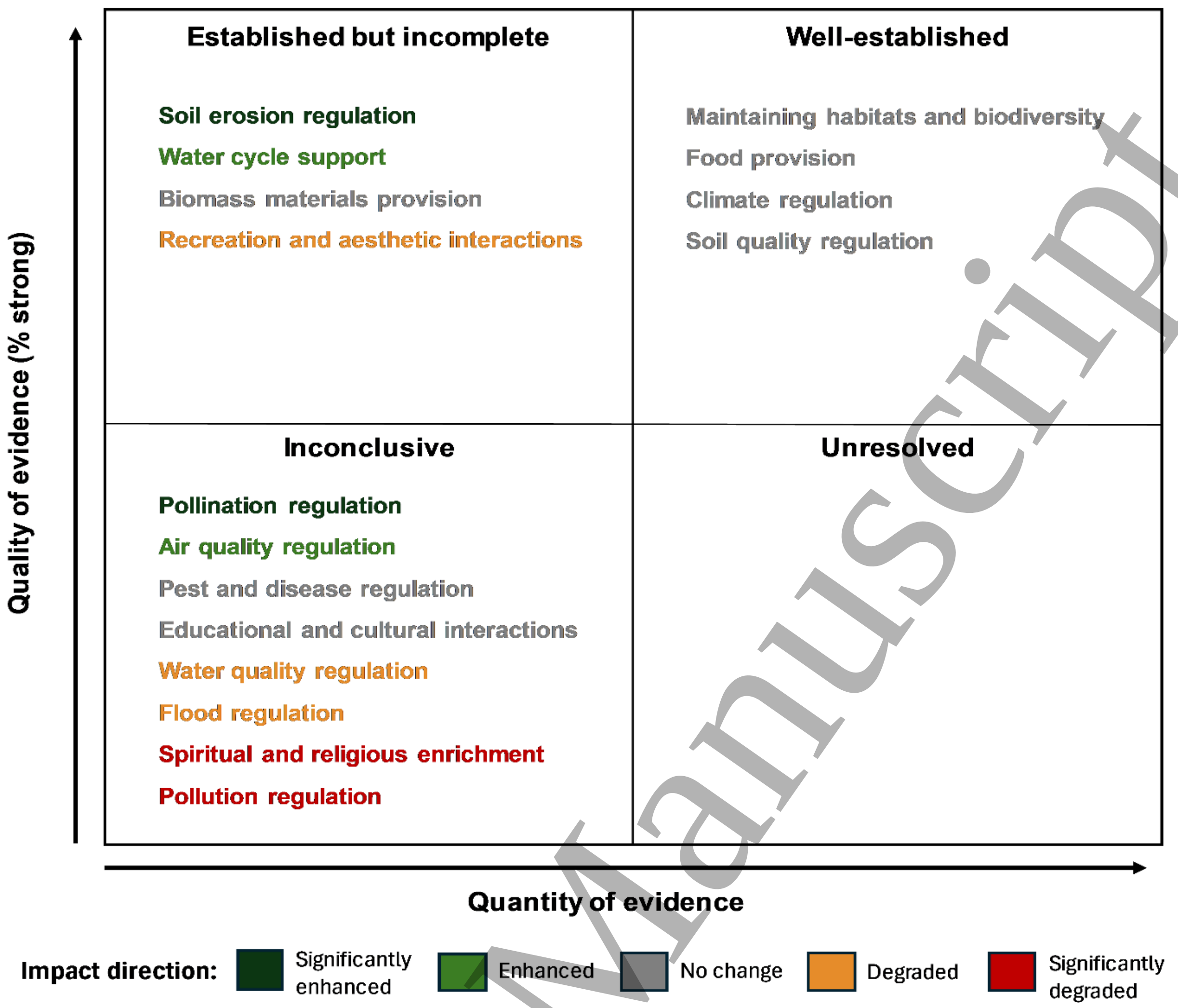

Figure 2. Confidence levels assigned to the 16 ES impacted by SPs, an adaptation of the IPBES four-box model. Each ES was assigned a confidence level according to the quantity and quality of evidence linked to that ES. Quality of evidence is defined as the percentage of evidence classified as strong, i.e., sourced from empirical or field data. Confidence levels assigned to each ES (top right - bottom left) are as follows: well-established**:** higher quantity and quality (4 ES); established but incomplete: higher quality but lower quantity (4 ES); unresolved: higher quantity but lower quality (0 ES); inconclusive: both lower quantity and quality (8 ES). Impact direction was calculated using positive, negative and neutral data, ranging from significantly enhanced (80-100% positive evidence) to significantly degraded (80-100% negative evidence) and is indicated with text shading.

Table 1. The counts of evidence categorised as positive (+) or negative (-) impacts for database fields used in the QSR. The remaining evidence is summarised (Appendix: Table 4). Only database categories where the total number of pieces of evidence ≥ 10 were included in statistical analysis, as per assumptions of the Chi-square goodness of fit test. Ecosystem service impact counts in bold text represent a statistically significantly higher positive or negative evidence count, respectively, in comparison to expected counts ($p \leq 0.05$), whereas impact counts in plain text indicate no significant difference, or database fields with evidence counts < 10. Numbers in bold marked with an asterisk in the evidence quality column indicate a significantly higher count of evidence considered strong or weak quality. For publication year, values in the total column are displayed as: number of articles (number of pieces of evidence), and values in ES impact and evidence quality columns relate to the number of pieces of evidence extracted from articles published in each year.

Database category	Sub-category	Total	ES impact		Evidence quality	
			+	-	Strong	Weak

Publication year	2009	1 (1)	0	1	1	0
	2011	1 (3)	1	2	3	0
	2012	1 (3)	3	0	3	0
	2013	2 (4)	2	2	4	0
	2014	4 (18)	8	10	3	**15***
	2015	3 (4)	0	4	1	3
	2016	9 (25)	6	**19**	6	**19***
	2017	13 (38)	10	**28**	12	**26***
	2018	7 (35)	**31**	4	7	**28***
	2019	10 (45)	**30**	15	22	23
	2020	17 (47)	27	20	30	17
	2021	25(95)	42	53	**77***	18
	2022	31 (128)	68	60	**83***	45
	2023	43 (176)	78	98	**105***	71
Ecosystem Service	Maintaining habitats and biodiversity	153	59	**94**	87	66
	Food provision	133	70	63	**91***	42
	Climate regulation	84	39	45	42	42
	Soil quality regulation	64	29	35	**56***	8
	Water cycle support	43	**30**	13	**30***	13
	Biomass materials provision	29	17	12	19	10
	Soil erosion regulation	23	**19**	4	12	11
	Recreation and aesthetic interactions	22	8	14	10	12
	Pollination regulation	20	**16**	4	4	**16***
	Flood regulation	13	4	9	0	**13***
	Pest and disease regulation	13	6	7	3	**10***
	Educational and cultural interactions	6	3	3	1	5
	Air quality regulation	6	4	2	1	5
	Water quality regulation	5	2	3	0	5
	Pollution regulation	4	0	4	0	4
	Spiritual and religious enrichment	4	0	4	1	3
Location	USA	167	78	89	**98***	69
	China	120	**83**	37	**88***	32
	N/A	76	37	39	7	69
	Italy	50	25	25	26	24
	France	49	16	**33**	**47***	2
	UK	22	13	9	9	13
	South Korea	20	6	14	**18***	2
	Germany	18	10	8	**15***	3
	India	17	6	11	9	8
	Australia	14	3	**11**	4	10
	Greece	10	5	5	5	5
	Spain	10	1	**9**	2	8
	South Africa	9	2	7	4	5
	Belgium	8	3	5	7	1
	Czechia	7	5	2	1	6
	Japan	5	2	3	5	0
	Hungary	4	1	3	4	0
	Bangladesh	3	3	0	2	1
	Pakistan	3	2	1	0	3
	Mexico	3	0	3	0	3
	Chile	3	2	1	3	0
	Switzerland	2	0	2	2	0
	Thailand	1	0	1	1	0
	Brazil	1	1	0	1	0
Climate type	Temperate	222	110	112	**163***	59
	Dry	183	90	93	**114***	69
	N/A	136	72	64	21	**115***
	Continental	72	32	40	**53***	19
	Tropical	9	2	7	6	3
Ecosystem type	N/A	225	110	115	67	**158***
	Agricultural	219	120	99	**166***	53
	Deserts and semi-deserts	97	45	52	**68***	29

	Savannas and grassland	38	8	**30**	**29***	9
	Polar/alpine	25	16	9	**18***	7
	Urban	14	7	7	8	6
	Tropical sub-tropical forests	4	0	4	1	3
Life cycle phase	Operational	486	**272**	214	**318***	168
	Construction	69	4	**65**	23	**46***
	N/A	64	30	34	16	**48***
	Decommissioning	3	0	3	0	3

Table 2. Evidence counts and impact direction (+ or -) linked to ES (where total evidence ≥ 10) by location, climate type, ecosystem type and life cycle phase. Only database categories where the total number of pieces of evidence ≥ 10 were considered for statistical analysis, as per assumptions of the Chi-square goodness of fit test. Ecosystem service impact counts in bold text represent a statistically significantly higher positive or negative evidence count, respectively, in comparison to expected counts ($p \leq 0.05$), whereas impact counts in plain text indicate no significant difference, or database fields with evidence counts < 10. Numbers in bold marked with an asterisk in the evidence quality column indicate a significantly higher count of evidence considered strong or weak quality.

Ecosystem service	Database category	Sub-category	ES impact		Confidence	
			+	-	High	Low
Maintaining habitats and biodiversity	Location	USA	16	**37**	30	23
		China	19	13	**26***	6
		N/A	8	13	6	**15***
		Italy	5	8	6	7
	Climate type	Dry	24	31	**39***	16
		N/A	14	**29**	9	**34***
		Temperate	14	25	**27***	12
		Continental	7	8	**12***	3
	Ecosystem type	N/A	23	**55**	31	47
		Deserts and semi-deserts	10	17	**20***	7
		Agricultural	10	11	**16***	5
		Savannas and grassland	7	6	9	4
	Life cycle phase	Operational	50	45	**66***	29
		Construction	3	**38**	15	26
		N/A	6	10	6	10
Food provision	Location	USA	**19**	7	12	14
		France	9	14	**22***	1
		South Korea	4	**12**	**16***	0
		Germany	8	6	**13***	1
		Italy	5	5	7	3
	Climate type	Temperate	41	40	**70**	11
		Dry	11	6	6	11
		Continental	4	11	10	5
		N/A	**13**	2	0	**15***
	Ecosystem type	Agricultural	48	54	**85***	17
		N/A	**19**	5	2	**22***
	Life cycle phase	Operational	66	61	**91***	36
Climate regulation	Location	N/A	8	14	1	**21***
		China	11	10	**17***	4
		USA	8	10	11	7
	Climate type	Dry	11	20	**21***	10
		N/A	17	1	2	**26***
		Temperate	8	8	**12***	4
	Ecosystem type	N/A	22	17	7	**32***
		Deserts and semi-deserts	6	**17**	16	7
		Agricultural	7	4	**9***	2
	Life cycle phase	Operational	34	37	40	31
		N/A	5	5	2	8
	Location	China	14	9	**22***	1
		France	2	**11**	**13***	0

Soil quality regulation		USA	**9**	2	**11***	0
	Climate type	Temperate	3	**18**	**20***	1
		Dry	**15**	4	**16***	3
		Continental	7	9	**16***	0
	Ecosystem type	N/A	5	**15**	**16***	4
		Agricultural	7	10	**14***	3
		Deserts and semi-deserts	12	5	**17***	0
	Life cycle phase	Operational	23	30	**50***	3
Water cycle support	Location	China	**13**	2	**12***	3
	Climate type	Dry	10	9	**15***	4
		Temperate	**13**	3	**12***	4
	Ecosystem type	Agricultural	**18**	5	**19***	4
	Life cycle phase	Operational	**28**	11	**28***	11
Biomass materials provision	Location	USA	8	8	**14**	2
	Climate type	Temperate	11	5	**12***	4
		Dry	5	6	7	4
	Ecosystem type	Agricultural	11	7	**15***	3
	Life cycle phase	Operational	17	9	**19***	7
Soil erosion regulation	Location	China	**11**	1	7	5
	Ecosystem type	Agricultural	**9**	1	4	6
	Life cycle phase	Operational	**18**	4	11	11
Recreation and aesthetic interactions	Climate type	N/A	4	7	5	6
	Ecosystem type	N/A	6	9	6	9
	Life cycle phase	Operational	6	7	8	5
Pollination regulation	Climate type	Temperate	**9**	2	3	8
	Ecosystem type	N/A	**12**	1	0	**13***
	Life cycle phase	Operational	**14**	3	3	**14***

3.2 Impacts of SPs on ecosystem services

The following sections discuss the findings for each of the ES with sufficient evidence for statistical analysis (number of pieces of evidence associated with the ES ≥ 10), contextualised in light of climate zone, ecosystem type and SP life cycle phase. For ES where n > 10, neutral evidence is also summarised.

3.2.1 Maintaining habitats and biodiversity

SPs may impact habitats and biodiversity due to changes in management and the presence of the infrastructure, including land clearance and alteration to the local climate, with consequences for habitats, species movement and mortality [19, 21, 22, 48, 64-66]. Overall, there was a significantly higher count of negative evidence (61%) compared to expected counts ($X^2 = 8.01$, $p < 0.001$, Table 1). However, evidence was evenly distributed between strong and weak quality ($X^2 = 2.88$, $p = 0.09$, Table 1). Similarly, positive and negative evidence was evenly distributed across climate and ecosystem types (Table 2), however more evidence from the construction phase was associated with degradation of the ES (Table 2), largely due to the potential initial habitat loss. A further 24 pieces of evidence associated with neutral impacts were extracted.

Negative impacts

Just under half of the negative evidence related to habitat degradation, loss, or fragmentation. Multiple studies highlighted the actual or potential loss of habitat due to SP expansion [51, 53, 67-69] including overlap of SPs with conservation areas [53, 70, 71] and rare wildlife habitats [52], for example the loss of grey-crowned babbler (*Pomatostomus temporalis*) habitat and nest removal prior to SP construction in Australia [19]. In addition, habitat fragmentation [72], degradation of habitat corridors [73], concerns over the close proximity of SPs to protected areas [66] and the resulting potential barriers to animal movement [69] were also identified as possible negative impacts which may worsen with increasing SP development.

Around a quarter of negative evidence was linked with actual or potential changes to species abundance, richness, evenness, diversity or community composition. This included lower species diversity [12, 48, 74-76] and abundance within SPs, often particularly under panels. For instance, areas under panels had lower floral abundance, insect species richness and diversity in Oregon, USA [77]. Furthermore, there is some evidence that the behaviour of species such as bats may be negatively affected at SPs, for example, bat activity was reduced at SPs in Hungary [78] and the UK [79], presumed due to loss or fragmentation of foraging and commuting habitat.

Around 15% of negative evidence focused on species mortality, survivorship, injury or welfare. There has been much focus on avian mortalities at SPs, with estimates in the Southwestern US ranging from 2.49 birds/MW/yr to 11.61 birds/MW/yr [64, 80, 81]. However, there is considerable uncertainty around fatality estimates, including difficulty attributing a definitive cause of mortality, demonstrating the need for further research [81]. Research on other taxa includes reduced growth of the rare desert annual *Eriophyllum mohavense* under solar panels in the Mojave Desert during a good rainfall year [82], and increased mortality of aquatic birds and insect species attributed to the polarised light produced by solar panels [83, 84]. Finally, concerns have been raised around potential future damage to wildlife due to the disposal of solar panels in the decommissioning phase [85].

The remaining evidence comprised negative implications for photosynthesis, productivity, biomass production (of non-food, fuel or fibre plants) and vegetation cover, attributed to reductions in PAR under solar panels [16, 86, 87].

Positive impacts

Positive impacts on maintaining habitats and biodiversity (39%) were evenly distributed across climate type, ecosystem type and SP life cycle phase (Table 2). Around two-thirds of this evidence quantified favourable outcomes for species abundance, richness, evenness, diversity and community composition, linked to the implementation of beneficial management, ceasing detrimental practices, or the solar infrastructure creating beneficial conditions. For instance, in the central Asian Steppe, *tenebrionid* beetle diversity was significantly higher within a SP compared with an ungrazed site, although this difference was marginal [88] and in China, increased plant species richness [16] and diversity [89] were observed under panels and between rows of panels compared to controls. Further evidence related to habitat enhancement, protection, or provision, including scope to enhance local biodiversity and wildlife habitat at SPs [22, 90, 91] through co-location with vegetation, wildflower planting, provision of shade and integration with the local landscape [21, 22, 90-95].

Around a quarter of evidence focused on productivity, aboveground biomass production (of non-food, fuel or fibre plants) and vegetation cover. Almost all of this evidence was from China, particularly areas with a dry climate or semi-arid ecosystems, where panel shade provides protection from strong solar radiation and wind erosion, allowing vegetation to establish and cover to increase [16, 18, 96]. For example, several papers reported an increase in NDVI [97, 98], aboveground biomass [89, 99] and vegetation cover [16, 100, 101] following SP construction.

The remaining evidence highlighted positive impacts on species survival, welfare and provision of resources at SPs. For instance, birds have been observed using SP infrastructure for shade, shelter, perches, foraging and nesting in South Africa and the USA [48, 56, 102, 103]. In the Mojave desert, seed bank survival for two desert annuals increased under the shade of experimental solar panels [104] and an increased number of the rare Mojave woolly sunflower (*Eriophyllum mohavense*) survived to maturity, likely attributable to reduced evapotranspiration in the shade [87]. However, impacts varied with species, habitat and weather conditions, highlighting the importance of site characteristics and species on outcomes [82, 87, 105].

Neutral impacts

One third of the neutral maintaining habitats and biodiversity evidence shows no significant impact on abundance, species richness or community composition in focal taxa. For example, no change was found in the abundance and community structure of *tenebrionid* beetles in a SP in China [88] or the richness or diversity of flowers between shade levels within a SP in the US [77].

Another third of evidence was split between neutral impacts on habitat size, corridors and animal movement and the cover of vegetation [78, 106, 107]. For instance, mitigation corridors established between two large-scale PV SPs in California were deemed sufficient to contain home ranges and maintain connectivity of Mojave desert tortoise (*Gopherus agassizii*) populations [65]. The remaining evidence highlighted no bird injuries, mortalities or attraction to the polarised light produced by PV panels, including in Australia [19], South Africa [48] and the USA [102, 103].

3.2.2 Food provision

SPs largely impact food provision through the use of agrivoltaic systems (AVS) - the co-location of solar panels and food crops or livestock on the same land [24]. Such AVS have seen increasing research focus in the last decade and offer significant scope to increase land use efficiency. The food provision evidence was evenly distributed between positive and negative impacts ($X^2 = 0.37$, $p = 0.54$), just under half (47%) of which related to negative impacts and 53% to positive impacts (Table 1). A further 27 pieces of evidence associated with neutral impacts on food provision at SPs were extracted. Overall, more evidence linked to impacts of SPs on food provision was deemed strong, with a high proportion of field data ($X^2 = 18.05$, $p < 0.001$, Table 1). Positive and negative evidence was evenly distributed across climate types, ecosystem types and life cycle phases (Table 2). A total of 27 pieces of neutral evidence were also identified.

Negative impacts

Just under half of evidence linking SPs to food provision was associated with negative impacts (Table 2), two-thirds of which was related to implications for crop health, growth and yield with many focused on crops such as wheat, maize and soybean that are more sensitive to lower PAR [108-110]. For example, in South Korea, the yield of sesame, soybean, and rice crops was reduced by up to 30% [110], and apples within an AV orchard in France had 24% lower dry matter content and thus reduced quality [111]. Delays to crop growth and maturity within AV systems were also identified. In South Korea, grapes grown under solar panels exhibited slower growth than those at control sites [112], and reductions in growth rate during the juvenile phase of lettuces and cucumbers were observed in France, which were attributed to the reduced light and altered soil temperature [113]. The majority of evidence linked to negative impacts of SPs on food provision is from temperate climates, where the potential benefits from shade such as shielding from strong solar radiation and improved soil moisture may be less apparent. Other negative evidence included implications of land use change from agricultural to standard solar farms with potential risks for food security [49, 114].

Positive impacts

Positive evidence was linked to potential enhancement of food provision (Table 1), principally improved crop or livestock health, growth and yield. The benefits were strongly influenced by the climate, crop selection and array design, with notable benefits in climates with high levels of solar radiation given the increased shade, higher soil moisture, and improved water use efficiency (WUE) [23, 115, 116]. For example, an agrivoltaic experiment in Arizona saw a 65% increase in WUE and double the fruit production for a heat sensitive tomato crop *Solanum lycopersicum var. cerasiforme* compared to unshaded crops [23]. Similarly, shading irrigated vegetable crops with PV panels resulted in savings of 14 - 29% of evapotranspired water [25].

In more temperate climates, yields were found to increase in drier years [27, 108, 117]; modelled crop yields from a Belgian study increased by 12% in 2022, which was drier, compared to the previous year [118]. Potentially negative impacts on yields were also found when tracker, vertical or bifacial systems were used as they allow significantly more light to reach crops [118, 119].

A further 14% of evidence linked to positive impacts on food provision discussed the general benefits of agrivoltaics, including potential improvements to food system resilience, increased diversity of crops grown, pollination benefits to surrounding crops, increasing overall land use efficiency [22, 24, 90, 120-123].

Moreover, SPs can provide grazing habitat and may improve the welfare of livestock through shade provision and protection from adverse weather conditions [4, 90, 124]. For example, the body temperature of cows in the USA shaded by solar panels was lower than those without shade, highlighting the potential to improve livestock wellbeing in agrivoltaic systems through reduced heat stress [125], and the liveweight of lambs under solar panels was comparable to those grazed in open pastures, despite a higher stocking density in the SP group [126].

Neutral impacts

Neutral evidence largely concerned neutral effects on crop yield and production within agrivoltaic systems. For example, no significant difference was observed in fruit production of jalapenos grown within the shade of an agrivoltaic system and in full sun in the USA [23], and whilst cows provided with solar panel shade at a farm in the USA had lower respiration rates than no shade cows, milk, fat and protein production did not differ [125].

3.2.3 Climate regulation

Climate regulation is strongly influenced by land use and land cover change [127, 128] and is inherently linked with many other ES. SPs impact climate regulation through biogeochemical effects e.g., acting as sources and sinks of greenhouse gases, and biophysical effects e.g., altering albedo, temperature, wind and precipitation receipts [12, 14-17, 129]. Evidence was evenly distributed across positive (46%) and negative (54%) impacts (X^2 = 0.43, p = 0.51), and strong (50%) and weak (50%) quality (X^2 < 0.001, p = 1.00, Table 1). A total of 22 pieces of evidence associated with neutral impacts on climate regulation at SPs were extracted. Climate regulation evidence was evenly distributed between positive and negative impacts across climate types and life cycle phases (Table 2), with a further 22 pieces of neutral evidence.

Negative impacts

Just over half of the climate regulation evidence was negative (54%; Table 1), with more evidence from SPs in desert and semi-desert ecosystems linked to negative impacts (X^2 = 5.26, p = 0.02, Table 2). Almost half of the negative climate regulation evidence related to observed or potential increase in air temperatures, thus exacerbation of climate change, largely in hotter, drier regions [13, 14, 23, 101, 130-132]. These increases may result from higher panel temperatures compared to ambient, leading to convection heat dissipation [101], or a reduction in albedo following conversion to SPs, which may be more apparent in desert environments given their naturally higher ground surface albedo [13, 23].

Indeed, almost a quarter of the evidence highlighted a reduction in albedo associated with the land cover change to SPs [14, 67, 101, 107, 130, 133, 134]. Increased air temperatures have largely been reported when measurements were taken from above panels, or from exposed areas within SPs (i.e. not directly under panels), as panels can increase heat transfer and radiate heat [13, 14, 130, 135]. Similarly, at night [23, 136] or during winter [12], panels may retain heat and contribute to elevated air temperatures under panels. Additionally, several modelling studies have predicted localised increases in air temperature at SPs [67, 134, 137].

A quarter of the evidence highlighted that SPs may reduce soil carbon, with negative implications for climate regulation. For example, studies in France [75, 138], China [139] and Italy [140] have observed reduced soil total and/or organic carbon within SPs compared to controls. Potential explanations include a reduction in the growth of herbaceous species combined with decreased soil moisture, increased salinity and pH [140]. Moreover, multiple studies [86, 138, 141, 142] hypothesised soil carbon may be reduced at SPs due to changes in soil moisture, air, or soil temperature. The remaining evidence included reduced precipitation [129, 137] following hypothetical construction of large-scale SPs, in addition to speculation on general degradation of climate regulation due to solar development [72].

Positive impacts

The positive evidence associated with climate regulation (46%; Table 1) was evenly distributed across all climate types, ecosystem types and lifecycle phases (Table 2). Approximately half comprised reductions in air temperature, indicating potential mitigation of climate change [15, 17, 23, 86, 132, 135-137, 143]. SPs can reduce local air temperatures, influenced by time of day, season and measurement location (i.e. directly under panels or above panels). During the day, air temperatures directly under panels can decrease, as the shade provided by panels reduces the amount of incoming solar radiation [12, 23, 136]. This trend may be more pronounced in spring and summer, when ambient temperatures are higher [12, 111, 144, 145]. SPs remove a proportion of incoming solar energy as electricity, which may contribute to a land surface temperature SP ‘cool’ island’ effect in arid ecosystems [17, 146]. At night, temperatures under panels or within SPs can remain lower than ambient [132, 135]. Similarly, where the difference in albedo between the panel surface and surrounding ground surface is less pronounced, e.g. in grasslands vs deserts, cooling at SPs may also occur [86]. In addition, the orientation and modality of panels may also influence the nature of impacts on air temperatures. For example, Suuronen et al. [136] found lower daily air temperature under panels in a fixed mount system compared to gaps and the surrounding Chilean desert, however these differences were less pronounced in a tracker system. Finally, incorporating wetland creation and vegetation planting into SP design may reduce air temperatures [91].

Whilst there was much field data supporting negative impacts for soil carbon, around a quarter of the positive evidence detailed increases in soil carbon, although most were predictions (i.e., no field data) [4, 21, 67, 86, 90, 147-149]. For instance, there is potential to utilise degraded lands for SPs, where landscaping with native vegetation may promote soil carbon sequestration [4]. A smaller amount of research details observed increases in soil carbon following SP installation, with links to vegetation cover [99, 150]. For example, in the USA, vegetated solar areas had higher soil carbon compared to bare areas [150]. Finally, general enhancement of climate regulation [22, 90] and solar PV’s substantial reduction in carbon emissions, compared to other energy sources was detailed [141, 151, 152].

Neutral impacts

The majority of neutral evidence related to no significant difference in air temperature at SPs compared to controls [18, 74, 95, 110, 113, 145, 153-155]. Other neutral evidence comprised little or no change in meteorological variables and carbon fluxes [12, 17, 113]. Further, some studies found no change in soil carbon at SPs [12, 89, 101, 156], which could be due to site characteristics or insufficient time since construction.

3.2.4 Soil quality regulation

Soil quality regulation is vital to delivering regulating services through the storage and degradation of organic matter, mediating exchange of gases to the atmosphere, storing, degrading, and transforming materials such as nutrients and contaminants, and regulating the flow of water [31, 157]. Evidence was extracted from multiple studies revealing a heterogenous distribution of soil physical, chemical and biological properties at SPs, attributed to altered microclimate and subsequent changes to vegetation cover and composition, construction and on-site management decisions. The soil quality regulation evidence was evenly distributed across positive (45%) and negative (55%) impacts ($X^2 = 0.56$, $p = 0.45$), however far more (88%) was considered strong ($X^2 = 36.00$, $p < 0.001$, Table 1). Positive and negative soil quality regulation evidence was evenly distributed across ecosystem types and life cycle phases. However, more negative evidence was from temperate climates and more positive evidence from dry climates (Table 2). An additional 25 pieces of neutral evidence were extracted.

Negative impacts

Just over half (55%) of the evidence linked to soil quality regulation was associated with negative impacts (Table 1), more of which was from temperate climates (Table 2). Direct degradation of physical soil quality was attributed to compaction, a common cause of anaerobism, waterlogging, nutrient depletion and reduced fertility in soils [158] from machinery during SP construction [56, 118, 133]. Further, soil temperature, an important physical property that can indirectly impact soil quality [159] through influencing plant growth, development, and nutrient uptake [160, 161], microbial community composition [162, 163] and decomposition of organic matter [164, 165], was higher under an agrivoltaic test bed in South Korea [112] and across a SP in an arid region of China [18].

Evidence reveals negative impacts on soil chemistry, both through the effect on ecological processes but also directly from the SP infrastructure. Soil nutrient concentrations, including nitrogen, were also negatively impacted in response to site management decisions, including topsoil stripping during construction [47] and removal of vegetation cover [150]. Soil nitrogen is an essential nutrient and low concentrations can limit soil organic matter, and thus carbon, accumulation [166]. Several studies in France and Italy have found lower nitrogen under panels [75, 76, 138, 140] and a corresponding decrease in SOM has also been observed [76]. Increases in soil salinity have also been found [98, 140], with concomitant adverse effects on plant growth [167, 168]. Other negative impacts on soil chemistry at SPs include higher levels of toxic chemicals such as lead [169] and chlorine [98], potentially the result of leaking from panels. Soil may also be contaminated with transformer oil during SP construction [19].

The negative effects on soil biological quality focus on implications for soil invertebrates and microorganisms which regulate organic matter decomposition and nutrient cycling [170-172]. For examples, substantial reductions in the biomass of soil microorganisms and abundance of mites, springtails, fungi and gram negative bacteria have been observed outside SPs compared to under panels [75]. The response of soil biology is tightly coupled to soil physical and chemical properties. For example, In Italy, a general reduction in soil microbial activity was observed in SP soils compared to controls, attributed to a combination of adverse environmental conditions including reduced soil moisture, higher temperature, increased salinity and reduced organic matter [140].

Positive impacts

Under half (45%) of soil quality regulation evidence was associated with positive impacts, of which significantly more related to dry climates (Table 1, Table 2). Soil temperature was commonly reduced, a climate change mitigation effect, under panels at SPs in more arid regions or those experiencing increased droughts [14, 75, 87, 138, 144, 156]. Given the climate sensitivity of these environments [173] temperatures may be close to thresholds for vital plant-soil processes such as productivity, decomposition and seed germination [12, 174], thus reduced temperature could mitigate increasing climate change impacts [175].

Soil chemical and biological quality was also enhanced at SPs. For instance, increases in soil nitrogen and organic matter in China [99, 176]. Moreover, there is potential for management to be selected to promote beneficial outcomes. For instance, through promotion of biocrust formation, a key component in soil formation in desert ecosystems, SPs could restore degraded dryland ecosystems [98, 177, 178]. Finally, general, non-specific references to enhancement of soil quality, including fertility and soil formation constituted 6% of positive evidence [22, 90] suggesting that there is some focus on using SP to improve soil health.

Neutral impacts

Much of the neutral evidence showed no differences in soil parameters between SPs and controls, including soil temperature [110, 179]; nutrients and pH [89, 99, 101, 139, 156], and bacteria and fungi [75, 89].

3.2.5 Water cycle support

Water cycle support encapsulates Earth's major water fluxes, such as precipitation, evapotranspiration and river flow, and water storages including lakes, groundwater, and soil, which together determine the spatial and temporal availability of water [31, 157]. SPs can impact water cycle support through redistributing water receipts at the surface and altering evapotranspiration rates, with implications for soil moisture. Moreover, water used for panel washing may impact water supply locally within arid regions, depending on the level of water scarcity and the frequency of panel washing. Evidence relating to water cycle support at SPs was unevenly distributed across positive (67%) and negative (33%) impacts ($X^2 = 5.23$, $p = 0.02$, Table 1), and strong (70%) and weak (30%) quality ($X^2 = 6.72$, $p = 0.01$, Table 1). More evidence from temperate climates, agricultural ecosystems and the operational phase was associated with enhancement of the ES (Table 2).

Negative impacts

Around one third of the evidence linked to water cycle support was negative (Table 2). This evidence was evenly distributed across climate and ecosystem types and SP life cycle phases (Table 2). The two reported effects were increased water scarcity due to use of water for panel washing, particularly in dry climates [19, 49, 56], and reductions in soil moisture under panels [117, 138, 140, 180], predominantly due to diverted rainfall by solar infrastructure [87, 96].

Positive impacts

Of the two-thirds of positive water cycle support evidence, more related to temperate climates, agricultural ecosystems and the operational phase of the SP life cycle (Table 2). Soil moisture was generally higher under the shade of solar panels, accounting for 60% of positive evidence, due to a combination of reduced evaporation in the shade and a tendency for precipitation to collect along the edges of panel frames [12, 13, 23, 149]. This effect was observed in arid zones [16, 133, 179] and more temperate zones [15, 77, 89, 150], yet differences in soil moisture in temperate climates may become particularly apparent in drier spring and summer months [126].

581 The remaining evidence comprised general non-specific references to the potential for enhancement of water cycle support at SPs [22, 90] and highlighted the opportunities to reduce water required for panel washing [91], reusing washing water for irrigation of agrivoltaic crops and rainwater harvesting [120, 181].

585 *3.2.6 Biomass materials provision*

586 Biomass materials provision refers to the provision of all biomass of use to humans, excluding food crops e.g., timber, biofuel, medicine and genetic resources, grazing and livestock forage [157]. SPs may enhance or reduce biomass provision depending on biomass type, location and management. Overall, the biomass evidence relating to water cycle support at SPs was evenly distributed across positive (59%) and negative (41%) impacts ($X^2 = 0.86$, $p = 0.35$, Table 1), and strong (66%) and weak (34%) quality ($X^2 = 2.79$, $p = 0.09$, Table 1). Positive and negative evidence was evenly distributed across climate, ecosystem types and life cycle phases (Table 2).

593 *Negative impacts*

594 Over two-thirds of negative biomass materials provision evidence was associated with decreased plant productivity, photosynthesis and biomass at SPs. For instance, the shade of solar panels led to reductions in aboveground net primary productivity (ANPP) and biomass of forage grassland, although factors such as array design, soil moisture, and seasonal and diurnal variations in light and temperature cause variation in outcomes [126, 180, 182].

599 The remaining evidence included the potential for reduced provision of raw materials following SP construction, with the scale of impacts varying with location, construction, and site management decisions [72, 142]. For example, there are concerns that yields of *Opuntia* cactus, a marketable product, may decrease alongside increasing solar development in the Chihuahuan desert [72]. Additionally, inhabitants living near SPs in Rajasthan, India, experienced reduced access to firewood [183].

604 *Positive impacts*

605 Evidence relating to positive impacts of SPs on biomass material provision was linked to increases in both quantity and quality of biomass. For example, at SPs in Oregon, USA, biomass increased by 90% [15] and forage quality and digestibility increased [124, 126]. Additionally, it has been speculated that SP management can be adapted to enhance raw materials provision [22]; for example, the growth of biofuel crops within SPs [91], and rosemary, thyme and *Medicago sativa* within 'photovoltaic gardens' in Italy [153, 184].

611 *3.2.7 Soil erosion regulation*

612 Soil erosion is one of the major global threats contributing to soil degradation through changes to processes such as nutrient cycling and decomposition, with subsequent impacts on a range of ES [185-189]. SPs may impact soil erosion regulation through changes to wind speed, distribution of precipitation and cover of vegetation [143]. Evidence associated with impacts on soil erosion regulation was largely positive overall (83%), with just 17% linked to negative impacts ($X^2 = 9.78$, $p < 0.001$, Table 1), although evidence was evenly distributed between strong (52%) and weak (48%) quality ($X^2 = 0.04$, $p = 0.83$, Table 1). Positive impacts were particularly associated with agricultural ecosystems and the operational life cycle phase (Table 2).

620 *Negative impacts*

621 Just 7% of the soil erosion regulation evidence was negative (Table 2), comprising increased erosion due channelling of the water [190], resulting in the creation of rills and gullies underneath panels [117]

and the consequence of soil disturbance, including topsoil stripping, on vegetation and soil properties on erodibility [47].

Positive impacts

On the whole, SPs have been shown to reduce soil erosion with most of the evidence showing reductions in soil erosion across a range of climates and ecosystem types, although this is likely more beneficial in arid regions, through reducing wind speed and thus wind erosion [15, 18, 96, 143, 150, 191]. Additionally, when vegetation cover has increased within the SPs [4, 22, 147, 148, 192], rainfall interception, reduced runoff rates and increased root binding have been shown to reduce soil erosion. Contrary to findings on drainage gullies under solar panels, the panels may intercept rainfall and thus weaken splash erosion [176].

3.2.8 Recreation and aesthetic interactions

Ecosystems can provide nonmaterial benefits through recreation and aesthetic experience, including aesthetic values and wellbeing [10, 31, 157]. Overall, evidence relevant to recreation and aesthetic interactions was evenly distributed across positive (35%) and negative (65%) impacts ($X^2 = 1.64$, $p = 0.20$, Table 1), and high (45%) and low (55%) confidence ($X^2 = 0.18$, $p = 0.67$, Table 1). Positive and negative evidence was evenly distributed across climate, ecosystem types and life cycle phases (Table 2).

Negative impacts

The negative impacts on recreation and aesthetics are related to the effect on visual impact, [50, 142, 193-196], especially in more natural areas [197], with implications for local wellbeing, community acceptance and tourism [50, 198-200]. For example, a survey of locals in the Jaén province in southern Spain found that one of the least popular options for installation of renewable energy (including SPs) was tourist areas, amid fears that the infrastructure would make the landscape less attractive for tourists [200].

Positive impacts

Limited evidence suggested enhancement of recreation and aesthetic interactions at SPs and the majority was prospective. For example, it was suggested there was scope to manage the vegetation to enhance aesthetics [22], and to integrate SPs into the landscape in a way that provides benefits to locals including access for recreational activities such as community gatherings or vantage points providing views over the landscape [94, 95]. An Italian study postulates that the creation of 'photo-ecological gardens', green spaces within urban areas that also generate electricity via solar panels, may improve mood and reduce stress and anxiety, among other benefits [153].

3.2.9 Pollination regulation

Pollinators are key to global biodiversity and regulating the delivery of final ES such as food and biomass provision [128, 201], yet pollinators are in decline, primarily due to habitat loss and fragmentation [201]. SPs offer an opportunity to enhance pollination services through the creation of habitat and provision of food sources, but could also lead to further loss of habitat depending on management actions [20, 42]. Overall, evidence relevant to pollination regulation was unevenly distributed across positive (80%) and negative (20%) impacts ($X^2 = 7.20$, $p = 0.01$, Table 1), with more evidence linked to positive impacts, particularly in temperate climates and the operational phase (Table 2). However, the distribution of evidence across strong (20%) and weak (80%) quality was uneven (X^2

= 7.20, p = 0.01, Table 1), demonstrating a lack of field data (Table 1) and the need for further empirical research.

Negative impacts

The loss of pollinator habitat due to SP expansion and potential subsequent impacts on the fitness and movement of pollinators accounted for approximately 20% of the negative evidence [20, 202]. Changes in habitat can also affect pollinator community composition. In Oregon, pollinator abundance, diversity and richness were lower under panels compared to gaps between rows and controls, possibly linked to the lower number of bloom units in the shade [77].

Positive impacts

Most of the pollination regulation evidence was associated with positive impacts, largely due to management decisions, although the majority of evidence was speculative, opinion or modelling based (Table 1). Specifically, evidence suggested that SPs managed with native vegetation and wildflowers for pollinators may provide more floral resources [42, 77, 147, 153] and habitat [22, 92, 121, 148, 184] compared to the prior land use, with subsequent benefits for pollinators. Additionally, a field study in the USA suggested that where water is limited, late season foragers may benefit from the increased floral abundance and delayed bloom-timing observed in gaps between rows of panels [77]. Despite the relatively small amount of peer-reviewed research on pollination regulation at SPs, actions to enhance the ES are increasingly incorporated into SP management plans, informed by industry guidance such as the Natural Capital Best Practice Guidance from Solar Energy UK [203] and pollinator-friendly solar legislative initiatives in some US states [204].

3.2.10 Pest and disease regulation

Regulation of pests and diseases, including invasive species, is important for maintenance of the health and wellbeing of humans, livestock, crops and ecosystems [128]. SPs can impact pest and disease regulation through changes in land management, disturbance to soil during construction and changes to microclimate. Evidence relevant to pest and disease regulation at SPs was evenly distributed across positive (46%) and negative (54%) impacts (X^2 = 0.08, p = 0.78, Table 1), climate and ecosystem types and lifecycle phases (Table 1; Table 2). However, more of this evidence was considered weak (77%), although this was only marginally significant (X^2 = 3.77, p = 0.05, Table 1).

Negative impacts

Just over half (54%) of the pest and disease regulation evidence was associated with negative impacts (Table 1), with the majority focused on construction and management increasing invasive species and pests [205]. For example, the presence of two invasive plant species - Mexican poppy (*Argemone Mexicana*) and Mesquite (*Prosopis julif*) - at a SP in South Africa was attributed to construction aiding the spread of invasive weeds and pest animals [56], whilst two shade tolerant invasive plant species - Common stork's-bill (*Erodium cicutarium*) and Arabian Schismus (*Schismus arabicus)* - increased at a SP test site in the Mojave Desert [87]. The remaining evidence focused on the negative impacts of SPs on human health, e.g., infections of construction workers after grading land harbouring the soil-borne fungal pathogen *Coccidioides immitis* [54, 55], or concerns around exposure to Electric and Magnetic Fields (EMF) [196].

Positive impacts

The remaining evidence (46%) implied positive impacts on pest and disease regulation (Table 1), two-thirds of which was general references to hypothetical enhancement of biological control [22, 90], human health [90] and crop pest predation [147] at SPs, associated with co-location of SPs with vegetation or sustainable integration into the landscape.

3.2.11 Flood regulation

Flood regulation concerns the capacity of an ecosystem to reduce flood hazards due to heavy precipitation events, by reducing the amount of runoff [128]. Evidence was evenly distributed across positive (31%) and negative (69%) impacts (X^2 = 1.92, p = 0.17, Table 1), climate and ecosystem types and lifecycle phases (Table 2). Notably, 100% of this evidence was considered weak, with a lack of field data (X^2 = 13.00, p < 0.001, Table 1).

Negative impacts

Two-thirds of evidence linked to flood regulation at SPs implied degradation of the ES (Table 1), largely associated with interception of rainfall by impervious solar panels, resulting in increased runoff. For instance, a modelling study found that long-term reductions in surface roughness under solar panels and between rows of panels resulted in increased runoff, thus potential for increased flooding [206]. Similarly, runoff volume was higher after SP construction due to increased inflow of rainwater which exceeds the infiltration capacity of the soil [190].

Positive impacts

The remaining third of evidence was associated with potential enhancement of flood regulation at SPs (Table 1). Constructing SPs on arable land and converting the landcover to grassland could reduce the risk of flooding through increased soil stability, vegetation cover and infiltration [147], with similar benefits predicted following establishment of pollinator habitat at SPs [21].

3.3 Future research needs

This study focusses wholly on the consequences of SPs on ecosystem services, without comparison to other electricity generation technologies or climate change impacts. As such, in order to inform electricity generation choices, further research should integrate the outcomes of this review with existing understanding of other technologies and climate change impacts.

To further advance understanding of SP impacts on ES, future research should consider the full range of potential impacts and any trade-offs between ES [207-210], the nature and extent of which will vary depending on factors including site location and management decisions (Section 4.1). In this study, each piece of evidence was linked to the ES it most likely impacted. However, linking environmental indicators to potential implications for ES is challenging, given the complex and interconnected interactions within ecosystems and between ES and the lack of standardisation amongst indicators [211]. Moreover, there will likely be trade-offs between ES, where some ES may be enhanced at a given SP, whilst others are degraded. Such trade-offs are particularly common between provisioning and regulating services [212], for example enhancement of food provision within an agrivoltaic system may result in degradation of maintaining habitats and biodiversity. There may also be secondary or indirect impacts on another ES, which were considered outside the scope of this review. Moreover, the review has identified that SPs have the potential to enhance a range of ES, including pollination, soil erosion regulation and water cycle support. However, in addition to the influence of factors including climate, ecosystem type, soil properties and prior land use, the extent to which positive outcomes can be achieved will likely rely significantly on on-site management priorities and decisions, such as wildflower planting, soil amendments and mowing and grazing regime [10, 29, 30]. Therefore, additional studies are required which quantify the impacts of such human interventions on ES at SPs.

Given the relative infancy of SPs, there are no longitudinal studies on ecosystem response to land use change for SPs, and relatively few studies more than ten years old. Long-term data are essential, given that the magnitude and nature of ES impact will likely vary temporally. For example, soil properties such as soil carbon content will respond to land use change over a period of decades [213], whereas changes in habitat extent and wildlife populations may become apparent far earlier.

Finally, given the accelerating rate of scientific articles, the literature search should be repeated periodically. If possible, studies should not be limited to English, as this may exclude relevant research. Periodic refinement would enable the incorporation of additional factors which may influence the nature and direction of ecosystem response to SP development, including soil type, plant species composition and past land use.

4.0 IMPLICATIONS FOR THE SOLAR INDUSTRY

4.1 General considerations

The solar industry is increasingly engaged in understanding and improving SP ecology, in response to environmental, social and governance targets, voluntary and mandatory reporting, and emerging environmental policies [33, 35, 214]. The outcomes of this review contribute some of the first multi-site insight into potential ES impacts of SPs, providing critical evidence to underpin policy development and industry decision-making. It is key to consider ES impacts throughout the SP life cycle, considering both site location (i.e., climate zone and ecosystem type) and management decisions. Current understanding suggests that:

1). ES impacts vary with SP location (both climate zone and ecosystem type). Whilst the impacts of other drivers, for example site management, precluded consistent outcomes, clear overarching trends emerged, including that savanna and grassland ecosystems were more vulnerable to negative impacts, climate regulation tended to be degraded in desert and semi-desert ecosystems and soil quality regulation was degraded in temperate climates yet enhanced in dry climates. Moreover, water cycle support was particularly enhanced in temperate climates and agricultural ecosystems, whilst soil erosion regulation was enhanced in agricultural ecosystems and pollination regulation enhanced in temperate climates.

2). The operational phase of the SP life cycle offers significant opportunities for ES enhancement, particularly for water cycle support, soil erosion regulation and pollination regulation. Conversely, the construction phase was associated with ES degradation, specifically of habitats and biodiversity (primarily attributed to disturbance).

3). Some sites have greater potential for enhancement or degradation of certain ES, and trade-offs between ES may occur. For example, prior agricultural sites may have greater scope for enhanced food provision ES if co-managed for grazing or converted to agrivoltaic systems, yet an agrivoltaic installation constructed on land of high biodiversity value may enhance food provision whilst degrading habitats and biodiversity. Consideration of these intricacies through development of industry best practice e.g., Solar Energy UK's Natural Capital Best Practice Guidance [203], may alleviate such trade-offs and could include avoiding environmentally sensitive areas, seeding pollinator habitat at SPs and mitigating habitat loss during construction [10, 42, 202, 215].

4). There are significant knowledge gaps for multiple ES including; pollution, air quality and water quality regulation, and cultural ES such as educational and cultural interactions. Additionally, the evidence base for nine ES is more prospective, highlighting potential uncertainties and the need for future empirical data. The solar industry must bear this in mind when making decisions and ideally must work collaboratively to address these uncertainties. Improved information exchange between stakeholders, perhaps through the development of standardised databases informed by on-site monitoring, would enable this collaboration whilst providing valuable additions to SP management tools [10, 202, 203, 216].

4.2 Embedding ES impacts during the SP life cycle

Appropriately designed and managed SPs have the potential to embed ES enhancements throughout the SP life cycle . SP practitioners should tailor management aims and actions to the local site conditions and consider the potential for trade-offs between ES. For example, in hot dry climates there may be scope to enhance ES such as food provision and water cycle support if SPs are managed as agrivoltaic systems, given the shelter from high levels of solar radiation and increased soil moisture provided by panels. Conversely, sites can enhance pollination services if sites are managed as grasslands and sown with areas of wildflowers in temperate regions. Although not exhaustive, considerations for practitioners during each stage of SP development are summarised below.

Planning phase

There is significant scope to incorporate ES enhancements and mitigate negative impacts during the planning phase, as highlighted by a growing body of academic [10, 217, 218] and industry-led research [219, 220]. The mitigation hierarchy, comprised of avoid/prevent, mitigate/minimise, rectify/restore and offset/compensate is a globally accepted framework which aims to prevent biodiversity loss from development [215]. This hierarchy should be adopted during the planning phase and applied throughout subsequent phases of the SP life cycle [203]. Further guidance relating specifically to the planning phase is outline below:

Generally, environmentally sensitive and designated landscapes should be avoided, potentially with the aid of decision support tools [9] e.g., the Carnegie Energy and Environmental Compatibility Model (CEEC) in the US [221]. Preference should be given for intensively managed or modified sites, as this is where impacts will likely be least severe whilst offering the best scope for ecosystem co-benefits [10, 222]. A plan informing environmental and land management should be developed which incorporates ES enhancements into the design, ideally involving ecologists with an understanding of the particular ecosystem. This may be aided by management tools, e.g., the SPIES tool in the UK [10]. The evidence indicates several beneficial management actions, including planting of native vegetation, which can provide wildlife habitat [91, 122] and sowing nectar species for pollinators in more temperate areas, which can enhance pollination regulation and food provision through increased pollination services to surrounding crops [21, 42, 122, 223]. Further, solar panels in arid areas can promote vegetation recovery, alleviate impacts of desertification [16, 22] and enhance food provision through increased soil moisture [23, 25]. Provision of habitat for protected species can be considered during the planning and design process, such as that implemented at the Topaz Solar Farm Project in California, USA for the federally listed San Joaquin kit fox (*Vulpes macrotis mutica*) [217].

Security fencing and lighting should be minimised to prevent disturbance to wildlife, and access allowed for animals to pass through the site to reduce potential issues with habitat fragmentation and gene flow [4, 202, 203]. Potential aesthetic and recreational impacts should be mitigated during planning through inclusion of natural screening features in design e.g., local vegetation, ridges and integration with the surrounding landscape [94, 224], and threats to local cultural and spiritual value should also be considered [72, 198, 225].

Construction phase

The construction stage has the potential to have the most detrimental impacts on ES due to the initial land use change, disturbance and potential habitat loss, therefore impacts should be mitigated where possible. This could include:

Locating construction compounds away from the most environmentally sensitive areas on this site [222] and reducing unnecessary disturbance from site machinery to reduce potential for dust, soil compaction and collisions with wildlife [19, 48]. For example, the use of low-pressure vehicles and ground protection in wetter locations, to protect vegetation and soil from compaction.

Removal of existing vegetation should be avoided where possible to protect wildlife habitat e.g., bird nests and bat roosts [224], maintain soil carbon and nitrogen [47, 226] and reduce soil erosion and dust production in arid areas [4].

The use of techniques such as grading, or levelling of land should be minimised due to impacts on carbon sequestration and biodiversity. In particular, grading in arid areas can increase soil erosion, one of the main contributors of dryland degradation [4, 227]. Where avoidance is not possible, topsoil should be retained, stored according to best practices and replaced following construction [203, 222].

Construction should also be timed to minimise detrimental impacts. For example; avoiding sensitive seasons for wildlife, including bird breeding seasons, and winter in temperate regions, where soil compaction is more likely [228].

Operational phase

The operational stage is generally the least damaging stage of the SP life cycle, as disturbance is often minimal once the SP is established. However, the nature, scale and severity of potential ES impacts will largely depend on the on-site management:

Given emerging policies that require quantification of ecological impacts, ideally impacts should be monitored throughout the operational stage. Monitoring protocols will vary with local requirements but could include vegetation, soil, bird, and pollinator surveys, for example as per the Solar Energy UK monitoring protocol [203, 216, 219].

An environmental management plan, informed by on-site monitoring and decision support tools, tailored for the specific site by input from land managers, stakeholders and local ecologists, should be developed and periodically refined [10, 203, 216, 222]. The most appropriate management will vary with location and potentially with management aims (i.e., carbon sequestration versus pollination regulation). For example, sites in temperate climates could be managed to enhance soil carbon (and thus climate and soil quality regulation) through a combination of measures including organic nutrient addition, low-intensity sheep grazing and planting legumes and a diverse sward of local plant species [229]. Reducing grazing on land previously grazed may allow for recovery of native vegetation, enhancing ES such as maintaining habitats and biodiversity, whilst continued maintenance of wildflower meadows, or ceasing pesticide and insecticide use may promote pollination services [10].

Decommissioning phase

There is limited evidence on the impacts of SP decommissioning, as SPs became a popular means of solar deployment in the mid-2000s and are predicted to be operational for around 20 – 40 years [4]. However, inclusion of the decommissioning phase within policy and SP management plans is vital to address this upcoming issue [6] and avoid potential ES impacts:

The site management plan should include detail on deconstruction, recycling, and future use and management [202, 203, 224]. The subsequent land use will determine impacts on ES and the appropriate land management decisions. Ideally, the site will either be reverted to former use or maintained for ES enhancement in consultation with an ecologist. For example, the Topaz Solar Farms Project secured approximately 22,000 acres of land for restoration and protection following SP decommissioning, ensuring continued habitat value [217]. However, both climate zone and ecosystem type will inform the outcomes, with arid areas slower to adapt to land use change and restoration [202].

A full ecological survey should be undertaken prior to deconstruction, and panels removed with care to reduce disturbance to wildlife and habitats. For example, ploughing land to remove panel structure should be avoided where possible, and panel removal should be timed sensitively e.g., outside of the breeding season for birds [203]. Panels should be recycled to minimise the potential for toxic chemicals such as Si and Pb to leach into aquatic systems [6, 85].

It is envisaged that decommissioning will have parallels with construction in terms of activities and potential disturbance to wildlife. Given the lack of evidence on the impact of decommissioning, studies assessing the environmental consequences should be undertaken as SPs begin to be decommissioned. Monitoring should continue during decommissioning, to address the lack of research associated with this phase.

5.0 CONCLUSION

Given the urgent need to decarbonise global energy supplies, the declining health of Earth's ecosystems and the rapid expansion of ground-mounted solar PV, it is imperative that we improve our understanding of the environmental and ES impacts of SPs. In this review, we linked the current evidence base on environmental impacts of SPs to ES for the first time and identified the significant influence of SP location (climate and ecosystem) and life cycle phase on the nature of ES impact. The evidence demonstrates a wide range of impacts of SPs on ES and varying responses between sites in light of their characteristics and management. Overarching trends indicate that savanna and grasslands are the most susceptible ecosystems to damage, that most negative impacts could occur during the construction phase (notably for maintenance of habitats and biodiversity), and that SPs in desert and semi-desert climates can have negative feedback on climate regulation. In contrast, the operational phase has significant potential for ES enhancement, including of water cycle support, soil erosion regulation and pollination regulation. However, knowledge of SP-ES impacts is relatively limited - particularly considering the global scale of solar PV deployment - with the evidence base for the majority of ES deemed inconclusive. This is compounded by a larger proportion of speculative, hypothetical, and conceptual evidence, especially for positive impacts. Consequently, further empirical research is required across a range of former land uses, climates, ecosystems, phases of the SP life cycle and management regimes, particularly concerning potential SP-ES benefits, to help inform SPs that address both the climate and ecological crises. This, in addition to closer collaboration between researchers, policy makers and SP stakeholders, will create a more robust evidence base through which site-specific design and management throughout the SP life cycle can be implemented.

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We describe contributions to the paper using CRediT roles:
LT: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization.: **AA**: Conceptualization, Methodology, Validation, Writing – review and editing.: **S.P.S**: Conceptualization, Methodology, Validation, Writing – review and editing.: **S.S**: Methodology, Validation, Writing – review and editing.: **G.P**: Validation, Writing – review and editing.

CONFLICT OF INTEREST STATEMENT

Lucy Treasure was co-funded by Eden Renewables LLC and Guy Parker is employed by Wychwood Biodiversity Ltd. Alona Armstong, Stuart Sharp and Simon Smart declare no conflicts of interest.

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8.0 APPENDIX

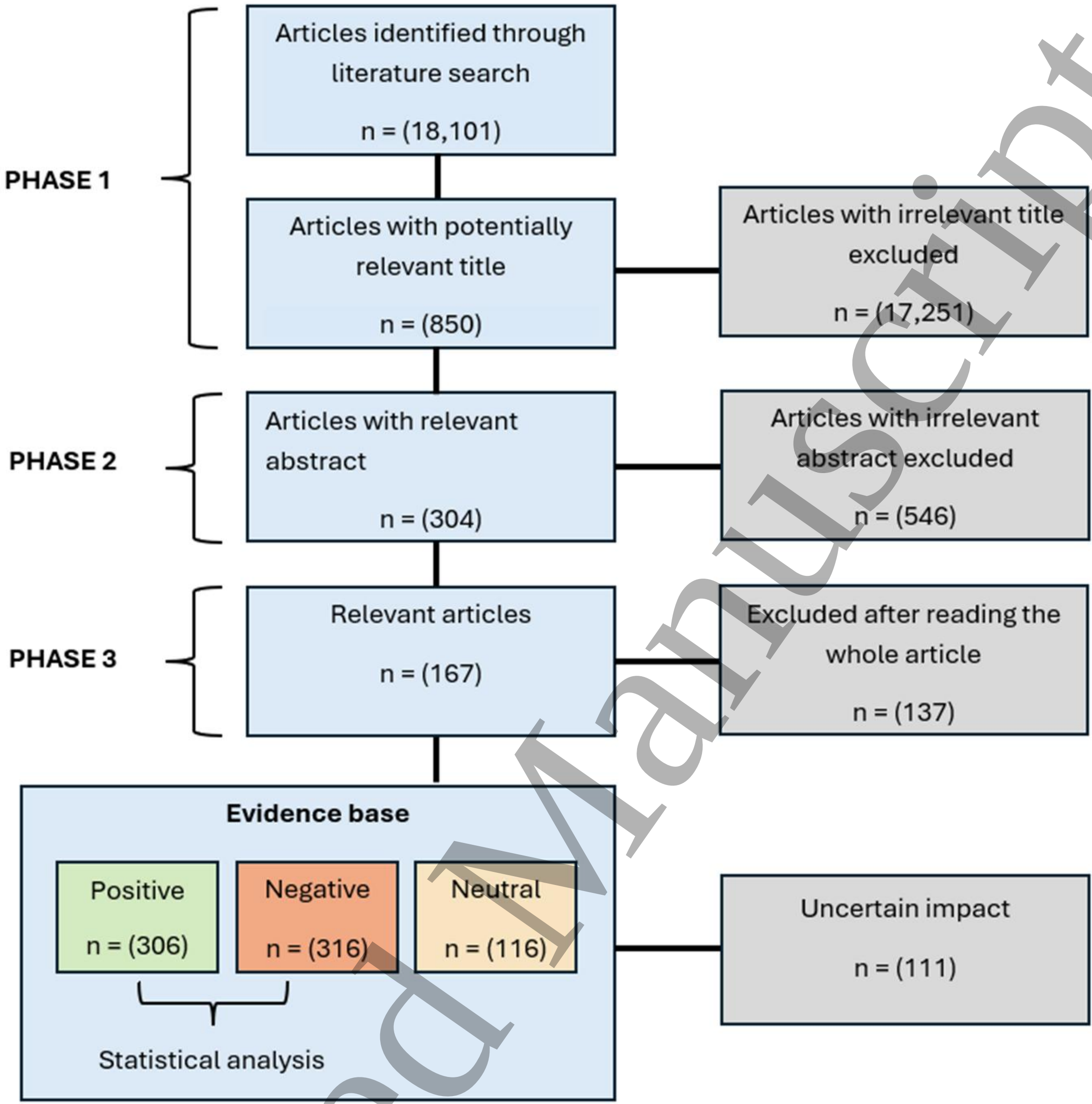

Figure 1. Flow diagram detailing the three-phase screening process used during the QSR.

Table 1. Search strings based on keywords associated with PICO elements derived from the primary question used in the QSR, "what are the ES impacts of SPs?" Boolean operators were used to combine keywords, where OR ensured each result contained at least one of the listed keywords, whilst AND ensured results contained all keywords. The asterisks wildcard operator specified zero or more of any alphanumeric character, e.g., dispers* located dispersal, dispersion, or dispersed. Keywords enclosed within double quote characters returned only results that contained the phrase as was typed. Each string began with TS to ensure the title, abstract and keywords of each result was searched, as per Web of Science™ search rules.

PICO element	Search string
Population, Control	TS = ("SP*" OR "solar farm" OR "solar panel*" OR solar array* OR "utility scale solar" OR photovoltaic* OR "solar-energy" OR "solar power" OR "solar facilit*" OR "Agri-voltaic*" OR "agrivoltaic" OR "agriPV" OR "rangevoltaics" OR "large scale solar" OR "large-scale solar" OR "ground mounted solar" OR "ground-mounted solar")

Outcome	TS = (wildlife OR pollinat* OR bird* OR insect* OR invertebrate* OR arthropod* OR mammal* OR reptile* OR amphibian* OR plant* OR vegetation OR primary prod* OR flower* OR wildflower* OR flora* OR nectar OR pollen OR soil* OR “species abundance” OR “species diversity” OR “species richness” OR ecosystem* OR ecolog* OR biodivers* OR metapopulation* OR dispers* OR “wildlife conservation” OR habitat* OR “land-use change” OR “land use change” OR “land cover change” OR “land-cover change” OR “environmental impact” OR landscape* OR “ecosystem service*” OR “natural capital” OR climate OR forag* OR crop* OR food OR agricult* OR grass* OR pasture* OR meadow* OR “brown field” OR livestock)

Table 2. Definitions/descriptions of the ecosystem services used to categorise evidence extracted from relevant articles, as per Randle-Boggis et al. [9] and taken from the UK National Ecosystem Assessment [96].

Ecosystem Service	Definition
Air quality regulation	Air quality regulation concerns the regulation of atmospheric pollutant concentrations and their deposition onto water and land surfaces.
Climate regulation	Climate regulation provides goods and services that regulate climate so that adverse impacts on human well-being and biodiversity are avoided. Ecosystems regulate climate through biogeochemical effects and biophysical effects; including sources and sinks of greenhouse gases (GHGs), photosynthetically active radiation (PAR), albedo and local regulation of temperature, wind and precipitation.
Flood regulation	Flood regulation concerns the capacity of an ecosystem to reduce flood hazards due to heavy precipitation events, by reducing the amount of runoff.
Pest and disease regulation	Disease and pest regulation directly affects human health and wellbeing and has a potentially large impact on regulating the provision of final ecosystem services, such as crops, other plants and livestock. In addition, evidence concerning invasive species has been included in this ES.
Pollination regulation	Pollination has a potentially large impact on regulating the provision of final ecosystem services, such as crops and other plants, which deliver food and fibre.
Pollution regulation	The capacity of the ecosystem to regulate pollution, including noise, air, water, soil, and polarised light pollution.
Soil erosion regulation	Soil erosion regulation concerns the retention of soil on the land surface, which can be affected by vegetation cover, climate (wind, precipitation) and land management practices.
Soil quality regulation	Soil quality regulation is vital to delivering regulating services through the storage and degradation of organic matter, mediating exchange of gases to the atmosphere, storing, degrading, and transforming materials such as nutrients and contaminants, and regulating the flow of water.
Water cycle support	Water cycle support underpins the delivery of many other ecosystem services and concerns the major water fluxes, such as precipitation, evapotranspiration and river flow, and water storages including lakes, groundwater, and soil, which together determine the spatial and temporal availability of water.
Water quality regulation	Water quality regulation is determined primarily by catchment processes; therefore, it is closely linked to other ecosystem services e.g., soil and air quality, and climate regulation. Key ecosystem processes regulating water quality include plant and microbial nutrient uptake, pollutant sequestration in soil and sediment organic matter, breakdown of organic pollutants, acidity buffering and denitrification. These processes contribute to final ecosystem services e.g., detoxification and purification, drinking water and fisheries provision, and recreation.
Biomass materials provision	The provision of all biomass excluding food crops e.g., grazing, timber, biofuel, medicine, genetic resources.

Food provision	The provision of food crops, livestock and their products.
Educational and cultural interactions	The nonmaterial benefits people obtain from ecosystems through education and cultural interactions e.g., knowledge systems, cultural identity.
Recreation and aesthetic interactions	The nonmaterial benefits people obtain from ecosystems through recreation and aesthetic experience, including aesthetic values and wellbeing.
Spiritual and religious enrichment	The nonmaterial benefits people obtain from ecosystems through spiritual enrichment and reflection.
Maintaining habitats and biodiversity	Includes species abundance and richness, habitat provision, enhancement, fragmentation and loss, direct wildlife impacts e.g., mortality and indirect impacts e.g., dispersal, movement, and gene flow.

Table 3. Categories for ecosystem type classification, adapted from the IUCN terrestrial Global Ecosystem Typology 2.0 (Keith et al., 2020).

Code	**Definition**
T1	Tropical-subtropical forests
T2	Temperate-boreal forests and woodlands
T3	Shrublands and shrubby woodlands
T4	Savannas and grasslands
T5	Deserts and semi-deserts
T6	Polar/alpine (cryogenic)
T7	Intensive land use:
	a. Urban
	b. Agricultural

Table 4. Ecosystem services for which the evidence base was classed as inconclusive (n = < 10).

Ecosystem service	**Database field**	**Sub-category**	**ES impact**		**Evidence quality**	
			+	-	Strong	Weak
Air quality regulation	Location	Australia	0	2	1	1
		China	2	0	0	2
		N/A	2	0	0	2
	Climate type	N/A	3	0	0	3
		Dry	0	2	1	1
		Continental	1	0	0	1
	Ecosystem type	Agricultural	1	2	1	2
		N/A	2	0	0	2
		Polar/alpine	1	0	0	1
	Life cycle phase	Construction	1	2	1	2
		N/A	2	0	0	2
		Operational	1	0	0	1
Water quality regulation	Location	Australia	0	1	0	1
		China	1	0	0	1
		Italy	0	1	0	1
		N/A	1	0	0	1
		India	0	1	0	1
	Ecosystem type	Deserts and semi-deserts	1	1	0	2
		Agricultural	0	1	0	1
		N/A	1	1	0	2
	Life cycle phase	Operational	2	0	0	2
		Construction	0	1	0	1
		Decommissioning	0	1	0	1
		N/A	0	1	0	1

Spiritual and religious enrichment	Location	USA	0	3	0	3
		UK	0	1	1	0
	Climate type	Dry	0	3	0	3
		Temperate	0	1	1	0
	Ecosystem type	N/A	0	2	0	2
		Deserts and semi-deserts	0	1	0	1
		Savanna and grassland	0	1	1	0
	Life cycle phase	Construction	0	4	1	3
Pollution regulation	Location	Italy	0	1	0	1
		South Africa	0	1	0	1
		USA	0	2	0	2
	Climate type	Dry	0	1	0	1
		N/A	0	3	0	3
	Ecosystem type	Savanna and grassland	0	1	0	1
		N/A	0	3	0	3
	Life cycle phase	Construction	0	1	0	1
		Decommissioning	0	1	0	1
		N/A	0	2	0	2
Educational and cultural interactions	Location	Mexico	0	2	0	2
		China	1	0	0	1
		Italy	1	0	0	1
		Greece	0	1	1	0
		N/A	1	0	0	1
	Climate type	Temperate	2	0	0	2
		Tropical	0	2	0	2
		Dry	1	0	0	1
		N/A	0	1	1	0
	Ecosystem type	Tropical-subtropical forests	0	2	0	2
		Deserts and semi-deserts	1	0	0	1
		Agricultural	1	0	0	1
		N/A	1	0	0	1
	Life cycle phase	Operational	3	1	1	3
		N/A	0	2	0	2

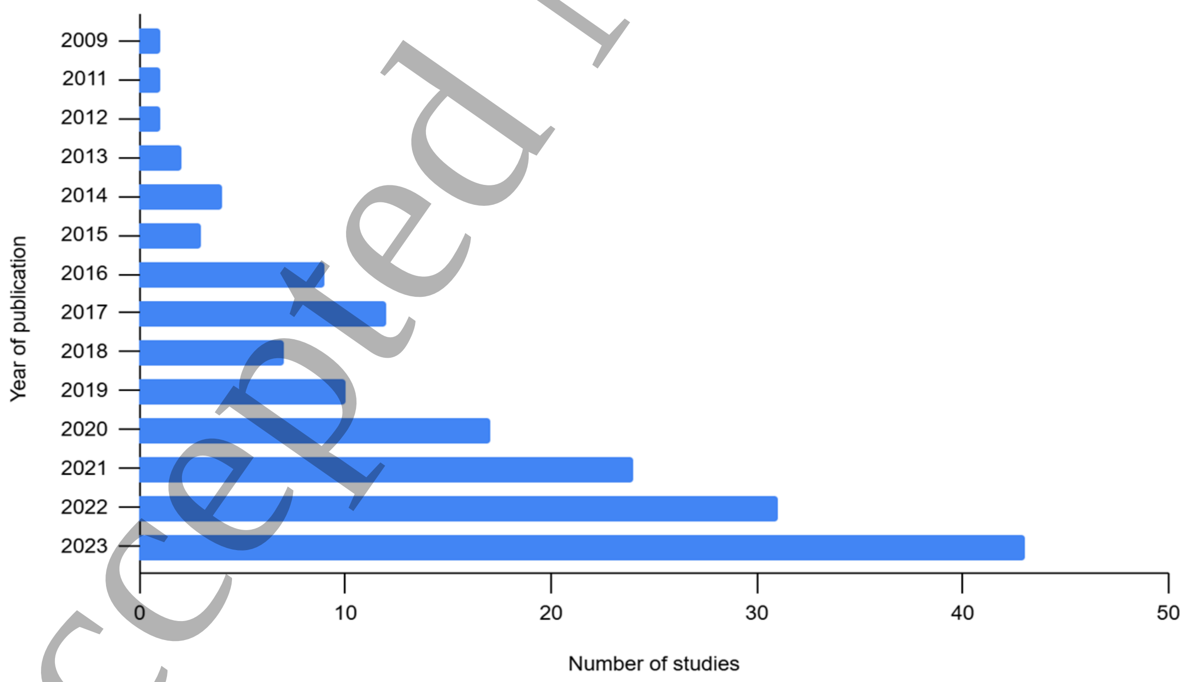

Figure 2. Publication year distribution chart for articles with evidence extracted during the systematic review and linked to potential positive or negative impacts on ecosystem services.