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Navigating the Nexus between Renewable Energy and Biodiversity: Impacts and Mitigation Strategies for Ground-Mounted Photovoltaic Systems

Christa Hainz-Renetzeder[1]*, Thomas Schauppenlehner [1], Patrick Scherhaufer[2], Bärbel Pachinger[3]

1) BOKU University, Institute of Landscape Development, Recreation and Conservation Planning, Vienna; Austria

2) BOKU University, Institute of Forest, Environmental and Natural Resource Policy, Vienna; Austria

3) BOKU University, Institute of Integrative Nature Conservation Research, Vienna; Austria

*Corresponding author email: christa.hainz-renetzeder@boku.ac.at

Christa Hainz-Renetzeder
https://orcid.org/0000-0003-4363-011X

Thomas Schauppenlehner
https://orcid.org/0000-0002-2552-210X

Patrick Scherhaufer
https://orcid.org/0000-0001-6531-296X

Bärbel Pachinger
https://orcid.org/0000-0003-1413-2752

Abstract

The dual crises of climate change and biodiversity loss demand integrated approaches to align renewable energy expansion with ecological conservation. Ground-mounted photovoltaic (PV) systems, a key component of renewable energy strategies, require significant land use, potentially impacting already vulnerable ecosystems. This study reviews the scientific literature on the ecological effects of ground-mounted PV systems under Central European conditions, with Austria as a case study. Findings reveal scattered evidence of altered environmental conditions, such as changes in microclimate and soil properties, and direct impacts on biodiversity, including habitat loss, fragmentation, and species behaviour. Current planning guidelines in Austria inconsistently address biodiversity concerns, often neglecting habitats outside protected areas. Mitigation measures, such as grazing, hedgerows, and structural elements, are widely recommended but lack robust scientific validation. The study highlights the urgent need for standardized Before-After-Control-Impact (BACI) studies and adaptive monitoring to better understand biodiversity impacts and improve mitigation. Strategic conservation planning at the landscape level is essential to balance energy and ecological goals, ensuring sustainable development. This research underscores the importance of harmonizing renewable energy policies with biodiversity conservation to address the intertwined climate and biodiversity crises effectively.

Keywords:
spatial planning, mitigation hierarchy, monitoring, strategic conservation planning

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1 Introduction

The International Panel on Climate Change (IPCC), together with the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES), is pushing for a comprehensive nexus approach to solve the coupled environmental crises (Pörtner et al., 2023). Important treaties in the field of climate protection, such as the Paris Agreement (UNFCCC, 2015) or the European Green Deal (European Commission, 2019), are only loosely linked to treaties of biodiversity protection, such as the Kunming-Montreal Global Biodiversity Framework (CBD, 2022), or the European Biodiversity Strategy (European Commission, 2020). In addition, legally binding regulations were adopted on the EU level such as the RED III Directive (European Union, 2023) with the designation of zones for an accelerated expansion of renewable energies and, on the other hand, the European nature restoration regulation (European Union, 2024), which aims to preserve and restore degraded ecosystems. The coordination or integration of these differing objectives require appropriate governance mechanisms, which anticipate and address the nexus between climate, biodiversity, and society (Pörtner et al., 2023).

The necessary transition from fossil to renewable energy sources calls for a very ambitious expansion especially of wind and photovoltaics (PV), with the latter in particular demanding a large amount of space (Kiesecker et al., 2024), and thus inevitably conflicting with other land uses such as agricultural production, flood protection, nature conservation and restoration, and human recreation. In addition, the reasonable expansion of protected areas and an effective conservation strategy outside these areas also need space (Watson et al., 2020) for maintaining connectivity and ecosystem functions (Boakes et al., 2019; Pörtner et al., 2023). Several studies, therefore, include protected areas as an exclusion criterion in the decision models for the development of renewable energy infrastructure and in particular for ground-mounted PV (e.g. Kiesecker et al. 2024, among others), while others consider this to be insufficient (Pérez-García et al., 2022), since mobile species also spend large parts of their life cycle outside protected areas. Furthermore, a large share of biodiversity can also be found outside protected areas (Dudley et al., 2018; Loiseau et al., 2021), especially in complex landscapes (Estrada-Carmona et al., 2022), which in turn are essential to maintain biodiversity levels of protected areas (Baldwin & Beazley, 2019; Rada et al., 2019). Hence, there is strong need to align the efforts of decarbonisation and the expansion of renewable energy with the protection and preservation of biodiversity locally and on a global scale.

However, the effects of large-scale expansion of renewable energy infrastructure, especially ground-mounted PV, on biodiversity are largely unknown and exert additional pressure on already multi-impacted landscapes (Pirotta et al., 2022). Very few publications before 2010, some of which only available in grey literature, show complex interrelationships (Jessel & Kuler, 2006; Herden et al., 2009; Peschel, 2010; Tsoutsos et al., 2005). Lovich & Ennen (2011) and Hernandez et al. (2014) formulated possible interactions between solar technologies and ecological aspects in a conceptual way as well as associated research gaps, and were, thus, able to trigger a development in the scientific community that has gained momentum in recent years (Lafitte et al., 2023). However, the state of knowledge is still very scattered, as reviews in recent years have shown (Chock et al., 2021; Gómez-Catasús et al., 2024; Lafitte et al., 2023; Nordberg & Schwarzkopf, 2023). Gómez-Catasús et al. (2024) summarized the available literature, showing a broad range of context-dependent settings, and thus making it difficult to relate to specific environmental conditions, which would be needed for identifying priority areas for PV-installations and necessary mitigation (Hermoso et al., 2023).

The rapid expansion of ground-mounted PV systems has created a strong demand for reliable knowledge, leading various authorities, institutions, and NGOs to develop numerous guidelines and criteria to recommend environmentally friendly spatial planning based on ecological and agroecological principles (Blaydes et al., 2021).

Representative for Central European conditions, this study focuses on Austria. In the case study the tension between the expansion of ground-mounted PV and nature conservation is predominant and subject to current political and societal debates. To achieve the national binding goal of being supplied with 100% renewable electricity in 2030, Austria aims to increase renewable electricity production by 27 TWh (EAG, BGBl. I Nr. 150/2021). Of these 27 TWh, 11 TWh should come from PV systems and experts suggest using open land, including agricultural areas, for the expansion (Fechner, 2020). Ground-mounted PV systems require 0.8-2.8 ha per generated GWh of electricity (Umweltbundesamt, 2022). Assuming two-thirds of the PV target for 2030 is met on built-up structures, 3,000-10,400 hectares of additional land is needed (Umweltbundesamt, 2022). Other studies indicate 7,000-8,000 hectares of land is required to meet the 11 TWh target (PV Austria & ÖIR, 2022). However, this expansion is only aimed at electrical power generation. To achieve climate neutrality (net zero emissions), which Austria aims to reach by 2040, a much larger area would have to be used for ground-mounted PV. This is obviously in contrast with the current biodiversity situation in Austria, where only 18% of the habitats and 14% of the species of community interest are in favourable conservation status (Umweltbundesamt, 2020). In addition, 32% of native breeding birds, 27% of mammals, 64% of amphibians and 60% of reptiles are endangered (Zulka, 2005 & 2007) as are many biotope types (Essl & Egger, 2010). As the installation of new ground-mounted PV systems might possibly impact already impaired ecosystems, immediate evidence-based strategic recommendations for a nature-compatible energy transition are needed.

The principle of the mitigation hierarchy (Jakle, 2012; Kiesecker et al., 2010) stipulates at the top that valuable sites should be avoided regardless of their protection status. However, this requires knowledge of the impact of a ground-mounted PV system on the site and its habitat. The aim of the article is therefore threefold: using Austria as a case study, we want (i) to pool existing knowledge in the scientific literature and apply it to variable Central European conditions, which highly probable change considerably over the next decades due to climate change with complex changes in precipitation patterns (Formayer et al. 2025); (ii) to compare current planning standards and guidelines in Austrian and neighbouring countries and regions with this knowledge and evaluate whether conservation interests outside protected areas are also considered, and (iii) to compare the reduction and mitigation measures in the guidelines with the scientific recommendations. We focus on ground-mounted PV without considering agrivoltaics (i.e. double use of land for both agricultural and energy production). Agrivoltaic systems, especially those installed on stilts, might affect local biodiversity less than ground-mounted systems, but biodiversity impacts also still remain unclear (Schwarz & Ziv, 2025).

2 Materials and methods

2.1 Review of scientific literature

A systematic literature search was carried out via Scopus for the period 2012 to 2023. The following string was adapted from Lafitte et al. (2022) and conducted in September 2023: TITLE-ABS-KEY (((photovoltaic$ OR “solar panel$” OR “solar array$” OR “solar development$” OR “solar power” OR “solar park$” OR “solar installation$” OR “solar facilit*” OR “solar plant$” OR “utility-scale solar energ*” OR “utility scale solar energ*” OR biosolar) AND (biodiversity OR fauna OR flora OR vegetation OR diversity))) AND (LIMIT-TO (SUBJAREA , “ENVI”) OR LIMIT-TO (SUBJAREA , “AGRI”)).

For the resulting 4.542 articles, a word count was carried out to extract how often the search terms in the search string appeared in the title, keywords and abstracts. Entries with a word count of three or more were processed further (375 articles). When screening the abstracts, we excluded studies in desert and tropical ecosystems, and studies dealing with Concentrating Solar Power (Khan & Arsalan, 2016) or limited to measurements of site conditions. 77 papers could be related to biodiversity aspects of interest in the Central European context of terrestrial ecosystems. These were maintained and downloaded as full texts. In a second step, we adapted the search string by incorporating more specific taxonomic terms to look for additional articles not found with the original search string: TITLE-ABS-KEY (((photovoltaic$ OR “solar panel$” OR “solar array$” OR “solar development$” OR “solar power” OR “solar park$” OR “solar installation$” OR “solar facilit*” OR “solar plant$” OR “utility-scale solar energ*” OR “utility scale solar energ*” OR biosolar)

AND (ecolog* OR ecosystem* OR wildlife OR “natural habitat*” OR vertebrate* OR mammal* OR bird* OR reptile* OR amphibian* OR invertebrate* OR arthropod* OR insect* OR arachnid* OR microbi* OR bacteri* OR microorganism* OR fung* OR restoration OR ecovoltaics))) AND (LIMIT-TO (SUBJAREA , “ENVI”) OR LIMIT-TO (SUBJAREA , “AGRI”)). This yielded ten additional articles. Finally, this bibliography was imported into research rabbit (https://researchrabbitapp.com/; Research Rabbit, s.a.), an AI-based tool that finds, organizes, and understands literature by visualizing a network of scientific articles and their connections, to ensure that all relevant literature has been found. This double-check resulted in adding another seven articles into the database. Information of the finally retrieved 93 articles was categorized into: (i) article type (a review, concept, descriptive, statistical, experimental, spatial analysis), (ii) biogeographic location, (iii) biodiversity indicator analysed (organism group, land use or land cover), and (iv) extraction of the main findings. We finally inductively categorized these to six knowledge clusters of impacts on biodiversity described in section 3.1. Subsequently, the focus in this study was on empirical articles that dealt with direct impacts on biodiversity and allowed drawing conclusions to the variable environmental conditions comparable to Central Europe, which in turn could be applied to our case study, Austria.

2.2 Site selection, planning guidelines, and recommendations available for the case study area

Planning regulations on ground-mounted PV of the Austrian federal provinces as well as guidelines in German language and recommendations from countries with comparable environmental conditions were collected via web search. This resulted in 26 documents and grey literature, ranging from institutional spatial planning guidelines to recommendations and position papers presented by NGO’s, umbrella organizations and interest groups, which will be summarized as “guidelines” from now on. They were screened for all measures along the mitigation hierarchy which were considered relevant for biodiversity, such as site selection and mitigation measures. These were extracted and grouped along thematic focuses respectively into main topics.

Finally, a comparison was made between the scientific findings of existing biodiversity effects and mitigation efforts with the recommended ecological measures in the guidelines.

3 Results

3.1 Review of scientific literature

Based on the bibliography extracted, research rabbit identified a few key papers that are extensively referenced like Hernandez et al. (2014), Armstrong et al. (2016), and Blaydes et al. (2021), while other articles show no reference to these, stand alone or only occasionally refer to these central studies. A table of all articles considered in this study is provided as Table S1. The number of publications per year has recently increased significantly, ranging from only a single one in 2012, to 25 articles in 2023, and in particular the period from 2020 onwards shows the increased interest of the scientific community in this topic. The articles demonstrate a broad geographical coverage including North America, Europe, Southern Africa, Arabian countries and Central Asia. 29 deal with the topic in a conceptual way or in the form of a review, 44 of the 93 papers use statistical methods for their analyses, and 21 mainly spatial analyses and spatial modelling. 28 of the spatial and statistical studies can be related to current and expected in the future Central European environmental conditions, because they were carried out for example in the temperate regions of North America, the continental climates of Eastern Europe or the mediterranean conditions of Southern France and Central Italy.

Based on the conceptual articles and reviews (i.e. Chock et al., 2021; Dhar et al., 2020; Gómez-Catasús et al., 2024; Hernandez et al., 2014; Lafitte et al., 2023), two major groups of drivers can be summarized: (i) planning and construction of the installations and (ii) operation of the installations (Figure 1). The first group primarily includes land conversion and the disturbance of soil and vegetation (removal, grading, erosion, sealing) caused by the installation of panels, cables and the construction of roads. During operation of the plant, disturbance from vehicles, noise and light as well as electromagnetic fields

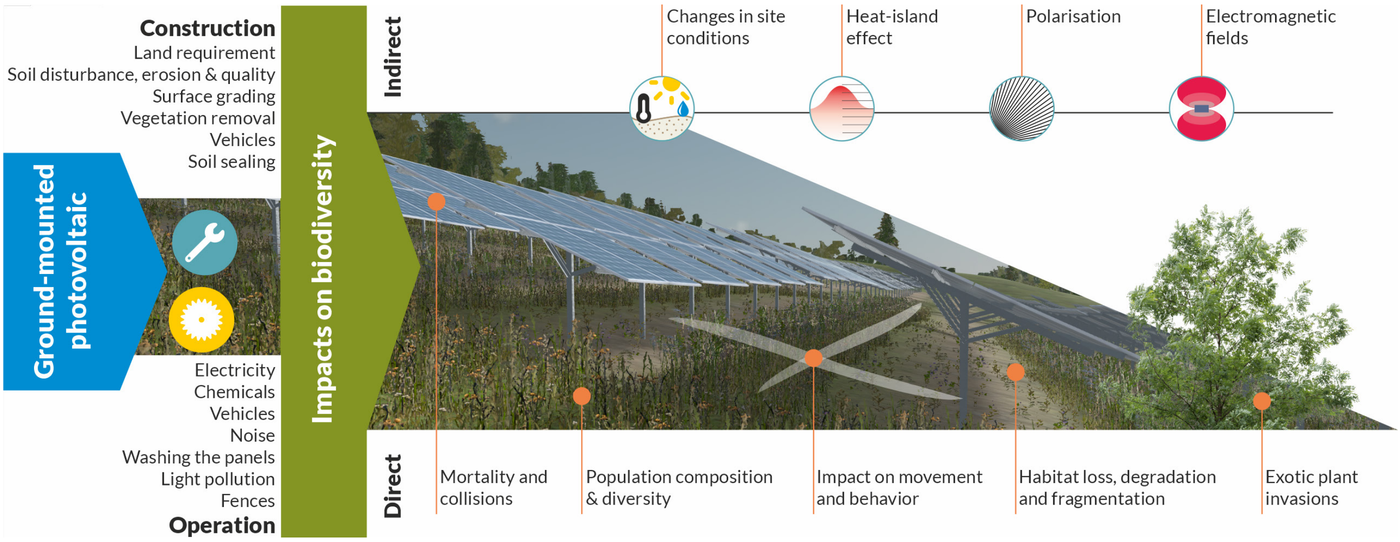

Figure 1. Categories of postulated drivers and impacts of ground-mounted PV plants summarized based on Hernandez et al. (2014), Chock et al. (2021), Dhar et al. (2020), Lafitte et al. (2023), Gómez-Catasús et al. (2024).

induced by electricity, chemicals and the barrier effect of the fences are listed.

These two groups of drivers change the site conditions by altering the microclimate in terms of light conditions (Tanner et al., 2020; Zhang et al., 2023) and thus also temperature (Armstrong et al., 2016; Zhang et al., 2023), and humidity (Liu et al., 2019, 2022; Zhang et al., 2023), as well as the physical and chemical properties of the soil (Moscatelli et al., 2022; Zhang et al., 2023) exerting indirect impacts on biodiversity. However, most of these studies have been conducted in arid ecosystems (Gómez-Catasús et al., 2024). Only a handful of studies are related to temperate conditions: Armstrong et al. (2016) observed in the UK a decreased temperature and moisture under the panels and less diurnal variation compared to the control sites, especially in summer. Under Mediterranean conditions, Lambert et al. (2021) showed a decreased soil temperature by 10%, and soil CO2 effluxes by 50%, without any significant changes in early successional plant communities in Southern France. In Central Italy, repeated measurements over seven years revealed significant reduction of water holding capacity and soil temperature, while electrical conductivity (EC) and pH increased, accompanied by a considerable reduction of soil organic matter under the panels (Moscatelli et al., 2022). Changes in temperature, water and light regime as well as altered soil properties indirectly impact plant growth and communities (Armstrong et al., 2016; Zhang et al., 2023), with both winner and loser species (Gómez-Catasús et al., 2024). According to the literature, the indirect effects of solar panels by changing environmental site conditions are evident (Table 1), whereas their quantification is strongly locality-dependent.

The state of knowledge of direct effects, on the other hand, is blurred and ambiguous (Table 1). Described direct effects of ground-mounted PV systems were categorized into five topics: (i) population composition and diversity, (ii) habitat loss, degradation and fragmentation; (iii) impact on movement and behav-

Table 1. Number of articles dealing with indirect and direct (i.-v.) impacts on biodiversity; articles include statistical, spatial as well as conceptual and review papers (number of statistical and spatial papers in brackets). Biodiversity level studied include different biodiversity indicators as well as spatial models.

Impacts	Number of articles	Biodiversity level studied	Clarity of results
Alteration of environmental conditions	26 (18)	site condition properties	clear results of altered conditions
i. population composition & diversity	33 (26)	plants, arthropods, bats, birds	large variation in results
ii. habitat loss, degradation and fragmentation	25 (15)	protected areas, wilderness areas, land cover, modelled habitats	ambiguous results
iii. impact on movement and behaviour (resident & migratory species)	9 (6)	pollinators, butterflies, bats, ungulates	ambiguous results
iv. mortality & collisions	19 (9)	birds, bats, aquatic insects	large variation in results
v. exotic plant invasions	5 (1)	non-native plants	higher cover of neophytes

iour of resident and migratory species; (iv) mortality and collisions; and (v) exotic plant invasion.

33 studies investigate effects on population composition and diversity. The groups of organisms studied include plants, arthropods, bats and birds and depending on the group studied, results varied between small to large impacts. With regard to habitat loss, degradation and fragmentation, the 15 statistical studies mainly use spatial models of habitats, protected areas, wilderness areas or land cover in general, with actual or possible PV locations. The results are ambiguous, as some articles showed a large spatial impact on important biodiversity areas (e.g. Rehbein et al., 2020), whereas other could only find an minimal overlap with conservation areas (f.ex. Dunnett et al., 2022). Nine of 19 articles on mortality and collision use statistical analysis to estimate the collision risk for bats and birds, or whether aquatic insects are attracted to the polarized light of the panels. The results demonstrate large variation in this topic depending on the organism groups studied ranging from small to large impacts. Nine papers describe possible influences on the movement and behaviour of resident and migratory species, six of them are based on statistical surveys of pollinators, butterflies, bats and ungulates. Some of these showed no to minor influence on the movement of butterflies (Guiller et al., 2017) but for ungulates, barrier effects could be described (Sawyer et al., 2022). Five articles discuss the increased probability of neophytes becoming established, although only one study was able to demonstrate this with data.

3.2 Site selection, planning guidelines and recommendations

An important point raised in the discussion of many scientific studies is the previous use of the site: the higher the naturalness of the ecosystem, the greater the negative impact of a ground-mounted PV system. This brings the question of site selection and its criteria into focus. In our review sample, spatial siting criteria relating to nature conservation assets outside of legally established nature conservation areas can hardly be found in scientific literature. A recently published article (Fakharizadehshirazi & Rösch, 2024) compares 31 international studies with regard to siting criteria used and does not list any other parameters relevant to nature conservation. Documents such as planning guidelines, recommendations and other grey literature resulting from the web search, on the other hand, mostly follow the first two steps of the mitigation hierarchy. This means firstly, to avoid (i.e., exclude areas of high conservation values), and secondly, to reduce or mitigate negative impacts (define mitigation measures).

3.2.1 Defining criteria for the exclusion of areas of high conservation value

In general, the different guidelines applicable in the case study area of Austria define protected areas, especially those with a high IUCN protection status, as not suitable for ground-mounted PV systems. Habitats of high conservation value that are outside protected areas, are not consistently treated in the guidelines, five not even mentioning them. The remaining guidelines listed in Table 2, are treating criteria for nature conservation either in detail, or only very superficially, usually in combination with other criteria (forestry, flood protection, protection of good agricultural soils). Many guidelines make a distinction between exclusion zones (complete ban) and reserved or conflict zones (on-site assessment of suitability or not). On the other hand, areas that are heavily impaired by anthropogenic factors, such as industrial landscapes, landfills, areas that have already been sealed, and the surroundings of large infrastructures such as roads, railroads or airports, are labelled as suitability zones. As spatial planning in general, and the approval of ground-mounted PV systems in particular are competences of the nine different Austrian federal states, the inclusion of nature conservation criteria differs enormously. In addition, the guidelines available from NGO’s or interest groups do not follow a common approach regarding nature conservation assets as well (see Table 2).

3.2.2 Definition of mitigation measures

Systematic scientific evaluation of ecological mitigation measures in ground-mounted PV installations were rarely available (Table S1). Five studies evaluated methods to reduce the light polarization of the panels and three studies investigated the effect of grazing as a management strategy for solar

Table 2. List of areas of high conservation values as identified in different guidelines. The sign '-' indicates that the respective habitat is not considered in the guidelines, the letter 'x' indicates the definition as 'conflict zone' (on-site assessment of suitability or not) and 'o' as 'exclusion zone' (complete ban). Only those documents that make a distinctive difference between protected areas and other areas are integrated. Numbers [1] to [16] indicate the following guidelines: [1] ÖIR (2020); [2] Amt der NÖ Landesregierung (2020); [3] Amt der NÖ Landesregierung (2022); [4] Amt der Steiermärkischen Landesregierung (2021); [5] Amt der OÖ Landesregierung (2022); [6] Amt der Kärnter Landesregierung (2021); [7] Wasser Tirol - Ressourcenmanagement-GmbH (2022); [8] Land Salzburg (2016); [9] Birdlife Österreich (2021); [10] im-plan-tat Raumplanungs-GmbH & Co KG (2022); [11] WWF Österreich (2021); [12] Naturfreunde Österreich (2022); [13] Naturschutzbund Österreich; [14] KNE (2021); [15] Hietel et al. (2021); [16] LfU Bayern (2014).

Habitats of high conservation value	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	**(12)**	**(13)**	**(14)**	**(15)**	**(16)**
Red list of endangered biotope types	x	-	-	-	-	0	0	-	0	-	0	-	-	-	-	-
Extensively managed, species-rich grassland / valuable grassland	x	-	0	-	-	-	-	-	x	-	-	-	-	0	0	x
Orchard meadows	x	-	-	-	-	0	-	-	x	-	-	-	-	0	-	-
Dry and semi-dry grassland	x	-	-	-	0	0	-	-	-	0	-	0	0	-	-	-
Slope and nutrient-poor meadows	-	-	-	-	-	0	-	-	-	0	-	-	-	-	-	-
Wetland meadows	x	-	-	0	0	0	-	-	-	0	-	0	-	-	-	-
Valuable alpine grassland and meadows	-	-	-	-	-	-	-	-	-	0	-	0	-	-	-	-
Moors	x	-	-	0	0	0	-	-	-	0	0	0	0	-	-	-
Designated wildlife corridors	-	-	0	0	x	-	0	-	x	-	x	-	-	x	-	-
Nutrient-poor embankments, verges	-	-	-	-	-	-	-	-	x	-	-	-	-	-	-	-
Field shrubs, solitary shrubs, solitary trees	-	-	-	0	-	-	-	-	x	-	-	-	-	-	-	-
Fallow land	x	-	-	-	-	-	-	-	x	-	-	0	-	-	-	-
High-quality landscape structures	x	x	-	-	-	-	-	-	-	-	0	-	0	-	-	-
Renaturation areas	-	-	-	-	-	-	-	-	-	-	0	-	-	x	-	-
Growth and discovery sites of particularly or strictly protected species / rare species	x	-	-	-	-	0	0	-	x	-	0	0	-	0	-	-
Reproduction and resting sites and essential resting areas of strictly protected species	x	-	-	-	-	0	0	-	x	0	0	-	-	0	0	-
Areas for the biotope network or ecological corridors	-	-	-	0	-	-	-	-	x	-	0	x	-	0	-	0
Regional green zones	-	0		0	x	0	0	-	-	-	-	-	-	x	-	-
Near-natural forests	-	-	-	0	-	-	-	-	-	-	-	-	-	-	-	-
Green bridges	-	-	0	-	-	-	-	-	-	-	-	-	-	-	-	-
Natural springs	-	-	-	-	0	0	-	-	-	-	-	-	-	-	-	-
Important bird areas grassland and field breeding bird	-	-	-	-	x	-	0	-	-	-	-	-	-	-	-	-
Waste land	-	-	-	-	-	-	-	0	-	-	-	-	-	-	-	-

parks. Modelling approaches and a literature review were used in two papers to identify synergies with ecosystem services such as pollination. Six studies analysed different management interventions for ecological upgrading and restoration potential of ground-mounted PV systems, such as the use of bee-friendly seed mixtures, inoculation with mycorrhiza, or transfer of seed material. All these articles discussed possible mitigation measures, while emphasizing the need for thorough experimental and BACI studies to better understand how effectively each measure reduces the panels' impact on biodiversity.

The guidelines emphasize mitigation measures despite the scarce scientific evidence. 17 of the 26 guidelines contain various specifications for impact mitigation (Table 3). Some documents provide very specific recommendations (for example Hietel et al., 2021; Moorman et al., 2019), some remain more superficial (BSW & NABU, 2021). Basically, the following thematic clusters can be found in the documents: Management approach (all documents) containing recommendations concerning extensive grazing or late mowing, the retention and creation of new hedgerows (13 documents), to refrain from fencing if possible (15 documents), park layout indicating module arrangement such as spacing and

Table 3. List of mitigation measures which are defined in the planning guidelines and recommendations. An ‘x’ indicates topics of mitigation recommendations addressed in the respective document. Numbers [1] to [17] indicate guidelines: [1] Schlegel et al. (2021); [2] Herden et al. (2009); [3] Montag et al. (2016); [4] Birdlife Austria (2021b); [5] BSW & NABU (2021); [6] Peschel et al. (2019); [7] Birdlife Austria (2021a); [8] Demuth & Maach (2019); [9] KNE (2021); [10] LfU Bayern (2014); [11] PV Austria & ÖIR (2022); [12] ÖIR (2020); [13] Hietel et al. (2021); [14] im-plan-tat Raumplanungs-GmbH & Co KG (2022); [15] Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg (2019); [16] WWF Österreich (2021); [17] Tiroler Umweltanwaltschaft (2013).

Mitigation measure	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	**(12)**	**(13)**	**(14)**	**(15)**	**(16)**	**(17)**
Management approach	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Hedgerows	x			x	x		x	x	x	x	x	x		x	x	x	x
Fencing	x	x		x	x	x	x	x	x	x	x	x		x	x	x	x
Park layout	x	x		x	x	x	x	x	x	x	x	x	x	x	x		x
Collision and light polarization	x	x		x	x				x		x						
Disturbance	x	x		x			x	x	x	x				x	x		
Structural elements	x				x	x	x	x	x	x	x		x	x	x		
Autochthonous seeds / plant material	x		x		x		x	x	x	x	x	x		x	x		
Chemicals	x	x	x		x	x	x	x	x	x	x	x		x	x	x	
Monitoring		x	x	x	x	x			x	x			x	x	x	x	

cover (15 documents), collision and light polarization as a problem for birds, bats and aquatic insects (6 documents), disturbance due to noise and light during operation (9 documents), the creation of structural elements like dead wood, rock piles, bare ground, wetland biotopes, etc. (11 documents), the use of autochthonous seeds and plant material (11 documents), to refrain from applying chemicals (14 documents) and recommendations for consistent monitoring (11 documents).

4 Discussion

4.1 Direct impact on biodiversity

Many statistical studies have investigated the population composition, the diversity of species and species communities, with some studies looking at the impact of panels within installations (Impact) and other articles looking at differences between PV systems and other land covers (Control-Impact). Only a single study in California (Sinha et al., 2018) was designed as a BACI analysis (Gómez-Catasús et al. 2024). The variability of the results presented in the articles is large and is partly explained by different local conditions such as habitat types, target species composition or maintenance concepts (Blaydes et al., 2022; Tsafack et al., 2022; Uldrijan et al., 2022, 2023; Zhang et al., 2023). More specifically, due to the reduced light conditions, shade-tolerant, nitrophilous and annual plant species develop below the panels, while perennials and herbaceous plants colonise between the panels (Armstrong et al., 2016; Uldrijan et al., 2021, 2022, 2023). Overall, higher biodiversity indices of the vegetation (Lambert et al., 2022, 2023; Vervloesem et al., 2022), and soil arthropods (Lambert et al., 2023) were also found. Not only a spatial differentiation in the species communities, but also a temporal one was described by Graham et al. (2021), who found a seasonal dependency in floral abundance as well as pollinator diversity. For bats, species composition was found comparable to other anthropogenic landscapes, like settlements and arable land (Szabadi et al., 2023; Tinsley et al., 2023). Kitazawa et al. (2019) concluded that wetlands and fallow land offer better conditions for birds than other habitats, including ground-mounted PV systems. Bird species that prefer herbaceous plants, nest on the ground, and open shrubs being those most likely to be found in PV systems (Zaplata, 2023).

Habitat loss, degradation and fragmentation at the landscape level was largely investigated using spatial analyses. Existing, planned or potential areas of PV systems were overlaid in GIS with protected areas (Dunnett et al., 2022; Rehbein et al., 2020; Valera et al., 2022), wilderness areas (Aycrigg et al., 2023), land cover (Hernandez et al., 2015; Kim et al., 2021; McCoshum & Geber, 2020) or modeled habitats (Evans et al., 2023; McCoshum & Geber, 2020). While some studies have found a very clear overlap with protected areas (Dunnett et al., 2022; Rehbein et al., 2020; Valera et al., 2022), Evans et al. (2023) see hardly any conversion of natural areas for PV systems and McCoshum & Geber (2020) consider urbanization to be a greater problem. As an interesting aspect Kim et al. (2021) also took the size of the ground-mounted PV system into account. Here, a greater loss of semi-natural areas due to medium-sized ground-mounted PV (defined as 0.5–10 MW) is observed than from large ground-mounted PV systems, which could accelerate the disappearance of small remnants of natural areas.

The impact of habitat fragmentation depends on the species groups studied and their mobility behaviour, and whether the ground-mounted PV installations affect movements and behaviour of resident and migratory species. According to Graham et al. (2021), as well as Guiller et al. (2017), pollinators in general, specifically highly mobile butterflies, could move regardless of the ground-mounted PV systems' presence, whereas butterflies with less dispersal activities were impeded in their interpatch movements. For bats, there were no clear results; in the UK, a negative effect was found on six out of eight species due to the presence of PV installations, suggesting that panels may cause some bats to alter their flight routes (Tinsley et al. 2023). In Hungary, no difference in the bat community was observed between agricultural landscape with and without PV systems, but activity was lower in solar parks (Szabadi et al., 2023). Sawyer et al. (2022) could show a clear effect of the movement behaviour of ungulates in the US rangelands, reducing their activity by 40% in a two kilometres radius after establishing a solar park. At landscape level, Levin et al. (2023) concluded that land conversion due to agriculture and urban development is a much more important driver for biodiversity loss than PV installations by overlaying potential PV areas with wildlife corridors in the US.

As Gómez-Catasús et al. (2024) have pointed out, the issue of mortality and collisions involving birds, bats and aquatic insects is a frequently discussed impact factor, but only scattered peer-reviewed literature exists. Száz et al. (2016) showed in their experiment that different families of aquatic insects are significantly differently attracted to shiny or matte PV panels, and the problem of polarized light pollution is also dependent on weather conditions. Estimates of bird deaths range from 37,800 to 138,600 (Walston et al., 2016) and more than 260,000 birds and 11,000 bats (Smallwood, 2022) associated to this type of renewable energy infrastructure in the United States. This substantial variation of estimates of mortality rates in literature is due to methodological differences, and it is not clear whether these mortality rates have a significant ecological impact, nor what role ground-mounted PV installations play in this system.

The increased spread of invasive plant species is another issue that can be exacerbated by soil changes (Hernandez et al., 2014). However, this influence has only been discussed marginally in other articles. Only Lambert et al. (2023) found that coverage of non-native species was four times higher under the panels than in-between them, and Uldrijan et al. (2023) expressed concerns in their discussion about their increased invasion potential into ground-mounted PV systems due to climate change.

All in all, the results of these studies are inconsistent. Lafitte et al. (2023) and Gómez-Catasús et al. (2024) attribute this to the fact that the studies took place in different climatic and landscape settings and in differently designed facilities. Hence, the importance of BACI studies, standardized survey methods, accurate descriptions of site characteristics and park layouts are a prerequisite for scientific knowledge gain.

4.2 Mitigation measures

Based on the results found in the literature, for some groups of organisms such as bats, mobile butterflies and ground-breeding/ open-shrub preferring bird species, ground-mounted PV installations provide a similar habitat as agricultural landscapes. Some authors have also investigated ways of developing ground-mounted PV arrays as habitat islands in agricultural landscapes (Nordberg & Schwarzkopf, 2023; Tölgyesi et al., 2023). In the only available BACI study, targeted grazing measures in combination with ground-mounted PV on former cereal cropland increased species diversity (Sinha et al., 2018). Grazing is also recommended by Randle-Boggis et al. (2020), to achieve a higher diversity of butterflies and bees in combination with wildflower meadows and set-aside areas. An additional benefit of the ecological enhancement of ground-mounted PV systems in agricultural landscapes also results from an improved provision of ecosystem services, such as pollination for adjacent fields (Blaydes et al., 2021; Mishra et al., 2023), carbon storage, sediment retention and water retention (Walston et al., 2021). Nordberg & Schwarzkopf (2023) as well as Tölgyesi et al. (2023) describe a possible design and associated research gaps for the concept of an “ecovoltaic” (Tölgyesi et al., 2023) or “conservoltaic” (Nordberg & Schwarzkopf, 2023) park as a basis for establishing win-win-situation for biodiversity and energy generation. Still a point of criticism is the largely hypothetical approach, as there are major gaps regarding an effective implementation (Tölgyesi et al., 2023): What is the optimal shape and size of a solar park? What is the perfect panel spacing, panel width, panel height? For which organism groups do solar parks act as a barrier? Which seed mixtures and which management fit the local conditions and can effectively generate multiple ecosystem services for the surrounding landscapes? Which factors can be specified generally, and which differ from site to site?

Despite these shortcomings, recommendations are formulated in scientific literature as well as in the guidelines. Concerning the management approach, some articles emphasize that extensive grazing is favoured to mowing from an ecological perspective; preferably with sheep and/or poultry. Mowing is treated somewhat differently - from one to three cuts per year, occasionally late mowing is noted, and that it is important to remove the cut material, not to mulch it. In the literature, a low intensity management is stressed, especially late in the year (Blaydes et al. 2021; Randle-Boggis et al. 2020).

Regarding hedgerows, there is a consensus about being made up of trees and shrubs that are appropriate to the local site conditions, blend in with the landscape, and do not conflict with the target species. In addition, planting or maintaining hedgerows at the site boundary is also recommended by Blaydes et al. (2021) and Randle-Boggis et al. (2020).

With regard to fencing, most guidelines prefer a design, which allows wildlife to pass underneath and not act as a barrier - a 15-20 cm lower fence bottom edge is mentioned, wherever fencing is unavoidable. Wildlife corridors for large mammals are also recommended in the guidelines, whereas in the scientific literature this issue is not specifically raised.

Concerning park layout, all guidelines call for a module bottom edge of 80 cm to prevent overheating of the area below. However, there are large differences in the degree of canopy cover (30% - 50%), the distance between module rows (2.5 m – 6 m) and the amount of open space (25% - 60% or ‘sufficient’). All guidelines specify a parameter of 2% - 5% sealing and, therefore, hardly see this as a significant impact. Randle-Boggis et al. (2020) also recommend the integration of wild flower meadows, buffer zones, field margins and set-aside areas within the ground mounted PV array.

Regarding mitigation measures for collision and light polarization, there is no great awareness of these issues in the guidelines, even though the problem is highlighted by scientific literature. Black & Robertson (2020) determined gridding as a highly effective mitigation measure. Different groups of aquatic insects seem to react in different manners to matte panels (i.e., panels less light-polarizing) (Száz et al., 2016). Száz et al. (2016) conclude that the most effective conservation measure may be locating solar panels away from riparian corridors that act as centres of aquatic insect activity and dispersal.

Disturbance due to noise and light is emphasized during the construction of the facility, but the measures suggested remain very vague in the guidelines, which could be illustrated with examples like ‘as little as possible’, or ‘not during the breeding season’.

All guidelines also agree on the creation of structural elements and recommend the introduction of dead wood, rock piles, bare ground, wetland biotopes, etc. Such recommendations can also be found in peer-reviewed literature, even though this is largely limited to pollinators. For example, Blaydes et al. (2021) argue to “provide a range of nesting, breeding and reproductive resources” and Randle-Boggis et al. (2020) specifically focus on bee hives, which are designed exclusively for honey bees and should be viewed as livestock farming rather than a measure to promote biodiversity.

The use of autochthonous seeds / plant material is stressed in all guidelines, and some point out that this is also a preventive management measure against the emergence of neophytes. Although Blaydes et al. (2021) argue for a diverse mix of flowering plant species, the availability of regional seeds might be limited (Meyer et al., 2023). In another study, Lambert et al. (2022) found that four years after seed transfer, plant succession created vegetation similar to the reference community outside the panel area. However, solar panels slowed the restoration process, as ruderal species from the soil seed bank in the early years hindered the growth of target species.

The use of chemicals is unanimously rejected in all guidelines as well as in the scientific recommendations (Blaydes et al. 2021, Randle-Boggis et al. 2020). Monitoring is generally desired, but only sporadic references are made to standardized methods and adaptive management in the guidelines. Scientific reviews and conceptual articles on the other hand stress the need for a standardized monitoring to gain better knowledge about the multiple factors influencing the development of the habitats and associated fauna and flora in solar parks (e.g., Gómez-Catasús et al., 2024; Lafitte et al., 2023; Nordberg & Schwarzkopf, 2023; Tölgyesi et al., 2023).

In the scientific literature, the importance of connected habitats is also highlighted (Randle-Boggis et al., 2020), especially for pollinators (Blaydes et al., 2021; Dolezal et al., 2021). Here a range of recommendations is provided, such as to ensure foraging resources also for the late season, variation in vegetation structure, and thus creating different microclimatic regimes and a targeted management.

5 Conclusions

Research on the influence of ground-mounted PV installations on biodiversity has increased in recent years. However, our review exemplified that the knowledge base is still very scattered. Authorities and NGOs demand in a large number of guidelines and recommendations, with good reasons, that ground-mounted PV installations should be implemented as biodiversity-friendly as possible. They argue in line with the scientific literature, that protected areas alone do not sufficiently preserve biodiversity (Hallmann et al., 2017). Therefore, renewable energy planning must also take biodiversity parameters into account. However, the problem is that these parameters must first be identified and quantified, which means corresponding databases on the occurrence of species and habitats that could be affected by ground-mounted PV expansion must be available. In addition, the need and possibilities of BACI-studies for a better knowledge about enhancing mitigation strategies and promoting alternative facility designs should be emphasized (Agha et al. 2020). As long as this data basis is not sufficiently available, especially outside legally protected areas, we suggest for the Austrian case study and other comparable Central European environmental conditions i) to strictly follow the mitigation hierarchy; ii) to define criteria for excluding areas of high conservation value; and iii) to integrate adaptive mitigation measures with a strong monitoring focus.

Based on the Austrian case study, we see an urgent need to mainstream integrated climate and nature conservation policies, and planning procedures. The expansion of ground-mounted PV systems is a critical component of achieving climate and energy targets, with significant land requirements projected for the coming decades (Schmidt et al., 2025; Auer et al., 2020; Jacobsen et al., 2017). Simultaneously, the European Union has set ambitious goals to restore at least 20% of its land and sea areas by 2030, and to ensure the restoration of all ecosystems in need by 2050 (European Union, 2024). In Austria, however, the legal framework for spatial and energy planning is fragmented, as these responsibilities, along with nature conservation and species protection, lie within the nine federal states. This has resulted in inconsistent, uncoordinated, and often non-transparent approaches to integrate nature conservation criteria into planning of ground-mounted PV systems. A harmonized approach for the whole case study region, grounded in scientific evidence, is urgently needed to ensure the consistent protection of habitats and the implementation of site-specific mitigation measures independent from regional administrative borders. This requires comprehensive data for strategic planning and standardized, scientifically supported monitoring of new ground-mounted PV systems. Such monitoring would not only facilitate the continuous evaluation and adaptation of maintenance measures, but also contribute to the generation of scientific insights for Central European conditions, a region currently underrepresented in the research field. Furthermore, integrative planning approaches that balance multiple objectives, could be adapted to Austrian conditions, taking into account the country's specific environmental characteristics.

Finally, based on our comprehensive review we have five recommendations to be made. These critical junctures rest on Moore-O'Leary et al. (2017) and are complemented with additional insights from our study: (1) Sustainable development in the field of ground-mounted PV must strike a balance between site selection, energy potential and ecological implementation. Systematic conservation planning shows a viable way to weigh different interests and to find a basis for further debates with stakeholders and interested parties (Jung et al., 2024). (2) Species react very differently to ground-mounted photovoltaic installations in the landscape and, depending on the design of the facilities, there are winner and loser species, which can also be deduced from the scientific literature database in this article. (3) Much less is known about the cumulative and large-scale effects in the landscape. Due to the complex interrelationships between the drivers of biodiversity loss, the additional use of ground-mounted PV adds to the combined effects of multiple stressors (Pirotta et al., 2022). (4) Depending on the location and initial situation, the impact of ground-mounted PV varies greatly and requires adaptation of the design and management of the plants, as well as regular evaluation of the mitigation strategies. (5) Long-term consequences for ecosystems and biodiversity are not known. Hence, according to the precautionary principle, careful consideration is essential if both climate and biodiversity targets are to be met. The nexus of combating the climate crisis and the biodiversity crisis is complex and requires a joint effort to mainstream biodiversity into climate and energy policies and vice versa (Pörtner et al. 2023).

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Declaration of Competing Interest

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

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Supplementary material

Table S1. Articles considered in the review listed alphabetically; article type (a review, concept, descriptive, statistical, experimental, spatial analysis); ‘1’ indicates the topic addressed in the article for indirect impacts and direct impacts (population composition and diversity, habitat loss, degradation and fragmentation; impact on movement and behaviour of resident and migratory species; mortality and collisions; exotic plant invasion) or other topics (f.ex. mitigation measures, ecosystem services, costs).

Reference	article type	indirect (alteration of environmental conditions)	population composition & diversity	habitat loss, degradation and fragmentation	impact on movement and behaviour	mortality & collisions	exotic plant invasions	other focus	biodiversity level studied
Abid, M. K., Kumar, M. V., Raj, V. A., & Dhas, M. D. K. (2023). Environmental Impacts of the Solar Photovoltaic Systems in the Context of Globalization. Ecological Engineering & Environmental Technology, 24(2), 231–240. https://doi.org/10.12912/27197050/157168	review			1					general
Agha, M., Lovich, J. E., Ennen, J. R., & Todd, B. D. (2020). Wind, sun, and wildlife: Do wind and solar energy development ‘short-circuit’ conservation in the western United States? Environmental Research Letters, 15(7), 075004. https://doi.org/10.1088/1748-9326/ab8846	review	1		1					site condition properties, general
Armstrong, A., Ostle, N. J., & Whitaker, J. (2016). Solar park microclimate and vegetation management effects on grassland carbon cycling. Environmental Research Letters, 11(7), 074016. https://doi.org/10.1088/1748-9326/11/7/074016	statistical	1							site condition properties
Armstrong, J. H., Kulikowski, A. J., & Philpott, S. M. (2021). Urban renewable energy and ecosystems: Integrating vegetation with ground-mounted solar arrays increases arthropod abundance of key functional groups. Urban Ecosystems, 24(3), 621–631. https://doi.org/10.1007/s11252-020-01063-6	statistical		1						arthropods
Ascensão, F., Chozas, S., Serrano, H., & Branquinho, C. (2023). Mapping potential conflicts between photovoltaic installations and biodiversity conservation. Biological Conservation, 287, 110331. https://doi.org/10.1016/j.biocon.2023.110331	statistical			1					land cover
Aycrigg, J. L., McCarley, T. R., Martinuzzi, S., Belote, R. T., Bosher, M., Bailey, C., & Reeves, M. (2023). A spatial and temporal assessment of energy development around wilderness areas. Biological Conservation, 279, 109907. https://doi.org/10.1016/j.biocon.2023.109907	spatial			1					wilderness area
Bai, Z., Jia, A., Bai, Z., Qu, S., Zhang, M., Kong, L., Sun, R., & Wang, M. (2022). Photovoltaic panels have altered grassland plant biodiversity and soil microbial diversity. Frontiers in Microbiology, 13. https://www.frontiersin.org/articles/10.3389/fmicb.2022.1065899	statistical	1	1						site condition properties, vegetation
Black, T. V., & Robertson, B. A. (2020). How to disguise evolutionary traps created by solar panels. Journal of Insect Conservation, 24(2), 241–247. https://doi.org/10.1007/s10841-019-00191-5	statistical					1			arthropods
Blaydes, H., Gardner, E., Whyatt, J. D., Potts, S. G., & Armstrong, A. (2022). Solar park management and design to boost bumble bee populations. Environmental Research Letters, 17(4), 044002. https://doi.org/10.1088/1748-9326/ac5840	statistical		1					1	arthropods

Reference	**article type**	**indirect (alteration of environmental conditions)**	**population composition & diversity**	**habitat loss, degradation and fragmentation**	**impact on movement and behaviour**	**mortality & collisions**	**exotic plant invasions**	**other focus**	**biodiversity level studied**
Blaydes, H., Potts, S. G., Whyatt, J. D., & Armstrong, A. (2021). Opportunities to enhance pollinator biodiversity in solar parks. Renewable and Sustainable Energy Reviews, 145, 111065. https://doi.org/10.1016/j.rser.2021.111065	review							1	arthropods
Cameron, D. R., Cohen, B. S., & Morrison, S. A. (2012). An Approach to Enhance the Conservation-Compatibility of Solar Energy Development. PLOS ONE, 7(6), e38437. https://doi.org/10.1371/journal.pone.0038437	spatial			1					land cover
Carvalho, F., Treasure, L., Robinson, S. J. B., Blaydes, H., Exley, G., Hayes, R., Howell, B., Keith, A., Montag, H., Parker, G., Sharp, S. P., Witten, C., & Armstrong, A. (2023). Towards a standardized protocol to assess natural capital and ecosystem services in solar parks. Ecological Solutions and Evidence, 4(1), e12210. https://doi.org/10.1002/2688-8319.12210	conceptual	1	1	1		1			site condition properties, general
Chock, R. Y., Clucas, B., Peterson, E. K., Blackwell, B. F., Blumstein, D. T., Church, K., Fernández-Juricic, E., Francescoli, G., Greggor, A. L., Kemp, P., Pinho, G. M., Sanzenbacher, P. M., Schulte, B. A., & Toni, P. (2021). Evaluating potential effects of solar power facilities on wildlife from an animal behavior perspective. Conservation Science and Practice, 3(2), e319. https://doi.org/10.1111/csp2.319	conceptual				1				animals
Conkling, T. J., Loss, S. R., Diffendorfer, J. E., Duerr, A. E., & Katzner, T. E. (2021). Limitations, lack of standardization, and recommended best practices in studies of renewable energy effects on birds and bats. Conservation Biology, 35(1), 64–76. https://doi.org/10.1111/cobi.13457	conceptual								birds, bats
Cypher, B. L., Boroski, B. B., Burton, R. K., Meade, D. E., Phillips, S. E., Leitner, P., Kelly, E. C., Westall, T. L., & Dart, J. (2021). Photovoltaic solar farms in California: Can we have renewable electricity and our species, too? California Fish and Wildlife Journal, 107(3), 231–248. https://doi.org/10.51492/cfwj.hwisi.6	spatial							1	general
Dhar, A., Naeth, M. A., Jennings, P. D., & Gamal El-Din, M. (2020). Perspectives on environmental impacts and a land reclamation strategy for solar and wind energy systems. Science of The Total Environment, 718, 134602. https://doi.org/10.1016/j.scitotenv.2019.134602	review	1		1		1	1		site condition properties, general
Dolezal, A. G., Torres, J., & O'Neal, M. E. (2021). Can Solar Energy Fuel Pollinator Conservation? Environmental Entomology, 50(4), 757–761. https://doi.org/10.1093/ee/nvab041	spatial		1					1	pollinators
Dunnett, S., Holland, R. A., Taylor, G., & Eigenbrod, F. (2022). Predicted wind and solar energy expansion has minimal overlap with multiple conservation priorities across global regions. Proceedings of the National Academy of Sciences, 119(6), e2104764119. https://doi.org/10.1073/pnas.2104764119	spatial			1					protected areas
Edalat, M. M., & Stephen, H. (2017). Effects of two utility-scale solar energy plants on land-cover patterns using SMA of Thematic Mapper data. Renewable and Sustainable Energy Reviews, 67, 1139–1152. https://doi.org/10.1016/j.rser.2016.09.079	spatial	1	1						site condition properties, land cover

Reference	**article type**	**indirect (alteration of environmental conditions)**	**population composition & diversity**	**habitat loss, degradation and fragmentation**	**impact on movement and behaviour**	**mortality & collisions**	**exotic plant invasions**	**other focus**	**biodiversity level studied**
Evans, M. J., Mainali, K., Soobitsky, R., Mills, E., & Minnemeyer, S. (2023). Predicting patterns of solar energy buildout to identify opportunities for biodiversity conservation. Biological Conservation, 283, 110074. https://doi.org/10.1016/j.biocon.2023.110074	spatial			1					land cover
Fraleigh, D. C., Heitmann, J. B., & Robertson, B. A. (2021). Ultraviolet polarized light pollution and evolutionary traps for aquatic insects. Animal Behaviour, 180, 239–247. https://doi.org/10.1016/j.anbehav.2021.08.006	statistical					1			arthropods
Fritz, B., Horváth, G., Hünig, R., Pereszlényi, Á., Egri, Á., Guttmann, M., Schneider, M., Lemmer, U., Kriska, G., & Gomard, G. (2020). Bioreplicated coatings for photovoltaic solar panels nearly eliminate light pollution that harms polarotactic insects. PLOS ONE, 15(12), e0243296. https://doi.org/10.1371/journal.pone.0243296	statistical					1			arthropods
Gerringer, M. B., Smith, K. T., & Kosciuch, K. L. (2022). Observations of Greater Sage-Grouse at a Solar Energy Facility in Wyoming. Western North American Naturalist, 82(1), 196–200. https://doi.org/10.3398/064.082.0121	descriptive		1						birds
Gibson, L., Wilman, E. N., & Laurance, W. F. (2017). How Green is 'Green' Energy? Trends in Ecology & Evolution, 32(12), 922–935. https://doi.org/10.1016/j.tree.2017.09.007	conceptual	1				1			site condition properties, general
Graham, M., Ates, S., Melathopoulos, A. P., Moldenke, A. R., DeBano, S. J., Best, L. R., & Higgins, C. W. (2021). Partial shading by solar panels delays bloom, increases floral abundance during the late-season for pollinators in a dryland, agrivoltaic ecosystem. Scientific Reports, 11(1), Article 1. https://doi.org/10.1038/s41598-021-86756-4	statistical	1	1						arthropods
Grippo, M., Hayse, J. W., & O'Connor, B. L. (2015). Solar Energy Development and Aquatic Ecosystems in the Southwestern United States: Potential Impacts, Mitigation, and Research Needs. Environmental Management, 55(1), 244–256. https://doi.org/10.1007/s00267-014-0384-x	conceptual	1		1		1			site condition properties, general
Guiller, C., Affre, L., Deschamps-Cottin, M., Geslin, B., Kaldonski, N., & Tatoni, T. (2017). Impacts of solar energy on butterfly communities in mediterranean agro-ecosystems. Environmental Progress & Sustainable Energy, 36(6), 1817–1823. https://doi.org/10.1002/ep.12626	statistical		1		1				arthropods
Hernandez, R. R., Easter, S. B., Murphy-Mariscal, M. L., Maestre, F. T., Tavassoli, M., Allen, E. B., Barrows, C. W., Belnap, J., Ochoa-Hueso, R., Ravi, S., & Allen, M. F. (2014). Environmental impacts of utility-scale solar energy. Renewable and Sustainable Energy Reviews, 29, 766–779. https://doi.org/10.1016/j.rser.2013.08.041	conceptual	1	1	1	1	1	1		site condition properties, general
Hernandez, R. R., Hoffacker, M. K., Murphy-Mariscal, M. L., Wu, G. C., & Allen, M. F. (2015). Solar energy development impacts on land cover change and protected areas. Proceedings of the National Academy of Sciences, 112(44), 13579–13584. https://doi.org/10.1073/pnas.1517656112	spatial			1					protected areas

Reference	**article type**	**indirect (alteration of environmental conditions)**	**population composition & diversity**	**habitat loss, degradation and fragmentation**	**impact on movement and behaviour**	**mortality & collisions**	**exotic plant invasions**	**other focus**	**biodiversity level studied**
Horváth, G., Pereszlényi, Á., Egri, Á., Fritz, B., Guttmann, M., Lemmer, U., Gomard, G., & Kriska, G. (2020). Horsefly reactions to black surfaces: Attractiveness to male and female tabanids versus surface tilt angle and temperature. Parasitology Research, 119(8), 2399–2409. https://doi.org/10.1007/s00436-020-06702-7	statistical					1			arthropods
Kamp, J., Koshkin, M. A., Bragina, T. M., Katzner, T. E., Milner-Gulland, E. J., Schreiber, D., Sheldon, R., Shmalenko, A., Smelansky, I., Terraube, J., & Urazaliev, R. (2016). Persistent and novel threats to the biodiversity of Kazakhstan's steppes and semi-deserts. Biodiversity and Conservation, 25(12), 2521–2541. https://doi.org/10.1007/s10531-016-1083-0	conceptual			1		1			general
Kim, J. Y., Koide, D., Ishihama, F., Kadoya, T., & Nishihiro, J. (2021). Current site planning of medium to large solar power systems accelerates the loss of the remaining semi-natural and agricultural habitats. Science of The Total Environment, 779, 146475. https://doi.org/10.1016/j.scitotenv.2021.146475	spatial			1					land cover
Kitazawa, M., Yamaura, Y., Senzaki, M., Kawamura, K., Hanioka, M., & Nakamura, F. (2019). An Evaluation of Five Agricultural Habitat Types for Openland Birds: Abandoned Farmland Can Have Comparative Values to Undisturbed Wetland. Ornithological Science, 18(1), 3–16. https://doi.org/10.2326/osj.18.3	statistical		1						birds
Kosciuch, K., Riser-Espinoza, D., Gerringer, M., & Erickson, W. (2020). A summary of bird mortality at photovoltaic utility scale solar facilities in the Southwestern U.S. PLOS ONE, 15(4), e0232034. https://doi.org/10.1371/journal.pone.0232034	review					1			birds
Kosciuch, K., Riser-Espinoza, D., Moqtaderi, C., & Erickson, W. (2021). Aquatic Habitat Bird Occurrences at Photovoltaic Solar Energy Development in Southern California, USA. Diversity, 13(11), Article 11. https://doi.org/10.3390/d13110524	statistical					1			birds
Kosciuch, K., Riser-Espinoza, D., Moqtaderi, C., & Erickson, W. (2021). Aquatic Habitat Bird Occurrences at Photovoltaic Solar Energy Development in Southern California, USA. Diversity, 13(11), Article 11. https://doi.org/10.3390/d13110524	statistical		1			1			aquatic birds
Kreitler, J., Schloss, C. A., Soong, O., Hannah, L., & Davis, F. W. (2015). Conservation Planning for Offsetting the Impacts of Development: A Case Study of Biodiversity and Renewable Energy in the Mojave Desert. PLOS ONE, 10(11), e0140226. https://doi.org/10.1371/journal.pone.0140226	spatial			1					protected areas
Lambert, Q., Bischoff, A., Cueff, S., Cluchier, A., & Gros, R. (2021). Effects of solar park construction and solar panels on soil quality, microclimate, CO2 effluxes, and vegetation under a Mediterranean climate. Land Degradation & Development, 32(18), 5190–5202. https://doi.org/10.1002/ldr.4101	statistical	1	1						site condition properties, vegetation
Lambert, Q., Bischoff, A., Enea, M., & Gros, R. (2023). Photovoltaic power stations: An opportunity to promote European semi-natural grasslands? Frontiers in Environmental Science, 11. https://www.frontiersin.org/articles/10.3389/fenvs.2023.1137845	statistical	1	1				1		site condition properties, vegetation

Reference	article type	indirect (alteration of environmental conditions)	population composition & diversity	habitat loss, degradation and fragmentation	impact on movement and behaviour	mortality & collisions	exotic plant invasions	other focus	biodiversity level studied
Lambert, Q., Gros, R., & Bischoff, A. (2022). Ecological restoration of solar park plant communities and the effect of solar panels. Ecological Engineering, 182, 106722. https://doi.org/10.1016/j.ecoleng.2022.106722	statistical		1						vegetation
Levin, M. O., Kalies, E. L., Forester, E., Jackson, E. L. A., Levin, A. H., Markus, C., McKenzie, P. F., Meek, J. B., & Hernandez, R. R. (2023). Solar Energy-driven Land-cover Change Could Alter Landscapes Critical to Animal Movement in the Continental United States. Environmental Science & Technology, 57(31), 11499–11509. https://doi.org/10.1021/acs.est.3c00578	spatial			1					land cover
Li, C., Liu, J., Bao, J., Wu, T., & Chai, B. (2023). Effect of Light Heterogeneity Caused by Photovoltaic Panels on the Plant–Soil–Microbial System in Solar Park. Land, 12(2), Article 2. https://doi.org/10.3390/land12020367	statistical	1							site condition properties, vegetation
Liu, Y., Ding, C., Su, D., Wang, T., & Wang, T. (2022). Solar park promoted microbial nitrogen and phosphorus cycle potentials but reduced soil prokaryotic diversity and network stability in alpine desert ecosystem. Frontiers in Microbiology, 13. https://www.frontiersin.org/articles/10.3389/fmicb.2022.976335	statistical	1	1						site condition properties, vegetation
Liu, Y., Zhang, R.-Q., Huang, Z., Cheng, Z., López-Vicente, M., Ma, X.-R., & Wu, G.-L. (2019). Solar photovoltaic panels significantly promote vegetation recovery by modifying the soil surface microhabitats in an arid sandy ecosystem. Land Degradation & Development, 30(18), 2177–2186. https://doi.org/10.1002/ldr.3408	statistical	1	1						site condition properties, vegetation
Lovich, J. E., & Ennen, J. R. (2011). Wildlife Conservation and Solar Energy Development in the Desert Southwest, United States. BioScience, 61(12), 982–992. https://doi.org/10.1525/bio.2011.61.12.8	conceptual	1	1	1	1	1			site condition properties, general
McCall, J., Macdonald, J., Burton, R., & Macknick, J. (2023). Vegetation Management Cost and Maintenance Implications of Different Ground Covers at Utility-Scale Solar Sites. Sustainability, 15(7), Article 7. https://doi.org/10.3390/su15075895	statistical							1	general
McCoshum, S. M., & Geber, M. A. (2020). Land Conversion for Solar Facilities and Urban Sprawl in Southwest Deserts Causes Different Amounts of Habitat Loss for Ashmeadiella Bees. Journal of the Kansas Entomological Society, 92(2), 468–478. https://doi.org/10.2317/0022-8567-92.2.468	spatial			1					pollinators
Menta, C., Remelli, S., Andreoni, M., Gatti, F., & Sergi, V. (2023). Can Grasslands in Photovoltaic Parks Play a Role in Conserving Soil Arthropod Biodiversity? Life, 13(7), Article 7. https://doi.org/10.3390/life13071536	statistical	1	1						site condition properties, arthropods
Meyer, M. H., Dullau, S., Scholz, P., Meyer, M. A., & Tischew, S. (2023). Bee-Friendly Native Seed Mixtures for the Greening of Solar Parks. Land, 12(6), Article 6. https://doi.org/10.3390/land12061265	conceptual							1	pollinators

Reference	**article type**	**indirect (alteration of environmental conditions)**	**population composition & diversity**	**habitat loss, degradation and fragmentation**	**impact on movement and behaviour**	**mortality & collisions**	**exotic plant invasions**	**other focus**	**biodiversity level studied**
Mishra, S. K., Zhu, M., Bernknopf, R. L., & Walston, L. J. (2023). Valuation of pollination services from habitat management: A case study of utility scale solar energy facilities in the United States. Environmental Research Communications, 5(6), 065006. https://doi.org/10.1088/2515-7620/acda7f	spatial							1	pollinators
Moore-O'Leary, K. A., Hernandez, R. R., Johnston, D. S., Abella, S. R., Tanner, K. E., Swanson, A. C., Kreitler, J., & Lovich, J. E. (2017). Sustainability of utility-scale solar energy – critical ecological concepts. Frontiers in Ecology and the Environment, 15(7), 385–394. https://doi.org/10.1002/fee.1517	conceptual								general
Moorman, C., Grodsky, S., Rupp, S., Moorman, C., Hardcover, S., & Boroski, B. (2019). Chapter 8 Solar Energy: A Technology with Multi-Scale Opportunities to Integrate Wildlife Conservation; in Renewable Energy and Wildlife Conservation, Johns Hopkins University Press Books.	conceptual							1	general
Mori, K., & Tabata, T. (2020). Comprehensive Evaluation of Photovoltaic Solar Plants vs. Natural Ecosystems in Green Conflict Situations. Energies, 13(23), Article 23. https://doi.org/10.3390/en13236224	descriptive			1					protected areas
Moscatelli, M. C., Marabottini, R., Massaccesi, L., & Marinari, S. (2022). Soil properties changes after seven years of ground mounted photovoltaic panels in Central Italy coastal area. Geoderma Regional, 29, e00500. https://doi.org/10.1016/j.geodrs.2022.e00500	statistical	1							site condition properties
Nordberg, E. J., & Schwarzkopf, L. (2023). Developing conservoltaic systems to support biodiversity on solar farms. Austral Ecology, 48(3), 643–649. https://doi.org/10.1111/aec.13289	conceptual							1	general
Nowak, A., Świsłowski, P., Świerszcz, S., Nowak, S., Rajfur, M., & Wacławek, M. (2023). Ecovoltaics—A Truly Ecological and Green Source of Renewable Goods. Ecological Chemistry and Engineering S, 30(3), 315–332. https://doi.org/10.2478/eces-2023-0032	conceptual							1	vegetation
Ormeño, M. S., Hervás, S., Amorós, J. A., Navarro, F. J. G., Gallego, J. C., & Pérez-De-Los-Reyes, C. (2016). Soil protection in solar photovoltaic farms by revegetation with mycorrhizal native species. Soil Research, 54(2), 237–241. Scopus. https://doi.org/10.1071/SR15026	statistical							1	vegetation
Peter, F., Reck, H., Trautner, J., Böttcher, M., Strein, M., Herrmann, M., Meinig, H., Nissen, H., & Weidler, M. (2023). Lebensraumverbund und Wildtierwege – erforderliche Standards bei der Bündelung von Verkehrswegen und Photovoltaik-Freiflächenanlagen. Natur und Landschaft, 98(11), 507–515. https://doi.org/10.19217/NuL2023-11-03	conceptual			1				1	land cover
Randle-Boggis, R. J., White, P. C. L., Cruz, J., Parker, G., Montag, H., Scurlock, J. M. O., & Armstrong, A. (2020). Realising co-benefits for natural capital and ecosystem services from solar parks: A co-developed, evidence-based approach. Renewable and Sustainable Energy Reviews, 125, 109775. https://doi.org/10.1016/j.rser.2020.109775	review							1	general

Reference	article type	indirect (alteration of environmental conditions)	population composition & diversity	habitat loss, degradation and fragmentation	impact on movement and behaviour	mortality & collisions	exotic plant invasions	other focus	biodiversity level studied
Rehbein, J. A., Watson, J. E. M., Lane, J. L., Sonter, L. J., Venter, O., Atkinson, S. C., & Allan, J. R. (2020). Renewable energy development threatens many globally important biodiversity areas. Global Change Biology, 26(5), 3040–3051. https://doi.org/10.1111/gcb.15067	spatial			1					protected areas
Santangeli, A., Di Minin, E., Toivonen, T., Pogson, M., Hastings, A., Smith, P., & Moilanen, A. (2016). Synergies and trade-offs between renewable energy expansion and biodiversity conservation – a cross-national multifactor analysis. GCB Bioenergy, 8(6), 1191–1200. https://doi.org/10.1111/gcbb.12337	statistical			1					protected areas
Sawyer, H., Korfanta, N. M., Kauffman, M. J., Robb, B. S., Telander, A. C., & Mattson, T. (2022). Trade-offs between utility-scale solar development and ungulates on western rangelands. Frontiers in Ecology and the Environment, 20(6), 345–351. https://doi.org/10.1002/fee.2498	spatial				1				ungulates
Semeraro, T., Pomes, A., Del Giudice, C., Negro, D., & Aretano, R. (2018). Planning ground based utility scale solar energy as green infrastructure to enhance ecosystem services. Energy Policy, 117, 218–227. https://doi.org/10.1016/j.enpol.2018.01.050	conceptual						1	1	general
Semeraro, T., Scarano, A., Santino, A., Emmanuel, R., & Lenucci, M. (2022). An innovative approach to combine solar photovoltaic gardens with agricultural production and ecosystem services. Ecosystem Services, 56, 101450. https://doi.org/10.1016/j.ecoser.2022.101450	conceptual							1	general
Sinha, P., Hoffman, B., Sakers, J., & Althouse, L. (2018). Best Practices in Responsible Land Use for Improving Biodiversity at a Utility-Scale Solar Facility. Case Studies in the Environment, 2(1), 1–12. https://doi.org/10.1525/cse.2018.001123	statistical		1						vegetation
Smallwood, K. S. (2022). Utility-scale solar impacts to volant wildlife. The Journal of Wildlife Management, 86(4), e22216. https://doi.org/10.1002/jwmg.22216	descriptive					1			birds
Smith, C. I., Sweet, L. C., Yoder, J., McKain, M. R., Heyduk, K., & Barrows, C. (2023). Dust storms ahead: Climate change, green energy development and endangered species in the Mojave Desert. Biological Conservation, 277, 109819. https://doi.org/10.1016/j.biocon.2022.109819	spatial			1					land cover
Smith, J. A., & Dwyer, J. F. (2016). Avian interactions with renewable energy infrastructure: An update. The Condor, 118(2), 411–423. https://doi.org/10.1650/CONDOR-15-61.1	review					1			birds
Smith, J. P., Lenihan, C. M., & Zirpoli, J. A. (2020). Golden Eagle Breeding Response to Utility-Scale Solar Development and Prolonged Drought in California. Journal of Raptor Research, 54(2), 154–165. https://doi.org/10.3356/0892-1016-54.2.154	statistical					1			birds

Reference	article type	indirect (alteration of environmental conditions)	population composition & diversity	habitat loss, degradation and fragmentation	impact on movement and behaviour	mortality & collisions	exotic plant invasions	other focus	biodiversity level studied
Sturchio, M. A., Macknick, J. E., Barron-Gafford, G. A., Chen, A., Alderfer, C., Condon, K., Hajek, O. L., Miller, B., Pauletto, B., Siggers, J. A., Slette, I. J., & Knapp, A. K. (2022). Grassland productivity responds unexpectedly to dynamic light and soil water environments induced by photovoltaic arrays. Ecosphere, 13(12), e4334. https://doi.org/10.1002/ecs2.4334	statistical	1							site condition properties
Szabadi, K. L., Kurali, A., Rahman, N. A. A., Froidevaux, J. S. P., Tinsley, E., Jones, G., Görföl, T., Estók, P., & Zsebők, S. (2023). The use of solar farms by bats in mosaic landscapes: Implications for conservation. Global Ecology and Conservation, 44, e02481. https://doi.org/10.1016/j.gecco.2023.e02481	statistical		1		1				bats
Száz, D., Mihályi, D., Farkas, A., Egri, Á., Barta, A., Kriska, G., Robertson, B., & Horváth, G. (2016). Polarized light pollution of matte solar panels: Anti-reflective photovoltaics reduce polarized light pollution but benefit only some aquatic insects. Journal of Insect Conservation, 20(4), 663–675. https://doi.org/10.1007/s10841-016-9897-3	statistical					1			arthropods
Tanner, K. E., Moore-O'Leary, K. A., Parker, I. M., Pavlik, B. M., & Hernandez, R. R. (2020). Simulated solar panels create altered microhabitats in desert landforms. Ecosphere, 11(4), e03089. https://doi.org/10.1002/ecs2.3089	statistical	1	1						site condition properties, vegetation
Tanner, K. E., Moore-O'Leary, K. A., Parker, I. M., Pavlik, B. M., Haji, S., & Hernandez, R. R. (2021). Microhabitats associated with solar energy development alter demography of two desert annuals. Ecological Applications, 31(6), e02349. https://doi.org/10.1002/eap.2349	statistical	1	1						site condition properties, vegetation
Tinsley, E., Froidevaux, J. S. P., Zsebők, S., Szabadi, K. L., & Jones, G. (2023). Renewable energies and biodiversity: Impact of ground-mounted solar photovoltaic sites on bat activity. Journal of Applied Ecology, 60(9), 1752–1762. https://doi.org/10.1111/1365-2664.14474	statistical		1		1				bats
Tölgyesi, C., Bátori, Z., Pascarella, J., Erdős, L., Török, P., Batáry, P., Birkhofer, K., Scherer, L., Michalko, R., Košulič, O., Zaller, J. G., & Gallé, R. (2023). Ecovoltaics: Framework and future research directions to reconcile land-based solar power development with ecosystem conservation. Biological Conservation, 285, 110242. https://doi.org/10.1016/j.biocon.2023.110242	conceptual							1	general
Tsafack, N., Fang, W., Wang, X., Xie, Y., Wang, X., & Fattorini, S. (2022). Influence of grazing and solar panel installation on tenebrionid beetles (Coleoptera Tenebrionidae) of a central Asian steppe. Journal of Environmental Management, 320, 115791. https://doi.org/10.1016/j.jenvman.2022.115791	statistical	1	1						site condition properties, arthropods
Uldrijan, D., Černý, M., & Winkler, J. (2022). Solar Park – Opportunity or Threat for Vegetation and Ecosystem. Journal of Ecological Engineering, 23(11), 1–10. https://doi.org/10.12911/22998993/153456	statistical		1						vegetation

Reference	article type	indirect (alteration of environmental conditions)	population composition & diversity	habitat loss, degradation and fragmentation	impact on movement and behaviour	mortality & collisions	exotic plant invasions	other focus	biodiversity level studied
Uldrijan, D., Kováčiková, M., Jakimiuk, A., Vaverková, M. D., & Winkler, J. (2021). Ecological effects of preferential vegetation composition developed on sites with photovoltaic power plants. Ecological Engineering, 168, 106274. https://doi.org/10.1016/j.ecoleng.2021.106274	statistical		1						vegetation
Uldrijan, D., Winkler, J., & Vaverková, M. D. (2023). Bioindication of Environmental Conditions Using Solar Park Vegetation. Environments, 10(5), Article 5. https://doi.org/10.3390/environments10050086	statistical	1	1				1		site condition properties, vegetation
Valera, F., Bolonio, L., La Calle, A., & Moreno, E. (2022). Deployment of Solar Energy at the Expense of Conservation Sensitive Areas Precludes Its Classification as an Environmentally Sustainable Activity. Land, 11(12), Article 12. https://doi.org/10.3390/land11122330	spatial			1					birds, land cover
Vervloesem, J., Marcheggiani, E., Choudhury, M. A. M., & Muys, B. (2022). Effects of Photovoltaic Solar Farms on Microclimate and Vegetation Diversity. Sustainability, 14(12), Article 12. https://doi.org/10.3390/su14127493	statistical	1	1						site condition properties, vegetation
Visser, E., Perold, V., Ralston-Paton, S., Cardenal, A. C., & Ryan, P. G. (2019). Assessing the impacts of a utility-scale photovoltaic solar energy facility on birds in the Northern Cape, South Africa. Renewable Energy, 133, 1285–1294. https://doi.org/10.1016/j.renene.2018.08.106	statistical		1		1				birds
Walston, L. J., Li, Y., Hartmann, H. M., Macknick, J., Hanson, A., Nootenboom, C., Lonsdorf, E., & Hellmann, J. (2021). Modeling the ecosystem services of native vegetation management practices at solar energy facilities in the Midwestern United States. Ecosystem Services, 47, 101227. https://doi.org/10.1016/j.ecoser.2020.101227	spatial			1				1	general
Walston, L. J., Mishra, S. K., Hartmann, H. M., Hlohowskyj, I., McCall, J., & Macknick, J. (2018). Examining the Potential for Agricultural Benefits from Pollinator Habitat at Solar Facilities in the United States. Environmental Science & Technology, 52(13), 7566–7576. https://doi.org/10.1021/acs.est.8b00020	spatial							1	arthropods
Walston, L. J., Rollins, K. E., LaGory, K. E., Smith, K. P., & Meyers, S. A. (2016). A preliminary assessment of avian mortality at utility-scale solar energy facilities in the United States. Renewable Energy, 92, 405–414. https://doi.org/10.1016/j.renene.2016.02.041	statistical					1			birds
Xia, Z., Li, Y., Zhang, W., Chen, R., Guo, S., Zhang, P., & Du, P. (2022). Solar photovoltaic program helps turn deserts green in China: Evidence from satellite monitoring. Journal of Environmental Management, 324, 116338. https://doi.org/10.1016/j.jenvman.2022.116338	spatial		1						vegetation
Xia, Z., Li, Y., Zhang, W., Guo, S., Zheng, L., Jia, N., Chen, R., Guo, X., & Du, P. (2023). Quantitatively distinguishing the impact of solar photovoltaics programs on vegetation in dryland using satellite imagery. Land Degradation & Development, 34(14), 4373–4385. https://doi.org/10.1002/ldr.4783	statistical	1							site condition properties, vegetation

Reference	article type	indirect (alteration of environmental conditions)	population composition & diversity	habitat loss, degradation and fragmentation	impact on movement and behaviour	mortality & collisions	exotic plant invasions	other focus	biodiversity level studied
Yang, Y., Wang, Z., Li, B., & Guan, J. (2023). The impact of photovoltaic projects on ecological corridors through the Least-Cost Path model. Global Ecology and Conservation, 42, e02381. https://doi.org/10.1016/j.gecco.2023.e02381	spatial				1				land cover
Zaplata, M. K. (2023). Solar parks as livestock enclosures can become key to linking energy, biodiversity and society. People and Nature, 5(5), 1457–1463. https://doi.org/10.1002/pan3.10522	conceptual							1	general
Zaplata, M. K., & Dullau, S. (2022). Applying Ecological Succession Theory to Birds in Solar Parks: An Approach to Address Protection and Planning. Land, 11(5), Article 5. https://doi.org/10.3390/land11050718	conceptual		1						birds
Zhang, H., Yu, Z., Zhu, C., Yang, R., Yan, B., & Jiang, G. (2023). Green or not? Environmental challenges from photovoltaic technology. Environmental Pollution, 320, 121066. https://doi.org/10.1016/j.envpol.2023.121066	review								general
Zhang, Y., Tian, Z., Liu, B., Chen, S., & Wu, J. (2023). Effects of photovoltaic power station construction on terrestrial ecosystems: A meta-analysis. Frontiers in Ecology and Evolution, 11. https://www.frontiersin.org/articles/10.3389/fevo.2023.1151182	statistical	1							site condition properties, vegetation