Effectiveness of solutions and good practices in place for limiting the impact of ground-mounted photovoltaic energy systems on terrestrial fauna

Knowledge synthesis

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EXECUTIVE SUMMARY

Background

The development of ground-mounted photovoltaic (PV) systems is accelerating in France, in a context of energy transition to net-zero carbon emissions by 2050. This trajectory implies increasing the electrification of end-uses and stepping up renewable energy production. Ground-mounted PV power plants represent a strategic solution for producing decarbonized electricity on a large scale.

However, this development raises major environmental issues, particularly in relation to biodiversity. These installations occupy large land areas, often in open agricultural or natural environments, and can have a negative impact on wildlife, habitats and ecological continuity. Applying the “avoid-reduce-compensate” (ARC) sequence (which is inscribed in French law) is now indispensable for developing projects and limiting their impact.

In this context, measures for mitigating the effects of PV installations on biodiversity are increasingly implemented. However, the effectiveness of these measures is still poorly known, due to a lack of homogeneous data and evaluated practical experiences, and insufficient exploitation of the available data at the national level. Documenting these measures, identifying which are the most effective, and organizing the monitoring effort are priorities that need to be shared by public authorities, developers, managers and the scientific community.

Objectives

The French Foundation for Biodiversity Research (FRB), with the support of the Mirova Research Center (MRC), conducted a Rapid Review (RR) of the literature to assess the effectiveness of measures for mitigating the impact of ground-mounted PV power plants on wildlife. This review covered the spectrum of terrestrial wildlife, from insects (aerial and terrestrial), small and large mammals, birds, bats, reptiles, amphibians, to gastropods.

The main objective was to identify the most effective practices, as supported by robust scientific evidence. The secondary objective was to formulate operational and strategic recommendations, based on available data, for improving existing practices and promoting concrete mitigation solutions. These recommendations are aimed at 1) the scientific community, 2) public authorities, and 3) project holders (developers, consulting experts, project owners).

Methods

The literature review was conducted following the standards and guidelines for Rapid Reviews of the Collaboration for Environmental Evidence (CEE), the benchmark for evidence syntheses in ecology and environmental science (CEE, 2022). Bibliographic references included scientific (peer reviewed) and grey literature (technical reports, expertise documents, case studies), retrieved from specialized databases and professional platforms. Selected publications were analyzed qualitatively using a narrative approach, with the aim of assessing the effectiveness of measures for mitigating the impacts of ground-mounted PV installations on wildlife.

To complement this review, a workshop attended by a diversity of stakeholders (public body representatives, consulting experts, developers, NGOs) was organized in November 2025. The objectives of this workshop were to compare the results from the scientific literature with experiences in the field, identify concrete levers of action, and formulate operational recommendations. These discussions enriched the analysis by contributing practical knowledge and feedback of experiences under varied conditions.

Overview of the selected publications

Following a rigorous, standardized and transparent selection process, thirteen relevant references (scientific articles published in peer-reviewed journals and technical reports) were selected for this review. This set of documents was analysed following criteria for methodological reliability, result precision, and protocol clarity.

Several important trends were uncovered from the selected articles:

- Studies were predominantly carried out in North America and Europe, with a strong Anglo-Saxon dominance. France only had a very limited number of publications that could be used in this review.
- The taxonomic range of taxa studied was very limited. Insects dominated the literature, while birds and bats were rarely studied. We could not find any study on any of the other groups (small and large mammals, amphibians, reptiles, gastropods).
- Measures that were studied generally belonged to two main categories: 1) actions for biodiversity (habitat enhancement or maintenance, vegetation management) and 2) solar panel design (reflectance, texture, orientation). The latter are usually studied ex situ, without any on-site validation. A wide range of measures have been not the subject of any assessment.
- Most articles describe in situ studies, which were directly carried out in operational PV power plants. These studies were based on before/after observations or comparisons between sites.
- Results mainly describe changes in species activity (presence, behaviour, reproduction) or local community structure (diversity, abundance, species composition). Studies that directly assess the effect of a particular measure are rare.
- **The vast majority of selected studies report** that the measures in place have **a globally positive effect** on wildlife. However, these results must be treated with caution: effects are often measured over a short period of time, at a small number of sites, without replicates or systematic control groups. This lack of methodological robustness limits the generalization of these results.

Overall, this analysis confirms that the state of knowledge on this topic is still in its infancy, geographically restricted, and thematically limited, but has enabled the identification of the first documented levers of action and the gaps that need to be filled to rigorously assess the effectiveness of measures in the years to come.

Limitations and level of evidence

The results presented here must be interpreted with caution. The review is based on a small number of publications (13 in total), which are heterogeneous in terms of context, biological group, type of measure and protocol. At this stage, this diversity does not allow for detailed comparisons of the effectiveness of different measures or robust quantitative meta-analyses.

The positive effects that were identified nonetheless provide encouraging, albeit fragile, signals that remain to be consolidated with more homogeneous and comparable multiannual monitoring. Reinforcing and standardizing monitoring protocols, as well as data sharing, seem to be essential levers to improve the robustness of future assessments.

Summary of the narrative synthesis on the effectiveness of mitigation measures

The decision to apply a mitigation measure must be taken on a case-by-case basis, taking into consideration the specificities of the project and the environment, following an in-depth assessment. In addition, it is crucial to undertake the study of species that are present in France, as most of the available scientific data come from species that are not.

Measure	Description	Taxon	Bibiliographic reference / Risk of bias / Page	Species	Country	Reported effectiveness *(Depending on the design and the aims of the study, some studies provide detailed results, while others are more succint. This also explains why mixed results are reported within a single study, or between different studies)*	Summary of effectiveness
Habitat / Biodiversity enhancement	The establishment and extensive maintenance of a diversified vegetation at solar farms (wildflower meadows, local species seed mixes, plant material transfer, reduction in mowing, maintaining structures (hedgerows, borders, habitat mosaics) in order to increase floral resources, habitats and refugia for wildlife.	Insects	*Martin, 2022* Weak (p. 26)	*Pollinators:* Native bees Syrphid flies Butterflies, etc. *Arthropods:* Beetles Other flies Hemiptera Other Hymenoptera, etc.	USA	* Taxonomic and functional diversity of insects at the pollinator-friendly solar farm (sowing native nectar-producing species, minimal mowing, targeted strategies against invasive species) were equivalent to those of the nearby meadow. * Taxonomic and functional diversity of insects at the pollinator-friendly solar farm were superior to those at the turfgrass solar site.	Overall, studies show that habitat management/restoration at solar farms (wildflower meadows, extensive management practices, structural diversity of habitats) improves the diversity and/or abundance of several animal groups (pollinators, other insects, birds) compared to intensive management (short turfgrass) or cropland. Nonetheless, these effects vary depending on the microhabitat. Moreover, the tested measures and protocols were too few and too different to allow conclusions to be drawn on the effectiveness of specific measures.
			Walston et al., 2024 Weak (p. 26)	*Pollinators:* Native bees Bumblebees Syrphid flies Butterflies, etc. *Other insects:* Wasps Hornets Beetles, etc.	USA	* Insect group diversity increased by approximately **150%** over the 5-year study period following conversion from cropland to wildflower meadow. * Total insect abundance **x3** after the establishment of the wildflower meadow. * Native bee abundance increased from **near-zero to over 5** average transect observations in year 4.	
			Biesmeijer et al., 2020 Moderate (p. 26)	*Pollinators :* Bees Bumblebees Syrphid flies	The Netherlands	* Seed mixes did not have a significant effect on pollinator abundance compared to the control. *Note of the authors:* The seed mixture plant species had a late start and in their first year made up only a small portion of the total vegetation. It was not possible to determine which seed mixture was best in terms of pollinators and maintenance.	

			Lambert et al., 2024 Very weak (p. 27)	*Soil mesofauna:* Mites Springtails Other arthropods	France	* The abundance of mite predators was **~x3** lower in the control and vermicompost treatments than with monospecific sowing and seed material transfer. * The abundance of mite detritovores was **~x3** lower in the control than in the sowing and seed material transfer treatments. * The abundance of total soil mesofauna was **~x1.5** higher in the sowing treatment than in the control and vermicompost treatments. Abundance was highest with sowing and lowest in the control. * Mite predator and total mesofauna abundance were ~x2 higher in the sowing and seed material transfer treatments than in the control and vermicompost treatments. * Effects of vermicompost treatment on mesofauna described as weak and not significantly different from the control (for mesofauna).	
		Birds	*Copping et al., 2025* Weak (p. 27)	Breeding birds in farmland and woodland areas	England	* Abundance was higher in "mixed habitat" solar farms (greater sward height, more diverse flora, woody features along the boundary fence) compared to "simple habitat "solar farms (short sward height, few wildflowers, no woody boundary features): **x2** for all species, **x2** for farmland birds, **x12** for woodland birds. * Increase in species richness: **x2.5** for all species, **x3** for farmland birds, **x9** for woodland birds.	

Vegetation management - grazing	The implementation of vegetation management practices that are compatible with soil biodiversity (grazing rather than mechanical mowing) in order to preserve soil arthropod communities and soil biological quality.	Insects	*Menta et al., 2023* Very weak (p. 28)	Soil arthropods	Italy	* Total abundance of arthropods higher at the site managed by grazing. * QBS –ar (soil biological quality index) higher at the site managed by grazing. * Increase in Acarina and Collembola at the site managed by grazing. * No difference for Hymenoptera and Hemiptera. * In parallel, the authors highlighted the risk of a negative effect of grazing under solar panels (grazing animals tend to rest under the panels), which could lead to habitat degradation and the local reduction of certain arthropods.	Results are promising, but the number of (very heterogeneous) studies is not sufficient to draw conclusions on the effectiveness of this measure. Additional studies are needed to confirm these results.
Modification of infrastructure design	Prefer designs producing more “mobile” shade e.g. solar tracking rather than fixed-mount panels, thus preventing extreme conditions between the panels, in order to reduce microclimate and community composition changes; depending on the system, shaded areas can also serve as refugia.	Insects	*Suuronen et al., 2017* Weak (p. 29)	Terrestrial arthropods	Chili	* Differences in microclimate conditions within the solar tracking facility less pronounced than in the fixed-mount solar plant: no net difference in arthropod composition between the area between panel arrays and the area under the panels, suggesting that the impact will be more limited than at sites with fixed-mount solar panels.	Results are promising but a single study is not sufficient to draw conclusions on the effectiveness of this measure. Additional studies are needed to confirm these results.
Panel surface treatment to reduce the “lake” or “mirror” effect	Add non-attractive partitions on/over the smooth surface (e.g. non-polarizing white lines/gridding, matte/anti-reflective	Insects	*Horváth et al., 2010* Strong (p. 30)	*Polarotactic aquatic insects* (and associated dipterans): Ephemeroptera Trichoptera Dolichopodid dipterans	Hungary	* Partitioned surfaces were less attractive: surfaces with white non-polarizing borders/gridding were 10 to 26 times less attractive than equivalent unpartitioned surfaces: **-10.3x** for Diptera, **-16.7x** for Ephemeroptera, **-26.5x** for Trichoptera.	The five studies show that measures designed to break the smooth uniform aspect of panel surfaces (non-polarizing fragmentation, micro-textures/biomimicry, fine surface

	coating, biomimetic micro-textures) in order to reduce sensory signals (polarized light, "lake" effect, specular reflection, echoes) that act as ecological traps.		*Black & Robertson, 2020* Weak (p. 30)	*Polarotactic aquatic insects:* Trichoptera Simuliidae Ephemeroptera	USA *Ex situ*	* Reduced attractiveness for most taxa with non-polarizing white gridding (1 – 5 mm wide lines), > 80 % less attractive with only ~2-3% reduction in solar-active area (order of magnitude).	coverings) are globally effective, especially for insects. However, more research is needed 1) on bats (only one study available), and 2) within actual solar farms and on a larger scale.
			Száz et al., 2016 Moderate (p. 30)	*Polarotactic aquatic insects:* Mayflies Horseflies Non-biting midges	Hungary *Ex situ*	* The matte black test surface was less attractive to horseflies than the shiny black test surface as seen from different behaviours: **3.4x** less looping, **5.6x** less touching, **5.2x** less landing. * The matte black test surface was **4x** more attractive to mayflies than the shiny black test surface. * Both surfaces **equally attractive** for non-biting midges.	
			Fritz et al., 2020 Moderate (p. 31)	*Polarotactic aquatic insects:* Mayflies Horseflies	Hungary *Ex situ*	* The "rose petal" surface was much less attractive than the smooth black surface: **95%** fewer interactions for mayflies, **91%** fewer interactions for horseflies. * Effect less pronounced with the glass-covered "rose petal" surface: **25%** less attractive than the smooth black surface for mayflies, **no difference** for horseflies.	
		Bats	*Abdul Rahman et al., 2024* Moderate (p. 31)	Kuhl's pipistrelle (*Pipistrellus kuhlii*, the majority) Savi's pipistrelle (*Hypsugo savi*) Common pipistrelle (*Pipistrellus pipistrellus*)	Hungary *Ex situ*	* Decrease in the frequency of "drinking" attempts at string-covered black plates compared to smooth black plates, and (non-linear) decrease with increasing string diameter, e.g. a **60%** decrease with 2.5 mm string. * String diameter being equal, "drinking" frequency was lower with a crossing pattern than with parallel strings: near-zero frequency at the plate with the crossed string pattern.	

Acoustic deterrence *(Controversial measure, not an avoid-reduce-compensate mitigation measure sensu stricto)*	Installation of a commercially available acoustic deterrent device (alarm sound/sound waves) that functioned only during the daytime.	Birds	*Itoh et al., 2018* Strong (p. 32)	Crows	Japan	Effectiveness seems high (but also high uncertainty!) * Presence on the ground and on the structure: 0 crow stopped during the period with sound emissions (vs. 3 and 6 before and after the treatment). * Number of passing crows (in flight): decrease from 3.8-4.5 crows/day without sound emissions to 2.3 crows/day with sound emissions, i.e. **-39%** to **-49%**.	Results suggest that acoustic deterrence can prevent landings and reduce the passage of crows near the device. However, the level of proof is weak, and requires confirmation by monitoring multiple sites over longer periods. Moreover, in other contexts, acoustic deterrence is described as having a short-lasting effect due to bird habituation, which suggests that this measure could a be short term/complementary solution. This measure is not strictly speaking part of the avoid-reduce-compensate strategy, as there are no known impacts (e.g. collisions). We present it here for exploratory and critical assessment purposes. .

Basis for the recommendations
The recommendations listed in these tables are based on the results of literature review and the discussions of the workshop. The aim was to reflect both the state of knowledge and practical experiences.

Recommendations for project developers and operators

Section	Recommendation	Specific action
Measure selection and eco-design	Prioritize measures considered to benefit biodiversity	– Install fences and wildlife passages that are designed to correspond to the local context and the needs of local species, to ensure the maintenance of these species.
		– Install bat roosts, ponds and hibernacula for amphibians and reptiles, and bird nest boxes, which are adapted to the local context.
		– Maintain panel-free natural areas within the solar farm when this measure is beneficial to biodiversity.
		– Use local seed mixes as much as possible and sow seeds produced on site.
		– Avoid installing PV projects in environmentally sensitive areas.
Vegetation and soil management	Adapt management practices to reconcile fire prevention, agriculture and biodiversity	– Limit vegetation cleaning practices that impoverish habitats and can become counter-productive for the resilience of the environment.
		– When possible, adjust the mowing and grazing calendar to avoid impacting wildlife during critical periods.
		– Integrate soil (infiltration, erosion, post-construction compaction) restoration into project design and management.
		– Experiment with differentiated vegetation management regimes, especially in agrivoltaic systems, in the context of insurance and agricultural constraints.
Monitoring and assessment	Systematically integrate monitoring and ecological assessments into projects	– Plan to have monitoring systems that include the initial state of the area, clearly defined indicators, and where possible, control sites at the start of the project.
		– Allocate sufficient human and financial resources for multiannual monitoring and the implementation of more robust protocols.
		– Make sites more easily accessible to monitoring and research teams.
		– Transfer monitoring data to state services and the Renewable Energy Observatory, in useable formats.

Regulatory and financial arbitrations	Anticipate tensions between biodiversity, fire prevention, agriculture, insurance and compensation	– Identify the constraints associated with fire prevention (vegetation clearing orders (*obligation légale de débrousaillement*, local orders) beforehand and, jointly with the relevant services, find solutions that are compatible with environmental targets.
		– Work with crop and livestock farmers regarding their obligation to eliminate/control certain plant species and the adjustments that could be made.
		– Integrate compensation and environmental management costs into the project's budget, to avoid late and costly setbacks.
		– Use eco-design guides and previous experience to rank measures according to their environmental benefit, in the light of the constraints.
Collaboration and sharing of experience	Reinforce collaborations with researchers and local players	– Participate in collective efforts (the Renewable Energy Observatory, collaborative programmes e.g. BIODIVoltaïque, "ecovoltaics" approaches).
		– Contribute to training programmes and cross-sector exchanges by sharing information (successes but also problems encountered in the field).
		– Involve local authorities, associations, and local residents in discussions on the selection of measures and present monitoring results to improve the acceptability of projects.

Recommendations for the scientific community

Section	Recommendation	Specific action
Priority research axes	Study more varied contexts and different taxonomic groups	– Reinforce the study of sites in France and Europe, and focus on mediterranean, tropical and arid environments.
		– Carry out more studies on pollinators, birds, bats, small and large mammals, reptiles, and amphibians.
	Assess a wider range of measures	– Systematically test habitat and vegetation management measures for vertebrates, including their seasonal effect.
		– Compare different deterrence measures (acoustic, visual, light) and the options for infrastructure design.
		– Steer R&D towards the influence of panel height and row spacing, soil restoration, and measures benefitting pollinators and small animals, including in agrivoltaic systems.
Methodology and study design	Improve the robustness of experimental designs	– Implement BACI-type designs with replicates and multiannual surveys.
		– Explicitly integrate the confounding factors in the analyses.
		– Increase the number of on-site validations of solutions tested ex situ and have different research teams carry out ex situ tests in a broader range of conditions.
		– Harmonize the metrics used in controlled conditions and on site to directly compare the effectiveness of measures.
Standardization and data	Develop harmonized protocols and indicators	– Contribute to the elaboration of a standard monitoring framework for each taxon/taxonomic group, with indicators and frequency applied nationwide.
		– Stabilize protocols to enable the extraction of robust trends over time.
		– Publish research data on photovoltaics in open access databases.
		– Publish results, including neutral or negative results, and be open about funding sources and conflicts of interests.
Collaboration with the sector	Co-design monitoring protocols with actors in field	– Involve developers, consulting experts, and managers in the design of BACI-type protocols.
		– Support collective bodies (the Renewable Energy Observatory, programmes such as BIODIVoltaïque) by providing scientific expertise.

		– Identify the knowledge needs of developers and make these the focus of research projects.
		– Contribute to the production of operational guides and training programmes (e.g. “photovoltaics and biodiversity”).
Valorisation and training	Improve knowledge dissemination	– Translate research results into operational recommendations for eco-design guides and existing technical tools.
		– Contribute to upskilling (consulting firms, developers and public services) via training courses and workshops.
		– Combine scientific knowledge and practical experiences to continually improve practices and prioritize the most effective measures.

Recommendations for government agencies

Section	Recommendation	Specific action
Regulatory and compensation framework	Clarify and stabilize the requirements of environmental compensation	– Clarify the criteria for calculating the size of compensation areas, and how these areas fit in with forested or agricultural areas.
		– Limit situations of "double compensation" and make the system clearer for project holders.
		– Integrate "no regret" measures (e.g. avoid sensitive areas, contribute to the conservation of open environments) as central to the project, rather than as a bonus.
Structuring of public policy	Improve the coordination of biodiversity, fire prevention, and agricultural policies	– Harmonize the interpretation of vegetation clearing orders (OLD) and fire prevention requirements nationwide to reduce contradictory demands.
		– Adapt vegetation management obligations (including actions against invasive species) so that they remain compatible with biodiversity conservation.
		– Implement interministerial coordination and coordination between isolated services (environment, agriculture, fire prevention, etc.) to provide a coherent framework for projects
Standardize monitoring practices	Implement national standards for ecological monitoring	– Coordinate the elaboration of harmonized protocols within the sector, with common indicators, frequency and methods for each taxonomic group.
		– Stabilize protocols to enable to the detection of trends over a 10 to 15-year period.
		– Integrate in the authorization process explicit requirements for before and after monitoring, and preferable BACI-type designs.
Data and transparency	Centralize and exploit environmental data	– Support the Renewable Energy and Biodiversity Observatory as the national resource centre and data hub.
		– Encourage the sharing of raw data and transparency regarding funding sources and conflicts of interests, to facilitate analyses and meta-analyses.
Support R&D and eco-designs	Steer R&D towards measure effectiveness and soil resilience	– Fund programmes on the influence of panel height and spacing between rows on habitats and the movement of wildlife.
		– Support soil restoration and conservation efforts (infiltration, erosion, post-construction compaction).
		– Encourage the study of pollinators, small fauna, and vegetation management in the context of agrivoltaics.

		– Prioritize projects that compare the effectiveness of measures instead of accumulating isolated studies.
Guides and training	Develop eco-design guides and training	– Support the production and update of eco-design guides for PV installations and “ecovoltaics”, based on the literature and practical experiences.
		– Support dedicated training sessions on “photovoltaics and biodiversity” for public services, consulting firms, developers and farmers.
		– Include feedback from pilot projects, notably agrivoltaic projects.
Third-party role	Reinforce the role of the state as arbiter and facilitator	– Organize the analysis of submitted monitoring data and share the results with project holders.
		– Actively engage in dialogues to arbitrate between the requirements for safety, agriculture and biodiversity.
		– Contribute to securing a clear and stable framework, so that researchers and industry players can project themselves into the future.

INTRODUCTION

The climate emergency calls for a rapid and profound transformation of our energy production systems. Current trends show that a temporary rise in global temperatures above 1.5°C is now inevitable (Copernicus Climate Change Service, 2026). However, to limit this rise and return to +1.5°C levels, greenhouse gas emissions will need to be rapidly and significantly reduced in the coming decade (IPCC, 2023). The electricity sector, still largely dependent on fossil fuels, contributes to around 42 % of global CO_2 emissions (International Energy Agency, 2022). The transition towards renewable energy sources is therefore a major lever for achieving carbon neutrality by 2050, a target of the Paris Agreement (UNFCCC, 2015). In parallel, the increasing electrification of end-uses, including in the transportation and buildings sector, reinforces the need to produce decarbonized electricity in sufficient amount. Nevertheless, this transition cannot ignore the issue of biodiversity. Target 8 of the Kunming-Montreal Global Biodiversity Framework states that it is important to minimize the negative impacts of climate action on biodiversity, while fostering its positive impacts (CBD/COP/DEC/15/4, 2022). Energy production, in whatever form, should therefore reconcile climate effectiveness and environmental sustainability (Stephen, 2023). This means that the effects of energy installations on ecosystems must be rigorously tested and measures must be put in place to avoid, reduce or compensate these impacts.

Photovoltaic (PV) energy has grown rapidly since 2010. In France, total PV production capacity passed the 20 GW mark at the end of 2023, while the target set for 2028 by the French Multiannual Energy Plan (PPE - *programmation pluriannuelle de l'énergie*) ranges between 35 to 44 GW (Ministère de la Transition Ecologique, 2023). PV energy is increasingly produced by ground-mounted installations, occupying large land surfaces, sometimes in natural or agricultural areas. In 2025, regulations were reinforced to control its deployment in France. The French Renewable Energy Acceleration Bill (APER law- *loi d'accélération de la production d'énergies renouvelables*), adopted in March 2023, constitutes the current legal framework.

Despite being noiseless and emission-free when in operation, PV power plants can have a variety of impacts on terrestrial wildlife. A wide range of taxa are impacted: birds, bats, insects, reptiles, amphibians, and mammals. Impacts vary depending on local environmental conditions, the type of installation, management practices, and the phase of the project (construction, operation, dismantlement). The first identified effect is the loss or transformation of habitats. The installation of solar panels often involves levelling the ground, building foundations, creating access roads, and sometimes putting up fencing. These modifications can potentially lead to habitat destruction, fragmentation, and the exclusion of species that are sensitive to human-induced landscape conversions (Lafitte et al., 2023; LPO, 2022). The vegetation, which is usually kept low by mechanical mowing or grazing, becomes less favourable to a variety of species, including pollinating insects, ground-nesting birds, and small mammals. Behavioural changes have also been reported. Some species actively avoid these installations, and this may impact their access to resources or force them to change their everyday movement patterns, especially in the absence of functional wildlife corridors (Hernandez et al., 2014; LPO, 2022). Conversely, some taxa may be attracted to solar installations, creating a local ecological disequilibrium. Opportunistic species (crows, foxes, boars) may benefit from these changes, sometimes at the expense of specialist species. Fences around PV power plants represent a physical barrier that can restrict the movement of mid-sized to large animals, such as rabbits, turtles, badgers, deer, foxes, boars..., depending on the height and depth of the fence (Fleming et al., 2025). This may fragment populations, prevent natural habitat recolonization, and increase roadkill numbers if, to avoid installations, animals come near roads.
Technical elements, such as reflective panels, may disturb the visual perception of aquatic insects or birds, resulting in maladaptive behaviours (Horváth et al., 2010). Equally, changes in microclimate (shade, temperature, humidity) under the panels influence plant species composition, and indirectly, animal communities (Armstrong et al., 2016; Graham et al., 2019). Finally, the indirect impact of human presence, noise, or maintenance work, should not be dismissed, especially during the construction phase. Temporary or recurring disturbances can affect the reproduction of certain sensitive species, notably birds, amphibians and bats (Lafitte et al., 2023). These effects are seldom

homogeneous and strongly depend on the local context. In areas with many installations, cumulated effects over time could have even larger consequences, which is why rigorous assessments, standardized environmental monitoring, and better experience capitalization are important.

Faced with these impacts, project holders are required under French law to implement the avoid-reduce-compensate (ARC) sequence in all phases of the life of a ground-mounted PV power plant. ARC is the core principle underlying environmental policies in France (Légifrance, 2023; ADEME, 2024). Its goal is to, first, avoid causing any significant harm to biodiversity, second, reduce the impacts that cannot be avoided, and as a last resort, take actions that compensate for any residual impacts.

Avoidance is the priority in this sequence. The first key step is spatial planning: projects should be developed in artificial areas such as parking lots, brownfield sites or next to existing infrastructure, to minimize the pressure on sensitive natural areas (France Renouvelables, 2023). The implementation decree of the French Renewable Energy Acceleration bill (APER) integrates this logic by excluding productive agricultural land and natural areas of high environmental value, unless this can be justified (Hellio, 2024). Avoidance also implies taking into consideration wildlife corridors and the breeding and/or wintering sites of sensitive species, and rejecting projects located on migration routes or in wetlands (LPO, 2022). Impact reduction involves technical solutions and adapted management practices. Good practices include installing wildlife permeable fencing, turning off lights at night, and adjusting panel height to facilitate the movement of wildlife (Lafitte et al., 2023; LPO, 2022). Managing vegetation in an ecologically appropriate way, with late mowing or grazing, also benefits pollinators and breeding birds (ADEME, 2024; Graham et al., 2019). To reduce the visual attractiveness of solar panels, less reflective or gridded surfaces can be used (Horváth et al., 2010).

For bats, recommendations include installing the power plant away from roosts and woodland corridors, and conserve hedgerows and edges (France Renouvelables, 2023). Acoustic or visual deterrent devices are being experimented (Lafitte et al., 2023). Compensation, when required, is a complex process and is rarely implemented in practice. When necessary, it can involve the restoration of open environments near power plants, the creation of refuge habitats (wetlands, wildflower meadows, hedgerows) or funding targeted conservation programmes (LPO, 2022). However, compensation must be adapted to the species affected and must be carried out for long enough to have a measurable ecological effect; such actions require rigorous monitoring, which is rarely undertaken at present (Lafitte et al., 2023; ADEME, 2024). Effective implementation of the ARC sequence therefore depends on several conditions: a coherent spatial planning strategy, precise diagnostic tools used prior to construction, robust monitoring protocols, and regular assessments of measure effectiveness. These are only partially or patchily implemented. The literature stresses the need to reinforce feedback from practical experience, standardize monitoring indicators, and create databases that are accessible to project holders, researchers and relevant authorities (Lafitte et al., 2023; France Renouvelables, 2023).

At present, the priority is to better assess the real effectiveness of these measures. A rigorous knowledge synthesis is therefore useful to identify which levers are effective, adapt practices, and ensure that the development of ground-mounted PV systems respects climate targets and the demands of biodiversity conservation.

MAIN OBJECTIVE OF THE REVIEW

The French Foundation for Biodiversity Research (FRB) initiated a review of the scientific and technical literature on the effectiveness of measures for mitigating the impact of solar farms on terrestrial and aerial wildlife. This project is part of a larger programme, funded by the Mirova Research Center, for the adoption of effective and sustainable practices in the renewable energy sector. Its objective is to review the effectiveness of mitigation measures, as documented by scientific research, and provide guidance to government agencies, regulators, project developers and operators. The projects aim to provide operational recommendations base on solid scientific evidence for optimizing the development and operation of ground-mounted PV projects and reducing their environmental impact.

This programme relies on the close collaboration of specialists from different fields and is structured around three complementary axes. First, it involves the production of scientific knowledge syntheses, including updates of previously published syntheses on the impact of renewable energy installations – onshore wind, offshore wind, and solar energy – on biodiversity, as well as three review papers assessing the effectiveness of mitigation measures. Second, it offers research funding opportunities and has already funded for four innovative projects that will provide new knowledge on this topic. Finally, expert-led workshops are organized to provide an opportunity for scientists, government agencies, regulators, and project developers and operators to meet. These workshops aim to foster dialogue, inspire new ideas and optimize biodiversity conservation practices.

This programme stands out by its integrated and holistic approach for tackling the environmental challenges posed by the development of renewable energy. It analyses the impacts of the main technologies (onshore and offshore wind energy, solar energy) and uses rigorous scientific evidence to propose effective mitigation measures. Moreover, by funding innovative research projects, the programme demonstrates its commitment to the production of new knowledge.

The FRB, in association with the Mirova Research Center, is responsible for providing a synthesis (a “rapid review”) of the interactions between ground-mounted PV systems and biodiversity. The programme’s scientific committee has steered this review towards a review of the academic and technical literature on the effectiveness of mitigation measures and the practices in place to minimize the impact of ground-mounted PV systems on aerial and terrestrial species : birds, bats, insects, small and large mammals, reptiles, and amphibians. A rapid review, an abridged version of a systematic review, aims to provide relevant information in a condensed format (best practices, success, failures and knowledge gaps). This overview is essential for guiding policy and future practices, as well as for steering investments towards biodiversity-friendly projects. The main question of this Review is the following: “What is the effectiveness of existing solutions for mitigating the impact of ground-mounted PV installations on aerial and terrestrial vertebrates and invertebrates?” (Figure 1). Elements of the question follow the PICO structure (population, intervention, comparator, outcome) (Table 1).

Note to readers:
For details of the methods used in this review, see the appendices (Appendix I). The bibliographic search strategy and the criteria for selecting documents are described in the Methods section. The approaches used for the narrative synthesis are also given. This information provides a complete description of the methods used to ensure the scientific rigour and robustness of the conclusions presented here.

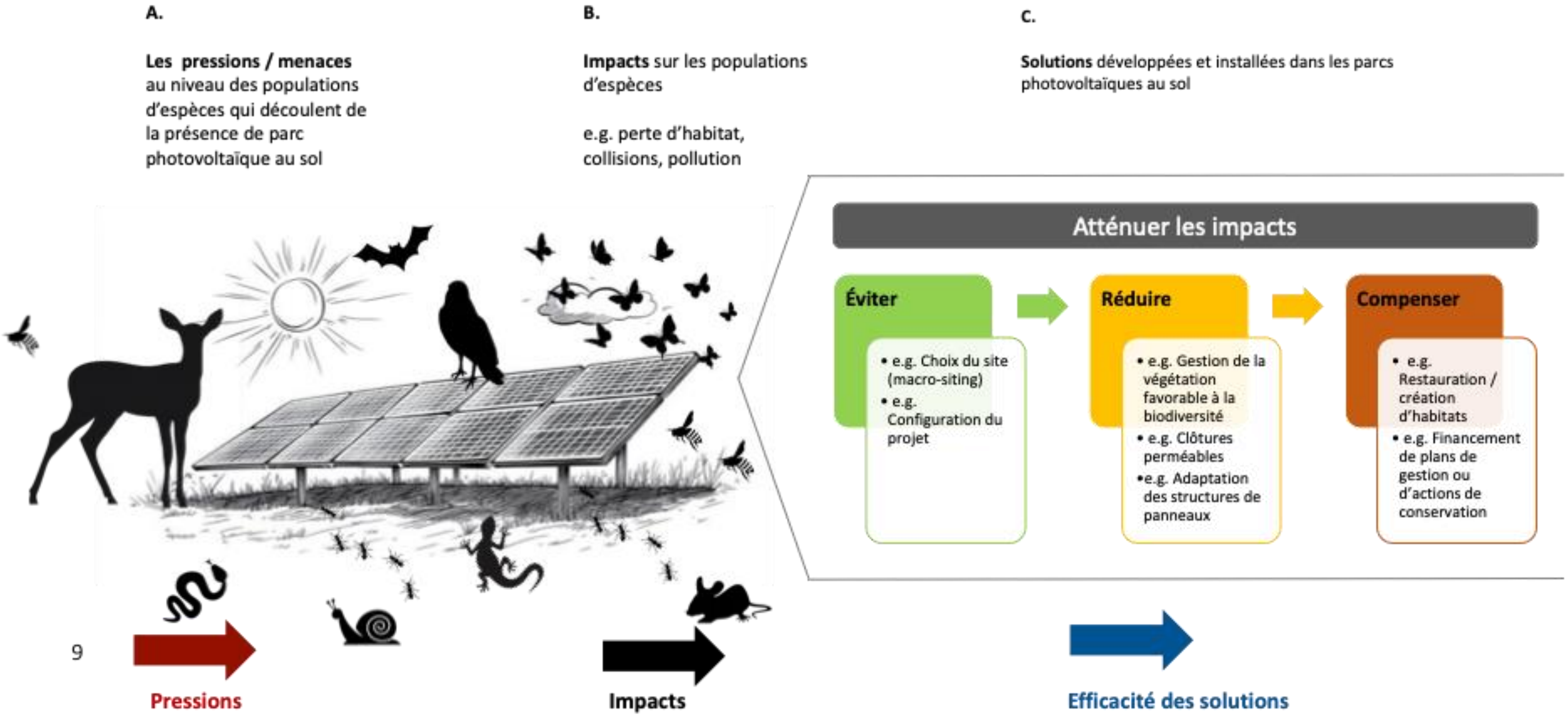


Figure 1. Diagram illustrating the question of the rapid review. A. The pressures exerted on ecosystems by ground-mounted PV installations, resulting in B: impacts on populations such as habitat losses. C: solutions for mitigating the impacts of ground-mounted PV installations on the environment [drawing of the solar panel: Adobe Stock, ID 1469513279v]

Table 1. Components of the question of the Rapid Review

PICO component	**Definition**	
Population	Most vertebrates, i.e. birds, small and large terrestrial and flying (bats) mammals, amphibians, and reptiles, and some invertebrates, especially terrestrial and flying insects and gastropods.	
Intervention	All mitigation measures implemented at the scale of a single solar panel, an array of solar panels, or a ground-mounted PV power plant, following the “ARC” approach.	
	Avoid	Includes solutions for avoiding impacts, e.g. the non-destruction of a wetland area.
	Reduce	Includes technological solutions that are integrated into ground-mounted PV installations to reduce the impact on biodiversity. For example: wildlife permeable fencing, switching off or adapting nocturnal lighting, eco-friendly vegetation management (late mowing, extensive pastures), and the creation of microhabitats.
	Compensate	Includes environmental restoration actions (including habitat management) elsewhere to compensate for the loss of habitats due to PV installations.
Comparator	**Spatial comparisons** (e.g. sites where mitigation measures are put in place vs. sites without any mitigation measure) or **temporal comparisons** (e.g. before vs. after the implementation of the mitigation measure), These can be “before-after”, “control-impact”, or “before-after-control-impact” studies.	
Outcome	All impacts on population size, density, and functioning such as direct mortality (e.g. collisions), avoidance behaviours, changes in activity or numbers at the site, and variation in abundance or composition.	

DESCRIPTIVE ANALYSIS OF THE SELECTED DOCUMENTS

Search and selection

Bibliographic reference selection process

Records were retrieved from different online publication databases and search engines: 1,446 records from Web of Science, 631 from BASE, and 818 from Google Scholar. In addition, complementary searches in review articles on the impact of ground-mounted PV installations on biodiversity allowed us to retrieve one additional scientific reference.

Of the initial 2,895 records, 1,968 unique references were retained after removing duplicates (Figure 2). 72 citations were retained after simultaneously assessing titles and abstracts.

Full texts were not available for 8 references (11.1 %). After assessing full texts, 12 relevant documents were selected. Full texts were excluded mainly on the basis of interventions (41.7 %) and comparators (27.7 %) that were not considered relevant.

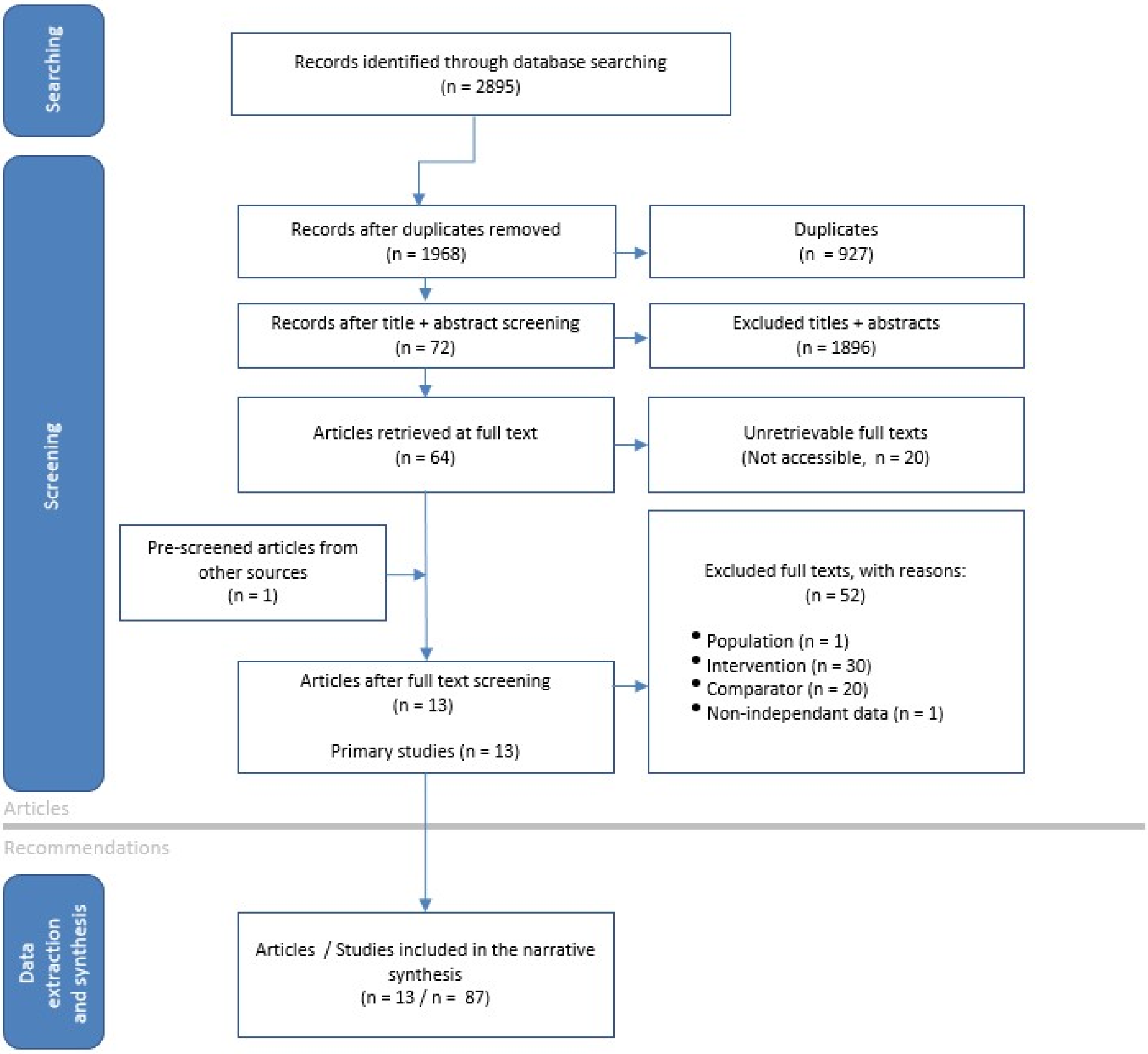


Figure 2. ROSES flow diagram of the selection process of the bibliographic references included in the systematic map and narrative synthesis.

Sources and types of references selected

Around one sixth of the selected references were retrieved through the main online publication databases, primarily Web of Science (seven articles, 53.8 %) (Figure 3). All references retrieved from Web of Science were scientific articles, indicating that this database is particularly rich in peer-reviewed academic publications. The BASE database provided two references (15.4 %): an academic thesis and a scientific article. It is important to note that most of the records retrieved from BASE were discarded because they were duplicates of those from Web of Science. Google Scholar also provided two references (15.4 %), both of which were scientific articles. Like BASE, many records from Google Scholar were duplicates of those from Web of Science (and/or BASE). Complementary searches provided two references (15.4 %): a scientific article and a technical report. Both were found by reading relevant and recent systematic literature reviews on the impact of ground-mounted PV installations on biodiversity.

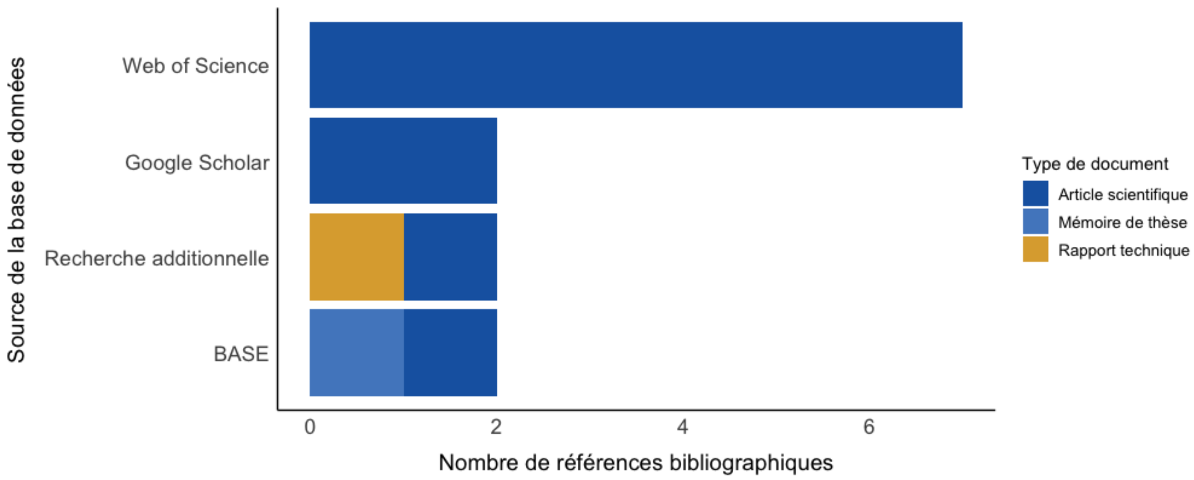


Figure 2. Number of selected bibliographic references by source and document type.

Key characteristics

Study validity

Among the selected bibliographic references, 38.5 % (five references) were rated as having a "weak" global risk of bias (Figure 4). Four references (30.8 %) were rated as having a "moderate" global risk of bias. There were fewer references at either end of the scale: only two references were in the "strong" (15.4 %) and two in the "very weak" (15.4 %) global risk of bias categories, and none were in the "very strong" global risk of bias category. Thus, the methodological robustness of most studies is within the intermediate range. Very positive or very negative ratings are in the minority.

It is important to note that, mainly due to time constraints, risk of bias was assessed from a small number of criteria (six in total). We focused on a limited yet representative set of factors, i.e. study context, confounding factors, mode of selection and detection, quality of the statistical analyses, transparency of funding sources, and conflicts of interest). Thus, the global risk of bias rating should be interpreted with caution: it is an artificial indicator that is useful for comparing studies, but it does not necessarily reflect the actual methodological quality (in all its complexity) of each study taken individually.

Figure 3. Number of selected bibliographic references in each global risk of bias category.

Temporal evolution

The earliest selected publication dates from 2010. The next reference was not published until 2016, which shows that there has been a relative and prolonged disinterest in investigating the effectiveness of measures for mitigating the effects of ground-mounted PV installations on wildlife (Figure 5). Indeed, the number of papers published each year between 2016 and 2025 ranged from one to three, with no noticeable increase over time. In their systematic map of the impacts of PV installations on plants and animals, Lafitte et al. (2023), showed that the first publication dated back to 2005, and that publication rates increased only after 2015. We can see a relationship between the publication rate of research on impacts and that of research on mitigation measures. However, a temporal shift between the two is to be expected. Indeed, the time it takes to design, implement and monitor mitigation tools delays their publication compared to the characterization of impacts. Moreover, becoming aware of the issues, devising mitigation solutions and designing robust experimental protocols to test these solutions also takes time. Our results reflect this.

Note that our literature search was carried out mid-June 2025, so that the numbers are incomplete for that year.

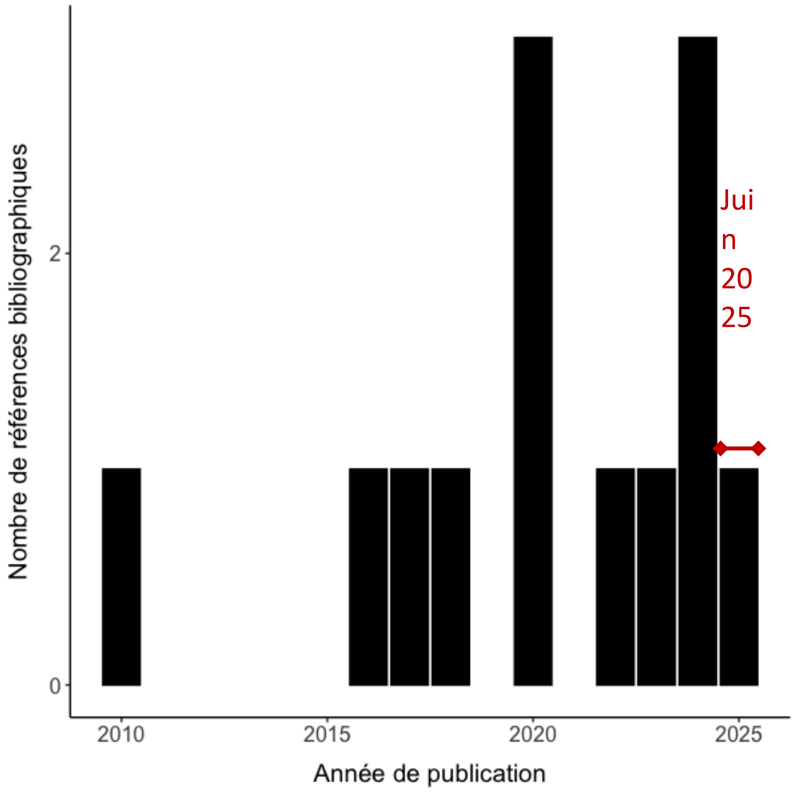


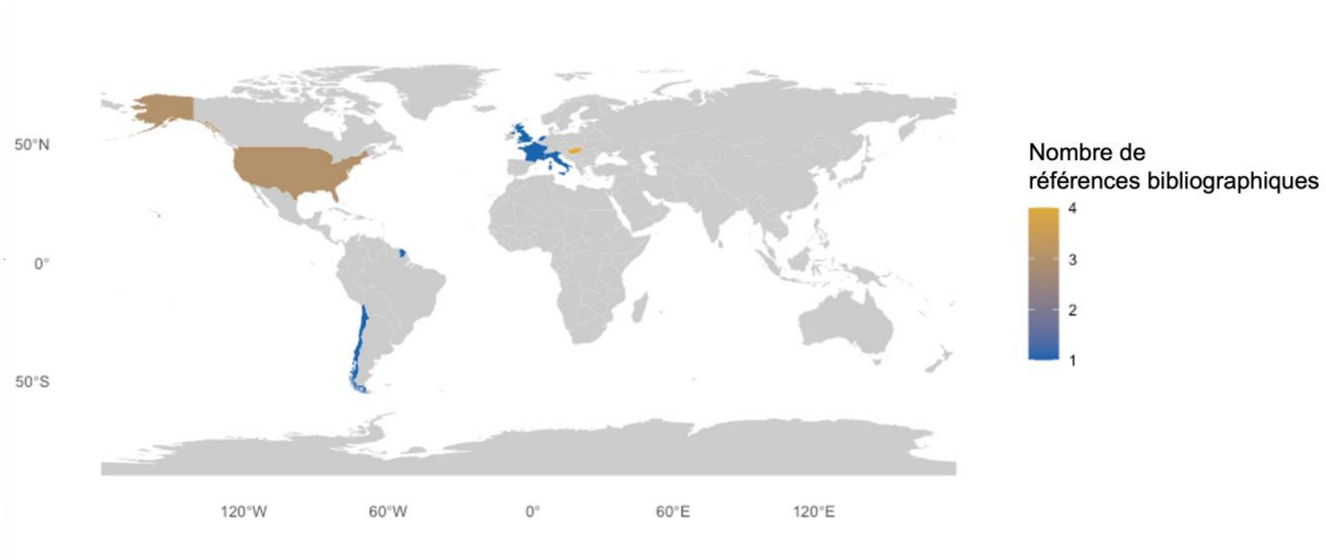
Figure 4. Number of selected bibliographic references per year. The search was carried out mid-June 2025.

Geographic distribution

Geographic distribution is sparse and very patchy (Figure 6). Studies were concentrated in a small number of countries, mostly in the United States and a few in western and central Europe (Hungary, the UK, France, and Italy). Isolated studies were carried out in South America in the southern cone and the Andean region. By contrast, vast regions remain absent: Africa, the Middle East, Asia (including China and India), and Oceania. The scale for the number of references in Figure 6 (1 to 4) confirms that the literature is still limited and dominated by a few countries.

The distribution pattern suggests there are several biases:

- A bias towards temperate climates and locations where ground-mounted PV installations are historically well-developed;
- A bias towards countries with research capacity and funds (with monitoring and publication programmes);
- A language and accessibility bias that disadvantages regions with an otherwise rapidly growing solar energy sector (MENA, south-east Asia). This limits the transferability of results: measures are rarely tested in arid, mediterranean or tropical biomes, even though these areas are crucial for global deployment.



(82.8 %) (Figure 7A). Studies on insects far outnumbered those on birds (8 case studies (9.2 %) from 2 references (15.4 %)) and bats (7 case studies (8.0 %) from a single reference (7.7 %)). By contrast, no study was found on small mammals, large mammals, reptiles or amphibians. This distribution has practical consequences: the available data mainly provide information on the effectiveness of measures that benefit insects. There is a conspicuous lack of data for other environmentally sensitive groups – small and large mammals, reptiles, amphibians – even though they may be affected by fence permeability and microhabitat fragmentation or availability.

Within insects, study distribution was very unequal (Figure 7B). Nearly half of the studies were on polarotactic aquatic insects, with 34 case studies (47.2 %) from 4 references, illustrating the problem posed by solar panels acting as "traps" by reflecting polarized light. Next were studies on soil arthropods (22 case studies (30.6 %) from 3 references) and, at a lower taxonomic resolution, unspecified flying species (10 case studies (13.9 %) from 2 articles). Pollinators, even though they are central to the provision of ecosystem services, are clearly underrepresented in the literature, with only 6 case studies (8.3 %) from 2 references.

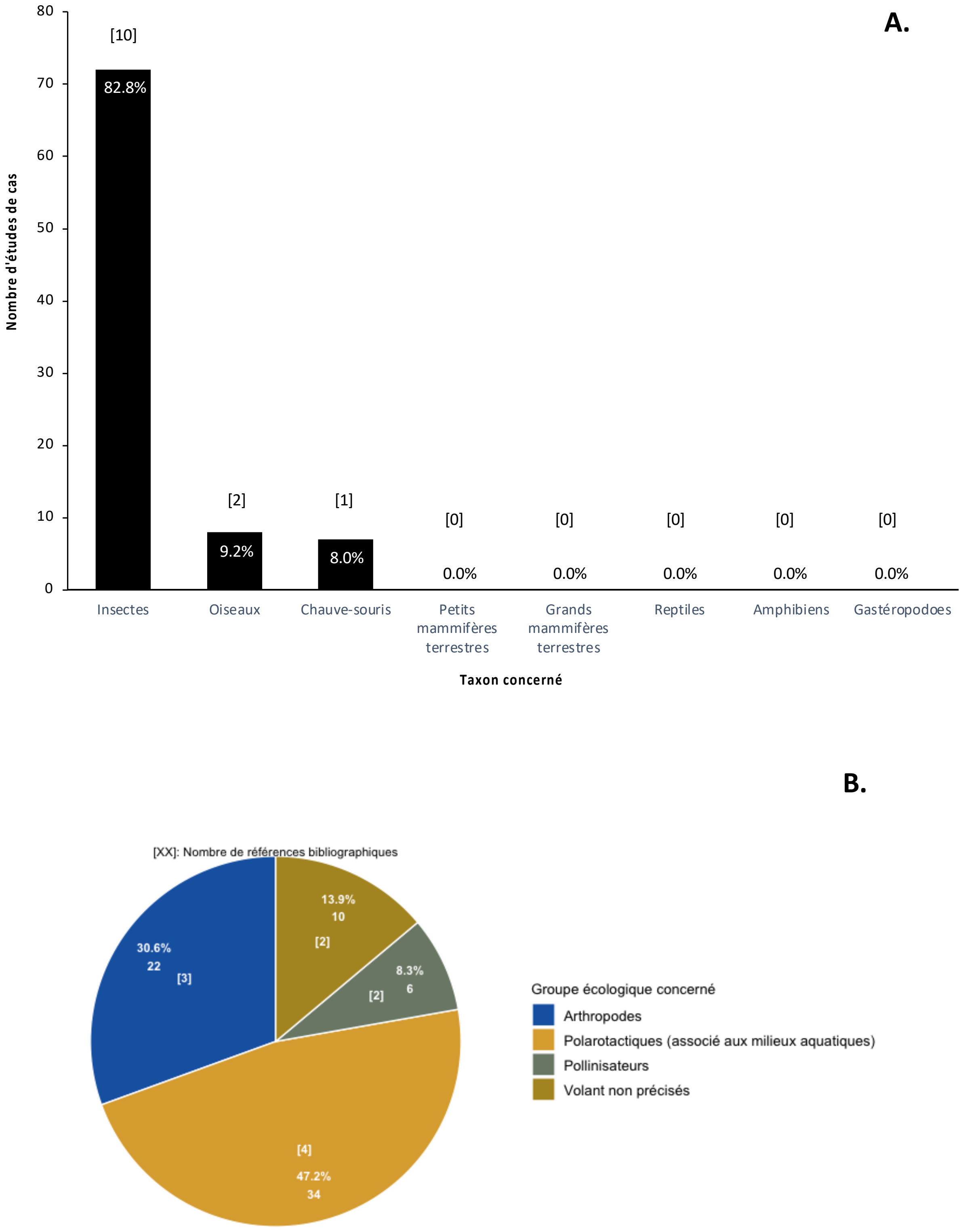


Figure 6. Number of case studies and bibliographic references (in brackets) by (A) taxonomic group (A) and (B) ecological group (insects).

Types of mitigation measures studied

Figure 8 shows that certain taxon x mitigation measure combinations are particularly prevalent in the literature (Figure 8A). For insects, two axes clearly dominate: the surface treatment of panels to reduce the "lake" effect (34 case studies from 4 references), and habitat/biodiversity enhancement measures (31 case studies from 4 references). Other levers are more marginal: vegetation management by grazing (6 case studies in a single reference), and changes to infrastructure design (1 case study from 1 reference). The 8 bird case studies (from 2 references) were split between habitat enhancement measures (6 case studies in a single reference) and acoustic deterrence, a still poorly documented measure (2 case studies from 1 reference). The 7 bat case studies (from 1 reference) focused on the effect of panel surface treatments. This distribution reflects bias in:

- the types of measures considered, with a focus on solutions related to the panels themselves (consistent with the issues related to polarotaxis[1]) and habitat/biodiversity enhancement
- taxonomic representation, in favour of invertebrates.

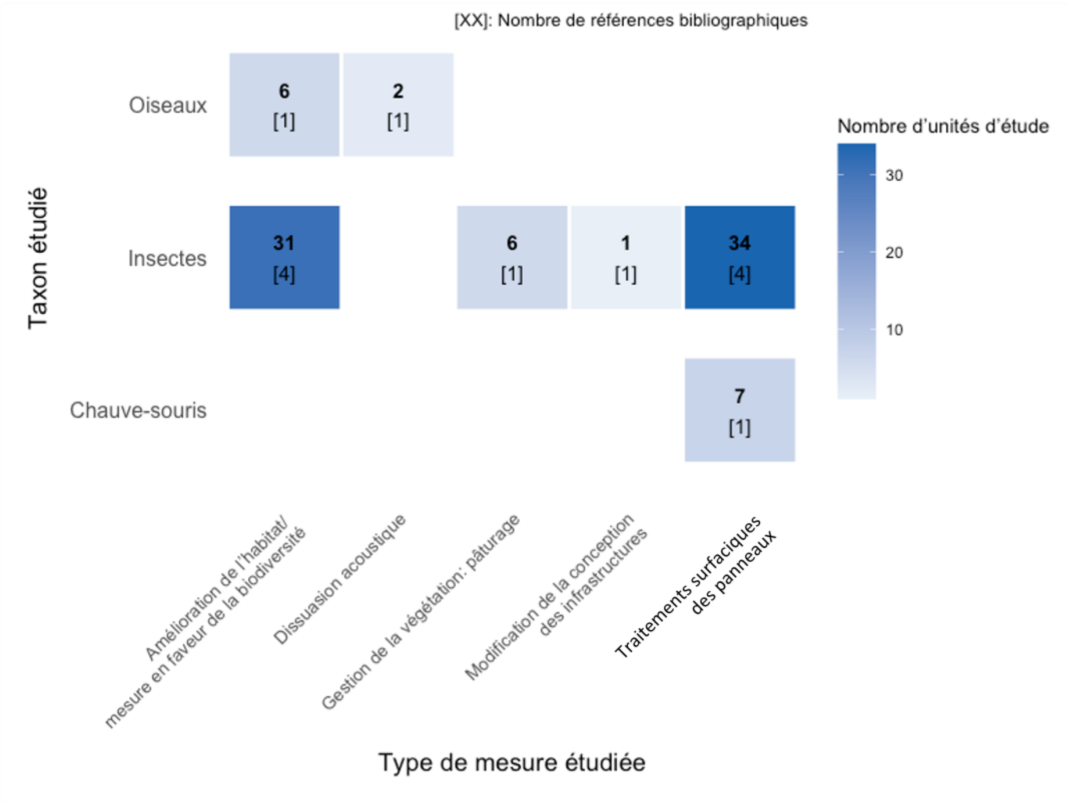
Many combinations are empty, and numerous levers have been barely investigated, or not all (e.g. infrastructure design, one reference) (see also the "Overview of the mitigation measures recommended by ADEME and LPO" in the Discussion and Perspectives section for an overview of the possible mitigation measures).

Focusing on insects, the heatmap shows a concentration of certain ecological group x mitigation measure combinations (Figure 8B). On the one hand, polarotactic aquatic species[2] are exclusively studied in the context of the surface treatment of panels with the aim of reducing the "lake" effect: 34 case studies (≈ 47.2 %) from 4 references. On the other hand, habitat/biodiversity enhancement measures are studied in relation to arthropods (15 case studies from one reference), unspecified flying species (10 case studies from 2 references) and pollinators (6 case studies from 2 references), i.e. a total of 31 case studies (≈ 43.1 %). Vegetation management by grazing is sporadic (6 case studies (arthropods only) from 1 reference), while changes to infrastructure design is anecdotal (1 case study).

[1] **Polarotaxis** is an orientation behaviour in response to polarized light, for instance an animal will follow the horizontal polarized light reflected by water.

[2] A **polarotactic species** is attracted to polarized light (in particular horizontal polarized light that is reflected by water or artificial surfaces).

A.



B.

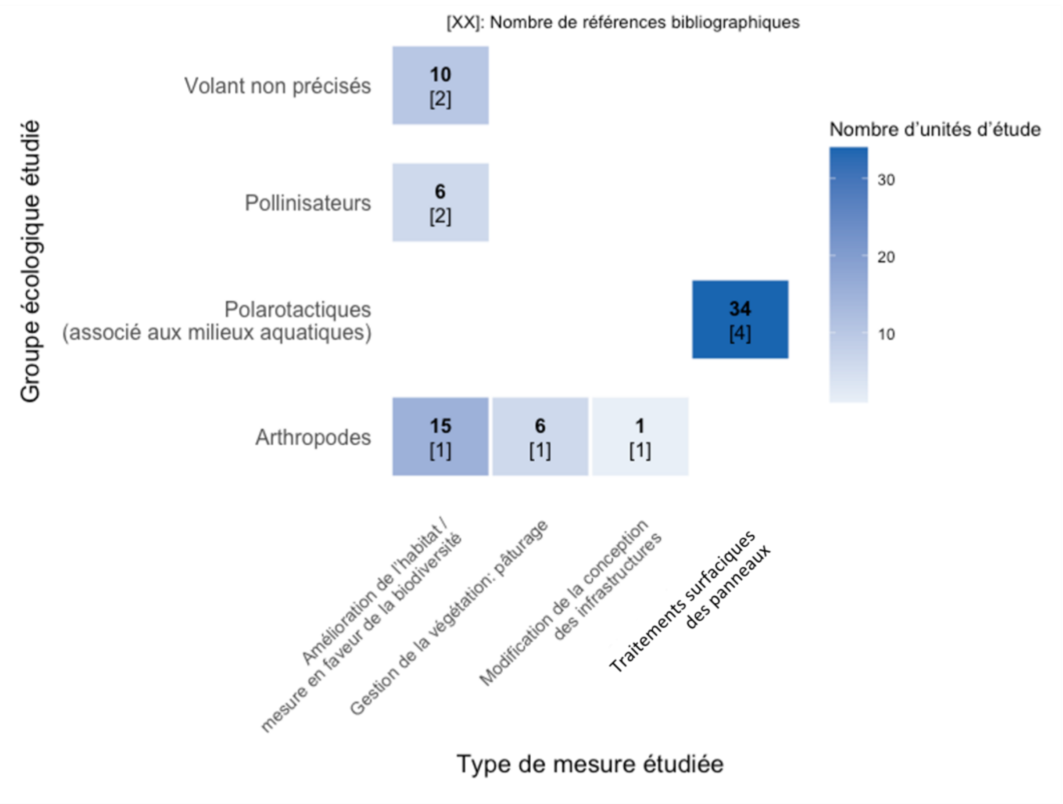


Figure 7. Heatmap of the number of case studies (and number of references in brackets) for each combination of mitigation measure x A) taxonomic group, and B) ecological group (insects only).

Localization of intervention: in situ vs ex situ

Figure 9 shows that there is a numerical balance between *in situ* and *ex situ* experiments, but not perfect equality (Figure 9). Indeed, *in situ* experiments represent 46 case studies (52.9 %) from 8 references, whereas *ex situ* experiments represent 41 case studies (47.1 %) from 5 references. In other words, the number of case studies is similar, but the number of publications is not: *ex situ* experiments are described in fewer articles containing multiple case studies, while *in situ* experiments are described in a greater number of publications, and thus provide a wider range of contexts.

Note that the five *ex situ* papers focused on testing the effectiveness of different surface treatments for reducing the "lake" effect in relation to insects, and to a lesser extent bats. This concentration of studies is useful for refining methods and comparing different technical solutions, even though contexts are not very diverse and there may be dependencies between case studies from the same experimental programme. By contrast, in situ studies offer a more realistic operational context and their results may be transferable to a wider range of settings, but they have less control over confounding factors.

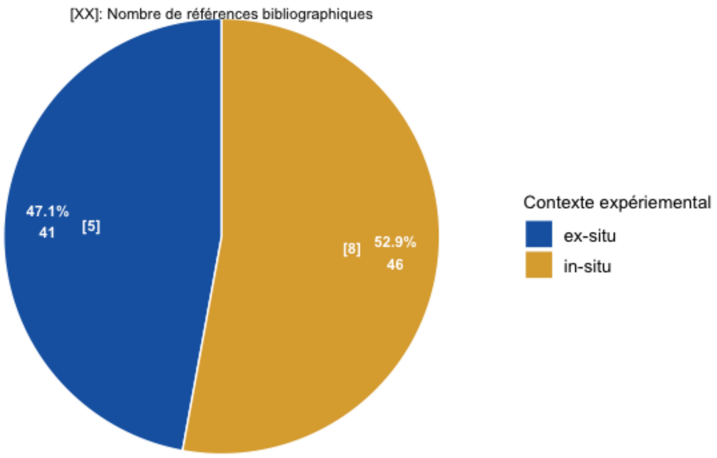


Figure 8. Number of case studies and bibliographic references (in brackets) for each experimental context, i.e. in situ (within a solar park) vs ex situ (outside a solar park).

NARRATIVE SYNTHESIS

The following synthesis provides a qualitative analysis of the 13 selected references grouped by mitigation measure. The aim was not to carry out a formal meta-analysis (this was not possible due to the low number of studies, the diversity of protocols, and the heterogeneity of indicators) but to extract the main findings for each measure category.

For each lever (habitat enhancement, vegetation management by grazing, modification of infrastructure design, panel surface treatment, acoustic deterrence), a summary of each study is given, followed by a "take home message" where key results, potential co-benefits, and limitations are highlighted. With this approach, we hope to provide a concrete and nuanced view of what current empirical evidence shows regarding the effectiveness of mitigation measures used in ground-mounted PV installations, bearing in mind that the data are still patchy and highly context-dependent.

Habitat/biodiversity enhancement

At ground-mounted PV power plants, habitat creation or restoration involves the transformation of simplified environments, often turf or cropland, into more structured and diversified environments. The issue here is to consider solar farms as an integral part of the landscape, capable of hosting a diverse flora and fauna, rather than a primarily technical area. Practical measures include creating wildflower meadows for pollinators, restoring degraded soils, maintaining taller sward height or fallows, planting hedgerows and groves, and creating small wetlands.

These management decisions change the composition and functioning of different ecological compartments. They impact plant, pollinator and other insect communities, soil biota and breeding birds. The five available studies show that observed outcomes depend on local context, prior land use and the time since construction.

Habitat enhancement for pollinators and other insects

- **Martin, 2022** (weak global risk of bias) compared three sites in Virginia, USA: a pollinator-friendly solar facility, and two management areas (under panels and open zone): a turfgrass landscaped solar facility and a non-solar meadow. Pollinator-friendly management involved sowing native nectar-producing species, minimal mowing, and targeted strategies to control invasive species. Insects and plants were collected in the 2021 growing season. Surveys showed that insect richness and functional group diversity at the pollinator-friendly solar facility were equivalent to those of the nearby meadow. Conversely, the turfgrass site was less diverse and overwhelmingly dominated by mosquitoes and other sanguivores. Microclimate analyses showed that forb-dominated vegetation slightly lowered PV panel temperatures by 1-2 °C in high irradiance conditions. Associated simulations predicted a potential increase in energy production of 0.5% per year, with up to 1% in summer. The study concludes that management practices that promote a pollinator-friendly landscape could also have a positive effect on overall energy output, although long-term monitoring is needed.

- **Walston et al., 2024** (weak global risk of bias) conducted a field study across 5 years (2018-2022) at two solar energy sites in Minnesota, USA, following conversion from cropland to a wildflower meadow (solar-pollinator habitat). Observational surveys of plants and insects were conducted on permanent transects each summer. A 7-fold increase in flowering plant species richness was observed by the end of the study period. In that same time, abundance of insect pollinators and beneficial insects tripled. The abundance of native bees increased over 20-fold, with over 80% of observations occurring after year 2. Bee visitation to soybean fields adjacent to the solar-pollinator sites were approximately 2 times higher than at roadside and 2.5 higher than in soybean field interior transects. However, the authors stress that the effects on crop pollination were small at the level of the agricultural landscape, and that these results were obtained in intensively restored experimental plots.

- **Biesmeijer et al., 2020** (moderate global risk of bias) describe the functioning of a large solar park constructed on a brownfield site that had been unused for the last 2 years within an industrial estate in Moerdijk, the Netherlands. Five seed mixes were sown, plus a control plot. Each mixture contained six plant species, with one mix containing only grasses. Monitoring was carried out between April and August 2019 and included pollinator (hoverflies and bees) and plant surveys. Results showed that seed mixes did not have a significant effect on pollinator abundance. Nonetheless, the authors state that “this may be due to the fact that the seed mixture plant species had a late start and in their first year made up only a small portion of the total vegetation. It was not possible this year to determine which seed mixture was best in terms of pollinators and maintenance due to the late sowing and low proportion of the seed mixture plants and consequence minimum maintenance."

Soil restoration and soil biota

- **Lambert et al., 2024** (very weak global risk of bias) studied a solar park constructed on an abandoned vineyard in Occitanie, France. An ecological restoration experiment with four treatments outside and under panels was initiated in 2016. Restoration treatments consisted of an untreated control, vermicompost addition, sowing of the grass species *Brachypodium retusum*, and transfer of seed material harvested in a neighbouring reference community. Four years after construction, total carbon and total nitrogen content were higher in the vermicompost plots but remained lower than in the reference ecosystem. Monospecific sowing and especially seed material transfer increased the abundance of soil mesofauna, particularly springtails and mite predators, near the reference ecosystem level. Solar panels affected soil temperature, humidity, microbial activity and trophic interaction networks. They tended to reduce the abundance of detritivores and predators. Under panels, mite predators and springtails were 25% and 50% less abundant, respectively, and total abundance of detritivores and mesofauna was two times lower than outside panels, without changing the relative level of performance of each restoration treatment. The authors suggest that active restoration practices may allow partial convergence with natural ecosystems, despite the microclimatic effects of solar panels.

Breeding birds and habitat management

- **Copping et al., 2025** (weak global risk of bias) compared bird populations on six solar farms and neighbouring arable land in the East Anglian Fens, UK. Solar farms were split into two categories based on their management type: intensively managed "simple habitat" solar farms, with a short sward height, few wildflowers and no woody elements, and "mixed habitat" solar farms, with taller sward height, abundant wildflowers, and hedgerows or trees along the boundary fence. Standardized surveys in spring 2023 showed that predicted abundance across all bird species was two times higher in mixed habitat solar farms compared to simple habitat solar farms. Predicted abundance was also two times greater in mixed habitat solar farms for farmland birds, and 12 times greater for woodland birds. Total species richness was around 2.5 times greater in mixed habitat solar farms. Farmland bird species richness was three times greater, and woodland bird species richness was around nine times greater, in mixed habitat solar farms. Greater abundance and species richness were also observed for bird species of conservation concern (red or orange on the IUCN list). Thus, solar farms could enrich bird communities in arable landscapes, provided their management integrates diverse habitats and is not intensive.

Take home message

The studies in this category show that habitat enhancement at ground-mounted PV plants could increase the richness and abundance of pollinators, beneficial insects, soil organisms and breeding birds. The conversion of cropland or lawns into wildflower meadows and structured habitats is accompanied by a marked increase in plant diversity and pollinators, which can sometimes indirectly *benefit neighbouring crops. Soil restoration, through organic amendments or by planting vegetation, would also benefit soil mesofauna and enhance the decomposition function, even under the influence of panel-induced microclimates. Lastly, the presence of mosaic habitats and woody elements at solar parks would support bird abundance and diversity compared to large crop fields. Nonetheless, these studies are few in numbers, are often restricted to a few sites and are carried out over a short period of time. Longer assessments, and under different conditions, are needed before generalizing these habitat enhancement measures.*

Vegetation management: grazing

At ground-mounted PV installations, vegetation management by grazing can be an alternative to mechanical vegetation management (mowing, shredding), with the idea of limiting the use of fertilizers, reducing disturbance, and potentially enhancing certain compartments of biodiversity, in particular soil biota. The actual effects of these practices remain poorly known for ground-mounted PV installations. In our selection, only one paper compared in detail the effects of mechanical management vs. grazing at ground-mounted PV installations, both in terms of soil properties and the edaphic[3] arthropod community.

- **Menta et al., 2023** (very weak global risk of bias) evaluated ground-mounted photovoltaic systems in two parks located in northern Italy (Lombardy and Emilia-Romagna) with different vegetation management: tractor-mown grassland and grassland managed by sheep and donkeys. In each park, three types of microhabitats were surveyed: under panels, between panel rows, and in the area surrounding the system and managed in the same way (control). Soil samples were collected two times, in June and October 2021. pH, soil organic matter, arthropod diversity (identified at the order and taxon level), and soil biological quality were measured or quantified for each sample. Results showed that the microclimatic conditions created by solar panels (shade, humidity) influenced arthropod community composition and soil properties. Arthropod diversity and abundance between panel rows was similar to that of controls, while areas under the panels had lower biodiversity, especially in the tractor-mown system. The presence of grazing animals increased the soil organic matter content, particularly in the control areas, although a high heterogeneity of results was observed under solar panels, probably due to trampling. The abundance of certain groups, such as Acarina and Collembola, was strongly influenced by soil organic matter. Seasonal differences were also observed, with Hymenoptera and Hemiptera being more abundant in spring. The authors conclude that park design and management had significant effects on below-ground soil fauna. Inter-row areas, under the right type of management, could act as a refuge for soil fauna. The study highlights the importance of integrating environmental criteria into the design and management of ground-mounted PV systems for reconciling energy production with biodiversity conservation.

Take home message

This study suggests that vegetation management by grazing at PV plants could increase soil organic matter content and enhance the abundance and quality of arthropod communities at the scale of the park, but that these positive effects could be counterbalanced under the panels when animals are stationary and compact the soil. For both types of management, the areas between rows could

[3] **Edaphic arthropods** (springtails, mites, woodlice and certain insects) live primarily in the soil (litter, humus, gaps in the soil), contribute to the decomposition of organic matter, and shape soil structure.

become hotspots for biodiversity within solar parks. As the only paper available on management by grazing, this study provides a first look at how it could work, but conclusions are limited by the small number of sites, the absence of gradients of animal density, and the short study period, so that more research is needed to generalize these results.

Modification de la conception des infrastructures

Changing the design and layout of solar farms (type of mount, spacing between rows, fixed mount vs. solar tracking technology) can strongly influence local microclimatic conditions and, ultimately, invertebrate soil communities. Infrastructure design parameters could act as potential levers for mitigating the impacts on biodiversity, or conversely, accentuate the degradation of fragile environments. In our survey of the literature, we found only one article on the effects of the design of ground-mounted PV plants, providing a first glimpse for this category of mitigation measures.

- **Suuronen et al., 2017** (weak global risk of bias) studied two PV plants situated in the Atacama Desert in northern Chili: one is a small plant consisting of north-facing arrays of fixed mounts built on former agricultural land; the other is large plant with solar trackers, allowing the array to follow the Sun (east to west). For both solar plants, three different environmental conditions were considered: Sun (between panels having sunny conditions during the hottest hours of the day), Shade (below the solar panels), and Reference (outside the panel area). Abiotic variables (temperature, humidity, and dew point) were recorded near the ground. Arthropods were sampled using interception traps. Microclimate conditions at fixed-mount installations were more extreme between panels (Sun) (very high temperatures and low humidity), while areas under the panels (Shade) were cooler and more humid, acting as a refuge for biodiversity. At the solar tracking facility, with more space between the mounts, differences in microclimate between Sun, Shade, and References were less pronounced. Arthropod species richness and composition varied between microhabitats, with a generally higher diversity and a distinct species composition under the panels in the fixed-mount installation. This could be due to a refuge effect or more favourable microclimatic conditions. Finally, the authors suggest that in desert environments, PV installations could provide cooler conditions that could be beneficial to local biodiversity. However, these effects could also modify regional ecological dynamics and warrant careful planning of large-scale installations and long-term environmental studies at solar power plants. The authors make several recommendations for the design of solar facilities, including having more space between the mounts to prevent extreme abiotic conditions, taking landscape heterogeneity into consideration, and decreasing the impacts of solar power plant construction if possible.

Take home message

This study shows that the design of ground-mounted PV plants (fixed mounts vs solar tracking, row density, surface area) influences on both soil microclimate and arthropod community composition. Fixed mounts can create very hot and dry conditions between rows, while offering cooler and more humid microrefugia under the panels. The solar tracking facility, with more space between the mounts, displayed less marked differences in microclimate. These results suggest that design (spacing, orientation, mount type, taking soil type into consideration) can be used as a ***mitigation lever*** *to limit the impact on soil fauna in desert environments. However, this preliminary study examined two sites that are not directly comparable and over a short period of time. Thus, additional research (at multiple sites, long-term) is needed before these recommendations can be generalized.*

Panel surface treatment to reduce "lake" or "mirror" effects

The surface of PV panels (texture, surface motifs, coating, and ability to reflect or polarize light) can influence their interaction with wildlife. Smooth shiny dark surfaces can act as sensory traps by mimicking the visual or acoustic signals of natural environments, particularly bodies of water (the "mirror" or "lake" effect). This mainly affects polarotactic aquatic insects such as mayflies, horseflies and aquatic beetles which use horizontal polarized light to find egg-laying sites. Attracted by the polarized light reflected off solar panels, these insects may lay their eggs on the panels, resulting in reproductive failure. In a similar manner, some bats can mistake smooth solar panels for watering points, resulting in aborted drinking attempts, a waste of time and energy, and sometimes collisions. Other animal groups could also be affected: aquatic birds have been observed attempting to land on panels, which they mistake for water. The five studies reported here examined measures that could reduce the attractiveness of solar panels by modifying their optical or physical properties without impacting their energy efficiency.

Optical modifications for aquatic insects

- **Horváth *et al.*, 2010** (strong global risk of bias) studied highly polarizing PV panels and showed that they could become ecological traps for several groups of aquatic insects (mayflies (Ephemeroptera), caddisflies (Trichoptera), dolichopodid dipterans, and tabanid flies). In ex situ conditions, solar panels reflected light as horizontal polarized light almost completely (~100%, more than water) and attracted more reproduction and oviposition behaviours than controls. White borders and white partitions drastically reduced attractiveness to insects: panels with white cell borders were 10- to 26-fold less attractive to insects than the same panels without white partitions, with a minimal loss of effective (energy producing) surface area (~1.8% less black surface). Thus, white nonpolarizing gridding integrated into the panel design could significantly reduce polarized light pollution while inducing only a small drop in performance.

- **Black & Robertson, 2020** (weak global risk of bias) refined this idea by carrying out a field experiment using simulated solar panels to test the effect of line width and density on the attraction of four insect groups (caddisflies (Trichoptera), mayflies (Ephemeroptera), non-biting midges (Chironomidae), and black flies (Simuliidae)). By comparing grid motifs and a smooth black surface, the authors showed that 1 to 5 mm wide lines were sufficient to reduce the capture of most taxa by more than 80%, with only a 2-3% loss in effective surface. Increasing line density did not provide any significant improvement. The trade-off curve between "black solar area lost /reductions in capture" was similar to that of Horváth et al. (2010), which suggests that it is mainly the relative amount of non-polarizing area within the field of view, rather than a specific pattern, that determines the reduction in attractiveness.

- **Száz et al., 2016** (moderate global risk of bias) evaluated the effect of matte anti-reflective coating, compared to "shiny" smooth surfaces mimicking the optical properties of standard solar panels, using polarimetry and field experiments involving horseflies (Tabanidae), mayflies (Ephemeroptera) and non-biting midges (Chironomidae). Under clear skies, shiny black surfaces reflected horizontally polarized light from all angles of view, while matte surfaces were only attractive when the sun was facing or behind the observer. Shiny surfaces were 3.4 to 7.5 times more attractive to horseflies than matte surfaces, while non-biting midges found both experimental surfaces equally attractive. However, under overcast or shady conditions, mayflies were more attracted to matte surfaces. Matte surfaces are similar to calmer bodies of water, exhibiting a smaller variation in the polarization angle but also slightly lower degrees of polarization. According to the authors, anti-reflective coating effectively reduced polarized light pollution under certain conditions, e.g. horseflies in bright sunlight. However, anti-reflective coating could increase attractivity for other groups, e.g. mayflies in overcast/shaded conditions. These results highlight the importance of combining anti-reflective coating with other complementary measures. For instance, designing panels with white gridding and locating solar panels away from aquatic environments could limit these undesirable effects.

- **Fritz et al., 2020** (moderate global risk of bias) tested a biomimetic approach by evaluating a microtextured polymeric coating that mimics the texture of rose petals. After confirming their good optical performance (low reflectance, good light-harvesting capacity), the authors compared the attractiveness of three test surfaces to mayflies and horseflies in field conditions: a smooth black plastic, a rose petal replica, and a glass-covered rose petal replica. For mayflies, the smooth black plastic was the most attractive surface (89% of individuals), while glass-covered rose petal and rose petal surfaces were unattractive (8% and 3%, respectively). Oviposition behaviours were observed only on smooth surfaces (smooth black plastic and glass-covered rose petal). For horseflies, nearly no landings were recorded on the rose petal surface alone, which was found to be significantly less attractive that smooth surfaces (90% combined). Analyses showed that the rose petal micro-texture reduced the degree and regularity of horizontal polarization compared to smooth surfaces, while retaining a good optical performance. The authors suggest that "rose petal" cover layers may be a solution for limiting polarized light pollution without significant loss of PV efficiency.

Physical/acoustic modifications for bats

- **Abdul Rahman et al., 2024** (moderate global risk of bias) studied the effect of a simple physical modification of a smooth surface on the drinking behaviour of bats. They positioned a smooth black plastic plate above the surface of a pond; this is analogous to an "artificial water body" like a field of solar panels. They compared the behaviour of several bat species over: open water, a smooth plate, smooth plates covered with parallel strings of varying diameter (0.25 to 2.5 mm), and a smooth plate covered with strings in a crossed pattern. Drinking attempts over the plate decreased non-linearly with the increase in string diameter: from 41.4% of bat passes at the smooth plate without strings to 17.1% with 2.5 mm strings, i.e. a reduction of nearly 60%. Even the thinnest strings (0.25 mm) produced a significant effect. With strings of equal diameter (0.5 mm), the drinking ratio was significantly lower with crossed strings (25.7%) than with parallel strings (32.9%), which is consistent with the idea that a strings in a crossed pattern would increase the likelihood of echoes reaching the bat. The authors suggest that linear thin objects (threads or strings) placed on smooth surfaces, like PV panels, could help make such surfaces less of a sensory trap for bats, but this remains to be tested specifically in the context of solar installations.

Take home message

The studies in the "panel surface" category show that relatively small changes to the surface of solar panels can drastically reduce their attractiveness to wildlife, especially polarotactic aquatic insects, and possibly bats. For instance, adding non-polarizing white gridding or borders fragmented the reflected light signal, and reduced the attractiveness to several groups of insects over ten-fold, with minimal loss of effective surface (1 to 5%). Matte antireflective coating reduced reflected polarized light and was less attractive to horseflies in full sunlight. However, these effects vary depending on the species and the light conditions: some mayflies even preferred coated surfaces in diffuse light. Bioinspired micro-textures, such as those mimicking the surface of rose petals, also show promise for reconciling energy production with a reduction in polarized light pollution by making these panels nearly invisible to certain sensitive species. For bats, placing fine thread or string on the surface of smooth panels altered the acoustic signals detected by echolocation, and thus significantly reduced the number of maladaptive drinking attempts. These simple structural modifications could be envisaged at exposed installations.

*Overall, these studies show that the physical and optical design of solar panels can play a role in mitigation. However, these designs have only been tested at a small number of sites, on a small number of taxa and under specific experimental conditions, and rely on evidence from small surfaces over a short period of time, and crucially, **from simulated PV panels, outside of solar farms, and not in the actual conditions of an operating solar farm.** These results therefore need to be confirmed by studies carried out in operational ground-mounted PV power plants.*

Acoustic deterrence

Acoustic deterrence as a mitigation tool has not been explored much in the context of ground-mounted PV installations, where interactions between infrastructure and birds are less documented than in the wind energy sector. These systems rely on the emission of sound signals that are perceived as disturbing or threatening to reduce the presence of birds near PV infrastructure. To our knowledge, only one study has been published focusing specifically on the effectiveness of crow deterrent systems in PV power plants. Note that this study was designed to assess the reduction in material damage rather than the measure's environmental impact. It may reduce impacts such as collision or maladaptive behaviours but is likely to have other impacts such as loss of habitats, and hunting and breeding areas. This paper was included in this review for illustrative purposes.

- **Itoh et al., 2018** (strong global risk of bias) carried out an experimental study between October and December 2017 at a PV power plant in Japan to assess the effectiveness of a crow deterrent system. Observations were made in two areas: near the deterrent device and further away. The deterrent system, emitting sound waves between 6:00 am and 6:00 pm, was coupled with an observation system made up of high-definition cameras (30 images per second) capable of automatically detecting and recording flight trajectories over a month. Inspection took place over three 20-days periods: before, during, and after activation of the sound device. No crow stopped in the observation range during the time that sound was emitted, while a few did stop before and after the treatment (3 and 6 crows, respectively). The number of passing crows also decreased from 3.8 (before) to 2.3 (during treatment) crows/day, i.e. by ~45%. Thus, the deterrent system seems to be effective for reducing crow numbers, even though the short observation periods and the low numbers recorded do not allow for formal statistical validation.

Take home message

*Although this study was not specifically designed to reduce the impact of PV installations on birds, results suggest that the use of **acoustic deterrent devices** could be envisaged as a mitigation tool. This needs to be confirmed with additional research over the long-term. Note however that this mitigation tool also has impacts, by creating large areas that exclude wildlife. It is therefore necessary to assess the impacts of this measure.*

DISCUSSION AND PERSPECTIVES: IMPLICATIONS FOR RESEARCH AND DECISION-MAKING

This review aimed to provide a snapshot of the state of knowledge on the effectiveness of measures for mitigating the impacts of ground-mounted PV installations on wildlife. From our screening of the literature, we retained 13 references representing 87 case studies. As the search was ended mid-June 2025, the review was incomplete for that year. We have since been informed of the publication of three new articles that, in theory, could have passed the screening process (Lec'Hvien, 2025;

Szoldatits et al., 2025; Walston et al., 2025). However, strict adherence to the protocol did not allow us to include these in our analysis. Nevertheless, the range of papers was sufficient to extract the main trends regarding the types of measures tested, the taxa targeted, and the methodological quality of the studies, while identifying the important knowledge gaps that would need to be addressed to accompany the deployment of ground-mounted PV installations in a way that meets the demands of biodiversity conservation.

The temporal dynamics of the publication output shows that this field is still quite new. The first publication in our reference list dates from 2010, with no new publications until 2016. Between 2016 and 2025, the number of publications varied between one and three per year, with no noticeable increase or change in scale. The output is therefore not steadily increasing but rather sporadic. This trend can be compared to that reported by Lafitte et al. (2023) for publications on the impact of PV installations, where the earliest publications date back to 2005, and a marked increase in publication rate only occurred after 2015. Our results suggest that there is a logical delay between the characterization of impacts and the assessment of measures for mitigating these impacts, which involves: becoming aware of the issues, designing mitigation tools, implementing these on site, then monitoring their effects. The time taken to complete this cycle explains why studies on the effectiveness of these measures appear later and are still scarce.

Moreover, geographic distribution is also very unequal. Most references originated from the United States, as well as from several western and central European countries. There were also a few isolated studies from South America. By contrast, there were no studies from Africa, the Middle East, Asia or Oceania, even though solar PV energy is being developed in countries like South Africa, Egypt, the United Arab Emirates, China, India, and Australia. This distribution reflects several possible biases. First, a geographical and climate bias: the studies were mainly carried out in temperate regions were ground-mounted PV infrastructure is historically well-developed. Second, a bias related to research capacity and funding: countries with structured research and monitoring programmes are over-represented. Finally, a language and accessibility bias is likely, with an under-representation of literature published in other languages or in less accessible outlets. These biases may limit the transferability of results. Measures were assessed almost exclusively in temperate environments. They are very rarely tested in arid, mediterranean or tropical biomes, even though these regions are crucial for the future deployment of ground-mounted PV infrastructure. Ecological responses are likely to be very different in these biomes, due to their more extreme conditions, different water regimes, and distinct species communities. It is necessary to expand the range of sites studied beyond North America and Europe and carry out more studies in arid or tropical environments. It is also important to harmonize indicators and protocols to compare the effectiveness of a measure in different regions. Finally, establishing collaborations with solar park developers and managers would facilitate access to sites and data, especially in areas that are currently under-represented. One must bear in mind that aggregated results from a single country often mask a high heterogeneity within that country and may under-represent measures implemented across multiple sites.

The selected references also show a strong imbalance in terms of taxonomic groups. Insects are by far the most predominant group: 10 references out of 13 (over 80 %) focused on insects. Birds featured in only two references, and bats in only one. No study was found on small or large land mammals, reptiles, amphibians or gastropods. This taxonomic bias has direct consequences. The available data mainly provide information on the effectiveness of measures that benefit insects. Conversely, there is a conspicuous lack of data on measures for other environmentally sensitive groups, such as land mammals, reptiles, and amphibians. Yet these groups are affected by key issues, such as boundary fence permeability, habitat fragmentation, refuge and micro-habitat availability, and wetland management. The research effort is also very unequal between insect groups. Nearly half of the studies (34 case studies) focused on polarotactic aquatic insects and the "lake" effect induced by smooth surfaces. Surveys of soil arthropods were the second-most common type of study (22 case studies). Pollinators, although central to the provision of ecosystem services, are under-represented (6 case studies). Several factors can explain this distribution pattern. Surveys of invertebrates are often simple and standardized, e.g. ground traps or yellow-pan traps, well-established protocols used in community ecology... By contrast, the study of vertebrates is more difficult: acoustic or telemetry surveys, authorizations, larger sample sizes, multiannual surveys... These constraints probably hinder the development of studies on mammals, reptiles, and amphibians. Addressing this bias requires setting new research priorities. First, research must be redirected towards understudied taxa. Second, measures designed for these groups, e.g. permeable fencing and corridors, habitat mosaics, thermal refugia, water management in wetland areas..., need to be tested. Finally, robust protocols need to be developed (e.g. BACI-type studies, multiannual surveys, functional indicators such as flower visitation or reproductive success rates). These developments are needed to compare the effectiveness of measures between different taxa and to improve recommendations for conservation.

The types of measures tested are also not equally distributed. Most studies on insects focused on two main axes:

- the surface treatment of panels, to reduce the "lake/mirror" effect in relation to polarization,
- habitat/biodiversity enhancement measures.

Other types of measures, e.g. grazing and infrastructure design (one article each), remain overlooked. The situation is even more critical regarding vertebrates. Birds only featured in two articles. One study focused on habitat enhancement and compared "simple habitat" solar farms (short sward height, intensive management, no woody elements) and "mixed habitat" solar farms (less intervention, taller sward height, abundant wildflowers, and hedgerows or trees along the boundary fence). The other focused on acoustic deterrence, which is not a mitigation practice in the "avoid-reduce-compensate" sense; it presented important biases and was not conservation-oriented. Bats featured in only article focusing on panel surface treatments. No other mitigation tool was tested in this group.

In practice, this reflects two biases. First, a thematic bias towards panel surface treatments and habitat enhancement measures. Second, a taxonomic bias towards invertebrates. If we focus on insects, this trend is very clear. Aquatic polarotactic species are studied only in relation to the effect of surface treatments. Conversely, habitat enhancement measures are studied in relation to their effect on arthropods, unspecified flying species and pollinators. Other levers (grazing, infrastructure design) remain anecdotal in terms of study number. This shows us two things : 1) each type of measure is associated with a specific group (panel surface treatment ↔ polarotactic species ; habitat ↔ arthropods/flying species/pollinators) leaving many combinations unexplored ; 2) the available evidence comes from a small number of studies, indicating that a few empirical research programmes dominate the literature and a diversity of independent contexts is not represented. There is a need for:

- testing panel surface treatments in situ, and broadening the range of taxa (birds, other vertebrates) and types of sites considered;
- a more systematic assessment of the effects of habitat and vegetation management measures on vertebrates, including their seasonal effects;
- diversifying infrastructure design options;
- improving assessment protocol design (BACI, replicates, multiannual surveys) to increase the comparability and transferability of results between different measures, taxa, and contexts.

The five ex situ studies, conducted outside of solar farms, specifically investigated the effectiveness of different panel surfaces for mitigating the "lake/mirror" effect related to polarization. These studies assessed the response of insects, and more marginally of bats, under controlled or semi-controlled conditions. This cluster of studies is useful for comparing in detail different technical options and explore the underlying mechanisms. However, it limits the range of ecological situations. By contrast, in situ studies are conducted under more realistic conditions. They integrate the functional constraints encountered at solar farms, the interactions with the surrounding environment, and the confounding factors that are difficult to replicate in controlled conditions. These studies examine different types of measures (habitat, vegetation management, panel surface treatment, deterrence) but often with small sample sizes and in specific geographic contexts. To improve the robustness of their conclusions, it would be advisable to:

- test in situ the solutions that have been tested ex situ;
- broaden the ex situ reference base to other research teams and contexts;

- use similar metrics in in situ and ex situ studies to make them more comparable.

The picture provided by these preliminary elements is that of a field that is still in its infancy, geographically restricted, centred only on a small number of taxa and types of measures with often variable designs. Most importantly, it shows that evidence is available for only a fraction of the measures that could be implemented. Indeed, many types of levers have been proposed in technical and practical experience reports (ADEME, 2023; Marx, 2022; see box below), but their effectiveness at mitigating the impact on wildlife has not yet been formally assessed scientifically. This calls for the a broader examination of these existing or potential measures, even when these have undergone little or no evaluation.

Overview of the mitigation measures recommended by ADEME (2023) and LPO (Marx, 2022):

Prior to installation, several measures can be envisaged to avoid impacts. For instance, selecting areas that are already built up or degraded, and avoiding conservation areas, wetlands and wildlife corridors. Site selection and comparison are important ways to significantly reduce impacts, yet very few studies have quantified these effects from actual biological data.

There are many possible reduction measures that can be applied to existing solar parks. Park design can be modified: e.g. panel density, minimal height, spacing between rows, management of water runoff. Vegetation management practices can also be adjusted: e.g. delayed or extensive mowing, extensive grazing, reducing the use of herbicides, the introduction or maintenance of semi-natural elements (borders, hedges, grass strips, mineral surfaces). Increasing boundary fence permeability, via openings for small animals or strategic passages, is also a good way of limiting internal fragmentation. These options are frequently described as good practice, but their effects on wildlife have not been formally tested, apart from a few studies on arthropods. Other measures are more targeted. For instance, changing the optical properties of solar panels (via coating, texture, or markings) has been suggested to reduce the attractiveness of panels for polarotactic species. Specific measures can be considered to maintain or restore adjacent wetlands, or create thermal refugia and micro-habitats. Once again, most of these measures are presented as recommendations, but are seldom accompanied by robust before/after or treatment/control assessments.

Compensation measures are even more difficult to assess. For instance, the creation or "opening" of environments at the edge of solar parks, is sometimes presented as compensation for habitat loss. However, such actions can themselves reduce the structural complexity of the environment, carbon sequestration and certain ecological functions. Data are lacking to assess the actual ability of such measures to compensate for the impacts on biodiversity and associated ecosystem services.

Finally, several environmental monitoring tools exist or are being developed. BACI[4]-type protocols, synthetic ecological quality indices, and multi-taxon approaches have been developed to monitor plants, certain invertebrates, and habitat evolution. Their use remains variable, and results are still rarely pooled together.

In this context, the central issue is to reduce the discrepancy between the number of measures that are recommended and those that have actually been assessed. Good practice needs to be based on testable hypotheses that are integrated into project monitoring programmes. Through closer collaboration, developers, consulting experts, and research teams could jointly design measures, assess them using robust protocols, and share the data. In this way, management recommendations could become more solid and transferable and accompany in a credible way the development of solar energy.

[4] A **BACI-type (Before-After-Control-Impact) protocol** is an experimental protocol used in ecology to detect the impacts of a disturbance or a management measure. Conditions are compared before and after the intervention, at impact and control sites, enabling the specific effects of the action to be distinguished from natural variations.

This review highlights the fact that knowledge on the effectiveness of measures for mitigating the impacts of ground-mounted PV on biodiversity is still emerging. Our analysis shows that there is a limited number of publications on this topic and studies are very heterogeneous, both in terms of the context studied, the taxonomic group and type of measure considered, and the types of indicators used. This heterogeneity makes direct comparisons between studies difficult and does not allow, at this stage, for robust quantitative meta-analyses.

Our risk of bias assessment was based on a deliberately small number of criteria, as we were constrained by the deadline for this “rapid review”. Global ratings should be interpreted as a tool for comparing these studies, and not as an exhaustive assessment of their methodological quality.

These observations highlight the need for harmonized monitoring protocols, methodological transparency and data sharing to progressively consolidate the evidence base and improve the assessment of the actual effectiveness of implemented measures.

CONCLUSION OF THE RAPID REVIEW

Results of this synthesis show that knowledge on the effectiveness of measures for mitigating the impact of ground-mounted PV is still young, limited and biased. Nevertheless, several practical recommendations can be drawn.

In terms of research, it seems necessary to:

- **Investigate a greater diversity of contexts,** including different environments (arid, mediterranean, tropical) notably in French metropolitan and overseas territories.
- **Redress the taxonomic imbalance** by developing studies on pollinators, birds, bats, as well as on small and large mammals, reptiles and amphibians.
- **Test different types of measures** beyond surface treatments and habitat enhancement measures, e.g. vegetation management, boundary fence permeability, deterrence systems, infrastructure design and compensation measures.
- **Make assessment protocols more robust** by using, when possible, BACI-type approaches, multi-annual surveys, independent replicates and explicit consideration of confounding factors.

In terms of methodology:

- **More standardization** would be useful. Harmonizing protocols (sampling area, survey rate, response indicators) and reports (statistics, uncertainties, detailed description of methods) would make comparisons easier and allow for future meta-analyses.
- **More transparency regarding funding and conflicts of interests** as well as **sharing of raw data,** when possible, would reinforce confidence in the results and their re-use.

From a management point of view, it would be desirable to:

- Better **anchor assessments within the project themselves**. The implementation of a measure (e.g. vegetation management, adaptations to park design, solar panels and fences, compensation) is an opportunity to integrate a monitoring project with a suitable control. PV parks can thus become experimental field stations where measures can be tested and compared under real conditions at a marginal cost. This implies reinforcing the **collaboration** of developers, consulting experts, managers and researchers.

To this end, the **French Renewable Energy Trade Association (SER), the Solar Energy Trade Association (Enerplan), the French Environment and Energy Management Agency (ADEME) and Biotope** (an environmental consulting firm) (Bodez et al., 2023) recently produced a framework for future research on the interactions between PV and biodiversity. Conclusions were based on the shared diagnosis from scientific experts, developers and institutional representatives. Five environmental priorities were identified (**birds, bats, open habitats, functional wetlands, aquatic biodiversity**) and a **standardized protocol** was established to guide the implementation and analysis of monitoring systems. Emphasis was placed on the importance of **capitalizing on the data generated**, **designing robust indicators**, and **pooling efforts nationally**. This initiative is a step towards a more rigorous, transparent and operational assessment of the effectiveness of environmental measures. It provides an opportunity to implement, on a large scale, the recommendations from this review.

Finally, it is important to consider these recommendations within the wider context of the energy transition. The ground-mounted PV sector will continue to grow. The question is therefore not only of "reducing the impacts" on an ad hoc basis, but of building a **solid evidence base** for guiding the planification, design and management of solar parks towards solutions that benefit biodiversity. Accelerating and structuring the production of knowledge on the effectiveness of measures is a key condition for the sustainable coexistence of solar energy development and nature conservation.

EXPERT OPINION

In a collaborative effort to assess and improve the effectiveness of **measures for mitigating the impact ground-mounted PV installations** on wildlife, experts were invited to a meeting to discuss the results of this synthesis. This meeting enabled representatives of the PV energy sector (developers, consulting experts, trade associations such as *France Renouvelables* and the French Renewable Energy Trade Association), public bodies such as the French Office for Biodiversity (OFB) and the French Environment and Energy Agency (ADEME), and nature conservation bodies such as *France Nature Environnement* and the IUCN, to interact directly and exchange constructively on their experiences of PV energy projects. A written questionnaire was handed out to all participants and identified partners after the workshop.
The primary aims of the workshop and the questionnaire were:

- to get feedback on our knowledge synthesis and on mitigation practices: their practical implementation, their perceived effectiveness, and the obstacles encountered;
- to identify the needs in terms research, coordination, and regulation.

By combining the discussions of the meeting and the answers given in the questionnaire, this "Expert Opinion" section of the report presents the various viewpoints, identifies consensuses and disagreements, and contributes to the formulation of our final recommendations by providing a better understanding of the practices, constraints, and expectations in the field.

Selection and effectiveness of mitigation measures: between ecological continuity, habitats and vegetation management

A variety of measures depending on context

Workshop participants described a range of measures implemented in **PV power plants**, and more recently in **agrophotovoltaic systems**. These measures fall within the avoid-reduce-compensate framework and lead us to consider not only the environment around the power plant, but also within the park's perimeter.

These measures fall into several large categories:

- measures related to habitat continuity, e.g. by adapting fences and creating passages for wildlife;
- habitat conservation or creation: installing roosts for bats, ponds and hibernacula for amphibians and reptiles, nesting boxes for birds, and maintaining patches of natural habitats within solar farms;
- vegetation management through the selection of seed mixes (including local species), sowing methods and mowing practices.

The workshop highlighted the differences between ground-mounted PV power plants and agrophotovoltaic systems. In the latter, measures often came from the "mitigation measure toolkit" designed for PV power plants, even though the agricultural context has specific production, regulatory and technical constraints (e.g. requirements to eliminate certain weeds, transition to grazing systems, sensitivity of environments such as dry grasslands, production targets).

Broadly speaking, measure selection involves crossing species ecology, technical feasability, safety requirements (including fire safety and insurance) and the agricultural context, with the help of consulting firms and naturalist societies. The following sections describe the measures that were deemed to be the most effective, and those that seemed less suitable or problematic.

Measures considered the most effective for biodiversity

From this variety of practices, the opinion of several participants converged on one point: **certain measures have a positive effect on biodiversity**, even though we lack scientific perspective over the long term. Nonetheless, results from field monitoring over a five to six-year period suggest that some measures are particularly effective.

A first set of measures is centred on **fencing and wildlife passages**. Several developers have highlighted the value of using fencing with wider mesh spacing at the bottom and narrower mesh spacing at the top. This system is easy to set up during the construction phase and allows small animals, including hares and foxes, to move around more freely by creating passages through the fence. In certain solar parks where passages are close together, i.e. 10 cm high x 20 cm wide holes every 15 m, reports indicate that these openings are indeed used by rabbits and hares. Thus, passage density and distribution play an important role in the effectiveness of this measure.

Measures for preserving bat habitats are also regarded as conclusive. At one park, three underground roosts for small and large horseshoe bats were conserved, including one located in the middle of the park (surrounded by solar panels and a managed copse). Regular monitoring was carried out during the construction phase, with regular visits to the site, recordings taken at exits and motion sensor cameras placed at each entrance. Bats remained on the site during the construction phase and continued to visit the shelters after the park became operational. Artificial roosts for pipistrelles were installed at another site, after the demolition of buildings containing asbestos, and these were occupied during the first spring after their installation, which is strong sign that the measure was successful.

Feedback was also positive for the **creation of ponds and hibernacula for amphibians and reptiles**. Several experts mentioned that, when these features are “well made” and well positioned around the power plant, they work very well. For instance, the largest population of natterjack toads observed by one participant was found within a PV power plant in south-west France, right in the middle of the park. These solutions are relatively simple to measure (i.e. presence/absence) by observing whether these ponds are occupied or not by the target species.

Bird nesting boxes are also cited as an effective measure when they are placed in environments that lack natural cavities. One participant mentioned that nesting boxes were installed for European rollers in the south of France, in the garrigue where trees are small and there a few natural options for nesting. In this context, nesting boxes are a useful addition. However, the effectiveness of this type of measure seems to be highly dependent on the local context, especially on the quality of local habitats.

Another measure that is considered to have a positive impact on wildlife is the **conservation of habitats within a park’s perimeter**; i.e. certain areas are kept free of solar panels. Developers describe **patches of dry grassland or small copses** that are left intact within the park. In certain parks, these areas were monitored for five or six years, with the help of consulting experts. Results indicated a strong species presence, and even the presence of new species that take advantage of these habitats. These patches were described as the most biodiverse within the park, with notably open field bird nesting sites. They may act as “stepping stones” for wildlife across the park and are appreciated for their landscaping function and for offering the possibility of having patches of vegetation where mowing is delayed, while strictly managing vegetation everywhere else to meet fire regulations.

Finally, several participants mentioned the use of **local seed mixes as a vegetation management strategy**. The Conservatory of Natural Areas of Nouvelle Aquitaine *PictaGraine* programme is cited as an example. Seeds from local grasslands are harvested, and after selection are sown elsewhere. This method was initially devised for agricultural pastures but is now used in solar parks. Developers have combined this approach with the use of seed mixes with recognized certification such as the French Office for Biodiversity's (OFB) "*Végétal local*". This choice is more expensive than using standard seed mixes but is a good way of promoting local plant species, some of which are important for insects, such as the large blue butterfly, and reconstitute a flora that is coherent with the environment around the solar park. Another measure is to **sow over multiple years**, and ultimately harvest seeds produced on solar farms for sowing in other areas.

Overall, **feedback has highlighted that the measures considered to be the most effective are those based on the ecology of target species (shelter location, pond design, selection of conservation areas) and which take the local context into consideration**. They produce visible results in terms of species presence and are relatively easy to monitor, even if more precise indicators still need to be developed.

Reservations, ineffective or poorly adapted measures, or measures with undesirable effects

Discussions during the workshop also highlighted which **measures were considered ineffective, poorly adapted or with undesirable effects**, especially in the context of livestock management, vegetation management, and compensation.

Reservations regarding wildlife passages: several participants mentioned instances where small artificial passages, created in high numbers around the power plant, appeared to be rarely used. Images taken by motion sensor cameras showed that animals dug passages under the fence more frequently than they used the nearby 20 x 20 cm passages. This puts into question the real effectiveness of these small artificial passages, where they should be located, and whether this measure should be rolled out when it does not correspond to the behaviour of wildlife. Conversely, larger passages sometimes have undesirable effects. One developer described how fences were destroyed and important levels of wildlife intrusion (including game such as boars) occurred at certain solar parks near woodland areas. In these instances, there is a demand for dropping this measure, and putting up electrified fences instead. Participants spoke of a real dilemma between maintaining large passages, which lead to problematic intrusions, and small passages that significantly limit the type of wildlife that can access the park. These difficulties are considered particularly marked in agrophotovoltaic systems, where livestock is present inside the park. Several livestock farmers have expressed their concern regarding the intrusion of predators, which is facilitated by these large passages. Cases of lambs getting their heads stuck in the openings were also mentioned. Participants highlighted that this can be problematic for sheep-based agrivoltaic systems, especially as many of these projects are being developed.

Late vegetation management, often presented as beneficial for biodiversity, can create problems in certain conditions. Developers described "full-scale explosions" of invasive species, especially thistles, at power plants built on land that was already degraded and full of seeds from these species. Thistles can reach up to 1.5 m in height and may shade solar panels and render the area unsuitable for grazing as livestock refuse to go in highly invaded areas. Participants explained that the timing of intervention plays a crucial role here. Thistles can only be effectively managed from the start of May, when they have finished growing: earlier intervention would only increase their vigour. However, in some places, mechanical vegetation management is not allowed in spring and summer. In the first year, intervention was not allowed during that period, so thistles bloomed, and the situation became worse the following year. Participants associate these problems with the usual timetable for carrying out impact studies, which often excludes the entire period from March to August. This implies that most work is carried out in winter, on very wet ground, which significantly increases the risk of modifying the structure of the soil and thus soil-vegetation-wildlife interactions. Some consider that these timetables can, under these conditions, become "counter-productive" for the resilience of habitats.

As for compensation, opinions are guarded (see the sub-section "*Economic pressures and the weight of compensation in decision-making*" below). The framework for compensation is described as lacking in clarity, with requirements that are difficult to anticipate and that can change significantly after evaluation by the French National Council for Nature Conservation (CNCN). Developers stress that this uncertainty regarding the scale of the measures, on top of the significant costs involved, may **dissuade them from carrying out compensation actions, and makes it difficult to integrate ambitious biodiversity conservation measures**.

Finally, bird deterrence measures do not seem to be effective (bird habituation). The technical limitations of these systems were pointed out: they may detect large raptors, but not small passerines. No one at the workshop mentioned using these systems in solar parks. In addition, participants pointed out that, in other sectors (agriculture, aviation), if deterrence did really work, it would be more evident. Moreover, they estimate that bird collisions with solar panels is probably very anecdotal, and technicians on site do not report regular instances of such collisions. For them, it would be necessary to quantify this impact before installing a deterrence system that could cause much disturbance, especially during the breeding season. Some consider that vegetation management and its effect on insects and other animals is a much greater priority than bird deterrence.

Overall, feedback showed that certain measures, despite being designed to have a positive impact, may turn out to be ineffective or pose significant problems when they are poorly adapted to local contexts, especially in the context of agrivoltaics, vegetation management or compensation. The following sections aim to explain how these observations relate to the methodological limitations of impact studies and the difficulties encountered in the field.

Difficulties in documenting effectiveness: methodological limits and scattered data

Heterogeneity of monitoring protocols and low comparability of results

The feedback described in the first section suggests that some measures seem to work well in the field. However, when it comes to the rigorous assessment of their effectiveness, participants immediately pointed out a **major obstacle**: **the absence of a common monitoring framework and protocols that vary from one project to the next.**

Indeed, to this day, there is no standard monitoring methodology across the PV sector. Monitoring is carried out using very different approaches, with **indicators, frequency and methods that vary from one consulting firm to the next**, from one taxon to the next, and from one project to the next. Put side to side, the results obtained by different developers for the same species cannot be analyzed together in a robust scientific way. This is viewed as one of the “big black spots” for PV systems. Protocols themselves change over time. The methods used in 2018 are not quite the same as those used in 2023. Without continuity over at least ten or fifteen years, it is difficult to uncover any well-supported trend. Even for taxonomic groups such as amphibians where indicators are more standardized, we find that each research group has its own “way of doing things”. For other taxonomic groups, especially birds, heterogeneity is very high. This contrasts with the situation for onshore wind energy, where legal constraints and protocols have had a clear framework for years. Meanwhile, the PV sector is just coming out of a phase of rapid expansion, and practices are less homogeneous. **Harmonizing monitoring protocols is now recognized as a central need** but largely remains to be carried out. In this context, the sector asks for a clear and structured monitoring framework. A common protocol remains to be defined in terms of materials, methods, frequency and indicators, for each taxonomic group. **Without this common framework, results will not be exploitable beyond the level of individual projects and comparisons between solar parks or regions will remain limited.**

Limitations are not only related to data gathering in the field, but also to the **treatment of data**. Developers send their reports to relevant government departments, but these lack the means to systematically analyse these data. **Data are deposited but seldom used beyond that. Project managers lack feedback on the real effectiveness of measures or on possible adaptations. The idea of a national database is therefore frequently mentioned.** This database would centralize results, allow the study of the cumulated impacts of solar parks, and allow for information to be drawn from the entire set of monitoring studies. At this stage, this does not seem feasible: data are neither structured nor open to allow for this type of synthesis. Moreover, experience from the wind energy sector shows that the existence of a platform is not sufficient if data are not standardized or exploited.

Recent initiatives aim to improve data structure. The BIODIVoltaïque project aims to provide a standard monitoring and analysis framework from collected data. The Renewable Energy Observatory (Observ'Er), alongside the French Office for Biodiversity, ADEME and other partners, have started playing a role as a resource centre, even if allotted means are considered insufficient and their production rate is still slow considering expectations.

Overall, we find that there is a marked difference between the mass of data produced and the ability to extract consolidated knowledge. As long as protocols remain variable and bringing together and exploiting data remains difficult, assessments of measure effectiveness will remain incomplete and fragile.

Difficulties setting up BACI-type protocols and control sites

Beyond protocol heterogeneity is the question of using more robust protocols such as BACI[5]-type protocols. There again, workshop participants describe important obstacles.

BACI protocols require a control site that is comparable to the project site but is free from any installation. In practice, this involves identifying and mobilizing more land, in addition to the land already used for the project and for compensation. In areas where **land is limited**, this requirement directly competes with the need for compensation and makes having a real control site very difficult.

In addition, there are **financial and organizational constraints**. Setting up and monitoring a control site requires additional manpower and financial investment, at a time when budgets and schedules are already tight. Initial inventories may be carried out four to five years before the power plant comes into service. In the meantime, the context may change, priorities may evolve, and it becomes difficult to maintain a coherent BACI protocol over the course of the project. Some consider that obtaining something that is "really scientific" is very difficult under these conditions.

There is also the question of site access, although this depends on the site. Access to PV power plants is generally granted to researchers and consulting experts, within the usual safety limits. However, areas chosen for compensation may be far away or in locations that are hard to get to, and monitoring these sites on a regular basis becomes difficult.

Finally, the treatment of data remains unsatisfactory. From the developers' point of view, they send their reports to the relevant government departments, but these lack the means to exploit them. The data exist; they are deposited but not really analysed or integrated within the logic of structured BACI protocols.

Overall, these constraints (land availability, costs, schedule, site access, data treatment) strongly limit the possibility of implementing complete BACI protocols that are comparable from one project to the next.

Temporality differences between industry and research

The limitations related to monitoring or research protocols are part of a bigger problem: the timelines of industry and research rarely coincide.

On the one hand, developers can seldom guarantee two years in advance that a park will effectively be built. Between financial issues, directives, local constraints and appeals, a site that is

[5] A **BACI-type (Before-After-Control-Impact) protocol** is an experimental protocol used in ecology to detect the impacts of a disturbance or a management measure. Conditions are compared before and after the intervention, at impact and control sites, enabling the specific effects of the action to be distinguished from natural variations.

monitored by researchers may never be developed. Research teams spend time over the course of a year monitoring a site but end up with data that cannot be used.

This difference in timing is also noticeable in the management of soils and vegetation. Requests to sow seeds can be made several years before the creation of a solar park, sometimes three to four years in advance. This represents a financial risk on unsecured sites and makes planning more complicated. In any case, the first year of operation is a post-construction “healing” phase, with potholes and degraded soils. In agrivoltaic projects, early intervention also implies changing the farming system, which compounds the difficulty.

On a scientific level, current efforts focus on studying the impacts of PV power plants (on bats, birds, wetlands, soils...). Programmes such as ENVoltaïque are mentioned, with the objective of obtaining a clear picture of the main effects by 2030. It is not a question of considering that these studies are sufficient or abandoning the idea of carrying out new studies on the impacts of PV projects, but of avoiding a situation where we would wait to have “complete” knowledge before shifting our attention to **mitigation measures**. On the contrary, it is argued that we should progressively rely on a few robust studies (from France and elsewhere) and at the same time initiate the assessment of mitigation measures (i.e. what works and what does not) and compare science-based and practical recommendations that are already applied by developers.

Another recurring issue is that of collaboration between research and industry. A common framework already exists, for example, in the wind energy sector, and is discussed during the biennual Conference on Wind Energy and Wildlife Impacts, which brings together researchers, consulting experts, wind energy developers, NGOs and public bodies on the topics of methods, tools and experiences related to the impacts of wind installations on wildlife. However, this requires a mutual engagement: each party must be willing to “meet halfway” and formulate practical questions and research priorities.

Finally, the ability to carry out research very much depends on the political and economic future of PV energy. A marked slowdown, or even a moratorium, would have a direct effect on the possibility of funding research programmes, gaining access to parks, and maintaining jobs in the sector.

In this context, collective systems are already in place. In particular, the Renewable Energy Observatory (OER; *Observatoire des Energies Renouvelables*) and large research programmes play a key role in coordinating these temporalities and structuring the production of knowledge, as described in the following sub-section.

Obstacles and arbitrations: reconciling biodiversity, fire prevention, agriculture and other uses

Fire prevention as a constraint

Alongside issues related to data and protocols, there are also very practical constraints, one of them being fire prevention. **Legal requirements to clear out excess vegetation (OLD; *obligation légale de débroussaillement*), issued by local fire and rescue services (SDIS; *Service Départemental d’Incendie et de Secours*) and often carried out by the National Forests Office (ONF; *Office National des Forêts*), have a direct impact on the design and management of measures for mitigating the impact of PV installations on wildlife.**

In certain *départements* such as Gironde, the interpretation of OLDs is very strict: the vegetation around solar power plants must be almost entirely removed. There have been instances where legal notices have been issued by the ONF, and mandated by the SDIS, to cut patches of wild vegetation that were close to the fence but outside the park on the grounds that they represent a fire risk for the solar farm and the nearby woodlands.

Checks carried out by the SDIS and the ONF at existing solar parks sometimes lead to requests to terminate some of the environmental measures already in place. These measures do work (return of wildlife, habitat creation) but are considered to pose too great a fire risk. When project managers turn to the administration, they are faced with a complicated administrative process: submitting an application to modify the authorization (including a protected species exemption (DDEP; *dossier dérogation espèces protégées*), and passing in front of the French National Council for Nature Conservation (CNCN; Conseil National de Protection de la Nature), to either remove certain measures or put compensation measures in place.

This situation creates **conflict** between on the one hand, government-issued orders and recommendations for fire prevention, which is considered a priority ("fire risk is the number one priority"), and on the other hand, the commitments made to restore or maintain habitats. **Developers are "stuck in the middle", without always knowing which one should come first.**

The interministerial order on OLDs, which is supposed to better reconcile the needs for fire prevention and biodiversity conservation, needs to be translated at the regional and/or departmental level. However, this has not been done everywhere nationally, and in areas where this adaptation is lacking, SDISs continue to request the strict application of OLDs that are not compatible with the conservation of patches of vegetation or woodlands.

In this context, certain practices seem like a compromise: maintain patches of late-cut vegetation in areas without solar panels and apply more intensive vegetation management practices elsewhere to meet fire prevention requirements. This allows the maintenance of areas for wildlife while limiting conflicts with the demands of SDISs.

Agrivoltaics: reconciling agricultural production and environmental conservation

The tensions around fire prevention mentioned above are compounded in agrivoltaic systems by strong contraints related to agricultural production. Agrophotovoltaic projects must in general guarantee a limited loss of yield, usually < 10 % less than initially. This requirement weighs directly on the scale of the environmental measures and on the amount of leeway given to operators.

In addition, there is the regulatory obligation to control certain plant species, especially thistles. The removal of these plants is mandatory for farmers. In effect, this leads to carrying out interventions during the bird breeding season, or at times that are not compatible with recommendations for late mowing to promote biodiversity.

The farming calendar (grazing, mowing, crop rotations) does not always coincide with the best periods from an environmental point of view. On land converted to pastures, including dry grasslands, certain practices can harm the environment, even though these habitats are known to be sensitive. Livestock farmers also have their own financial constraints (rearing costs and production targets), which limit the possibility of adjusting practices to the timing of events in the wild.

Another recurring point is having to resort to the same "measure bank" as ground-mounted PV projects, for which these measures were designed. Consulting firms often suggest the same measures for ground-mounted PV and agrivoltaic projects (wildlife passages, vegetation management, various adaptations), **without adapting these to the specificities of a farmed plot of land**: the presence of herds, the movement of farming equipment, maintenance constraints. These measures are sometimes found unsuitable or hard to implement in the long run.

Thus, agrivoltaics is at the intersection of two systems of constraints: that of the energy sector and that of the farming sector. The compatibility between agricultural production, regulatory requirements and environmental targets is one of the major hurdles for deploying ambitious measures that are beneficial to biodiversity in these projects.

Multiplicity of actors and contradictory demands

Tensions in agrivoltaics are not only related to land management and farming practices. They come about within a landscape where **a multiplicity of actors intervene on the same project: the fire and rescue service (SDIS), the national office for forests (ONF), government agencies, the farming sector, hunters, preventive archaeology services, insurance companies, and even the army. Each has their own framework, priorities and calendar.**

In the field, developers are not in control of all the decisions. Livestock farmers can for instance decide to “clear out” a patch of vegetation in the height of summer, because they consider the power plant “not clear enough”. This type of initiative can easily be at odds with current or future environmental measures at the site.

Insurance constraints add another complication, especially in agrivoltaic systems. Insurance companies are reluctant towards certain configurations combining PV installations, animals and the presence of vegetation. Biodiversity measures must remain compatible with the agricultural project and the practices of the farmer, as well as the requirements of the insurance company, so that there is even less leeway.

The local dimension reinforces the impression that there is a patchwork of rules. There are many scattered services, and some do not take part in the dialogue with the sector even though they are invited. **The feeling is that of a sector that “shows a lot of goodwill”, but cannot, on its own, solve the contradictions between the targets for energy, biodiversity, agriculture, fire prevention, archaeology, and defence.**

Financial pressures and the weight of compensation in arbitration

In addition to the demands of fire prevention and agriculture, and the multiplicity of actors, there are also strong financial pressures, in particular related to environmental compensation.

The framework for compensation measures is described as unclear. Anticipating the scale of these measures is difficult, e.g. prospection radius, land availability, and possible actions are poorly framed from the start. After passing in front of the French National Council for Nature Conservation (CNCN), project holders, who felt their proposal was adequate, may be told that the land surface area needed for compensation must be doubled, even though the criteria for this remain unclear.

Situations of “double compensation” were mentioned. For instance, the cutting down of a pine forest to restore open environments may itself imply compensation for the loss of woodland. Costs therefore accumulate: environmental measures on the one hand, compensation for the loss of woodland on the other. **In some cases, the cost of compensation can be very high, in the range of several millions of euros for moderately sized projects.**

Such uncertainties and costs weigh directly on the decision-making process. Indeed, **ambitious biodiversity measures become difficult to sustain when compensation requirements fluctuate and may have a disproportionate cost impact on these projects.**

Unifying practices and capitalization efforts: towards a “standardized” design of PV power plants

Standardization of monitoring practices: a summary of the needs

The observations laid out in section II highlight a clear need for a shift from the current patchwork of monitoring practices to a harmonized process. We have seen that, currently, there no common monitoring methodology within the PV sector, and a lack of protocols that are stable over time.
Expectations can be summarized by the following points:

- put in place a standard monitoring framework for each taxonomic group, with harmonized indicators, frequency, and methods;
- ensure that these protocols remain stable over time to allow the detection of trends over a 10 to 15-year period;
- have a national database of monitoring data (implemented measures, results) to compare different sites, regions and types of projects, and investigate cumulated effects.

Without these three elements, monitoring data can only be exploited at the scale of each individual project, and the sector cannot really capitalize on the full range of past experiences.

Eco-design guides and training programmes

Several avenues are already being developed:

- the production of an eco-design guide for solar farms by the REMEDE team under the aegis of the Renewable Energy Observatory (OER). A post-doctoral researcher is responsible for reviewing the available measures and organizing workshops for consulting experts and developers.
- the use of existing guides such as the PIESO guide, which are already used in the sector for avoid-reduce-compensate measures but are considered preliminary and require a stronger scientific basis.

In addition to such guides, there is also a need for training programmes: the development of an OFB training course on "photovoltaics and biodiversity", modelled on the existing "bats and wind energy" training course, is being considered. The aim is to diffuse knowledge more widely and better connect scientific evidence, operational practices and experiences in the field.

Steer R&D towards the effectiveness of measures and soil resilience

Alongside guides and training courses is the question of **research orientation**: what should research focus on over the next few years?

Several large research programmes are currently focusing on the impacts of solar farms on birds, bats, wetlands, and soils. The aim is to produce a solid enough knowledge base on these effects by around 2030.

The next step would be to shift research efforts towards the comparison of mitigation measures and their effectiveness. Possible avenues for research include:

- the influence of panel height and row spacing on habitats and wildlife movement;
- soil restoration and conservation (pedology, infiltration, erosion, post-construction compaction);
- measures benefitting pollinators and small animals, in relation to vegetation composition;
- vegetation management in agrivoltaic systems, taking into consideration agricultural and insurance constraints.

The idea is **not increase indefinitely the number of general studies on the impacts of PV systems, but to rely on a few robust studies, from France and elsewhere, to develop R&D to compare the effectiveness of different measures and the assess capacity of PV projects to maintain or improve the resilience of soils and habitats.**

The role of collective bodies and state services for a clearer trajectory

Steering R&D and producing guides cannot be sufficient without the action of collective bodies capable of ensuring their capitalization. This is role played by the **Renewable Energy Observatory (OER), and more generally, by state services.**

Regarding the OER, the message is clear: projects are initiated (synthesis work, reflections on eco-design, analysis of impact studies) but the human and financial means are insufficient. Without reinforcement, the OER will deliver below expectations, with unexploited data and slow capitalization.

Regarding the state and its services, the expectations are as follows:

- make compensation requirements clearer and more stable (scale, criteria, how these areas fit in with woodland areas);
- improve the coherence between biodiversity/fire prevention/farming requirements, via the translation of the interministerial order on vegetation clearing obligations (OLD) at the regional and departmental level;
- play an active third-party role: analyse monitoring data, provide structured feedback to project holders, and contribute to spaces of dialogue.

The aim is to have a clearer framework that secures the commitments made, avoids late reassessments of measures that were considered to be effective, and allows the sector to project itself into the future with a clear set of common rules.

Conclusion of the collaborative stage: PV power plants as an opportunity for open environments

Discussions showed that PV power plants may harbour biodiversity. Several measures work well and transform these sites into structured, and sometimes improved, open environments. This is the case for conserved or restored patches of vegetation within the park's perimeter, which often contain more biodiversity, with nesting sites and the establishment of new species. Similarly, the management of vegetation mosaics, inspired by certain vegetation clearing measures (OLD) (as in the Occitanie or Provence-Alpes-Côte d'Azur regions), can create environments that are more "interesting" than very closed forests or intensively cultivated fields, when local regulation allows it.

A number of "no regret" measures were highlighted, e.g. prefer avoidance (not siting PV power plants in sensitive areas) over compensation, maintain refugia, create ponds, shelters and hibernacula if they correspond to a species' ecology that is well-documented, consider vegetation as a support for habitats and act accordingly, etc. Conversely, other measures appeared less of a priority or maladaptive: artificial wildlife passages that are rarely used, deterrence (the effectiveness of which is in doubt considering the disturbance it causes), generic measures that are ill-suited to the PV context, costly compensation measures with debatable benefits. The question is not to pile on measures, but to better rank these according to their actual ecological benefit.

In parallel, several obstacles were mentioned: monitoring protocol heterogeneity, scattered data, difficulties associated with carrying out BACI-type protocols, differences in temporality between industry and research projects. To these are added the constraints linked to fire prevention (strict application of OLDs in certain *départements*), insurance requirements, conflicts between agriculture, biodiversity and safety, and the economic weight of compensation in the total cost of a project. These tensions can lead to abandoning measures that have worked in the past, or to having less leeway during the operational phase.

Possible solutions were clearly formulated. They involve:

- the creation of harmonized monitoring protocols and a national database, which would allow the comparison of results from different parks and help derive knowledge from the mass of data already produced;
- the production of eco-design and technical guides (ecovoltaics, REMEDE, PIESO), based on the literature and field experience;
- upskilling via dedicated training courses on "photovoltaics and biodiversity";
- steering R&D towards comparing the effectiveness of mitigation measures, using evidence from current large-scale programmes, and pilot sites, notably in agrivoltaic systems.

In this landscape, **the Renewable Energy Observatory (OER) and state services occupy a pivotal role.** The OER already has a range of projects (impact study analyses, ecovoltaics guide, reflection on the standardization of monitoring practices) but still lacks the means to meet sector expectations. State services are expected to bring clarifications regarding compensation requirements, improve the coherence between biodiversity, fire prevention, agriculture, and wetland management, and provide an explicit and stable framework.

The workshop ended on a lucid and constructive note. Lucid, because the trajectory of photovoltaics remains dependent on political choices, which will determine the resources available for research and the ability of industry players to invest in mitigation measures. Constructive, because all agree on the value of these exchanges, the willingness to work together, and the potential of solar farms to be a place where we can learn collectively. The idea is that by **combining avoidance, eco-design, fine-scale management of open environments, and a common monitoring framework, PV power plants can become, in an increasing number of cases, an opportunity for open environments** rather than a systematic threat.

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APPENDIX I: METHODS

Bibliographic reference search strategy

Key words and search equations

To meet our objectives, we combined all terms related to ground-mounted photovoltaic systems, fauna, mitigation measures, and results. Two search equations were defined: one for aerofauna and one for terrestrial fauna. Final search equations were constructed as follows in the Web of Science Core Collection (WOSCC) search engine:

TS= ((insect$ OR invertebrate$ OR butterfl* OR moth$ OR lepidoptera OR dragonfl* OR odonata OR avifauna OR aves OR avian OR bird$ OR passerine$ OR raptor$ OR vulture$ OR owl$ OR piciforme$ OR columbiforme$ OR passeriforme$ OR falconiforme$ OR bat$ OR chiroptera) AND (photovoltaic$ OR "solar energ*" OR "solar farm$"OR "solar panel$" OR "solar plant$" OR "solar park$" OR "solar array$" OR "solar power" OR "solar installation$" OR conservoltaic OR agrivoltaic) AND (evaluat* OR solution$ OR mitigat* OR assess* OR option$ OR measur* OR priorit* OR reduc* OR avoid* OR compensat* OR minimiz* OR adapt* OR interven* OR action$ OR manag* OR protect* OR manipulat* OR counteract* OR removal OR engineer* OR plan* OR strateg* OR offset* OR "flight divert*" OR "attract* remov*" OR "m?cro-siting" OR deterr* OR "habitat restoration$" OR "habitat enhancement$" OR "habitat creation$" OR "ecological engineering" OR "site selection$" OR "displacement$" OR "buffer zone$") AND (impact* OR effect* OR collision$ OR behavio*r OR aversion$ OR repulsion$ OR disturb* OR mortalit* OR fatalit* OR carcass* OR "glass reflection" OR "reflective surface$" OR "light pollution"OR "population size$" OR "population densit*" OR abundance OR occurrence OR "habitat loss*" OR "habitat fragmentation$" OR "habitat degradation$" OR "breeding success" OR nesting OR reproduct* OR "site fidelit*" OR richness OR composition OR surviv*))

TS= ((reptiles$ OR amphibian$ OR frog$ OR arthropod$ OR arachnid$ OR gastropod$ OR mammal$ OR rodent$ OR lagomorph$ OR hedgehog$ OR ungulate$ OR carnivore$ OR canid$ OR felid$) AND (photovoltaic$ OR "solar energ*" OR "solar farm$"OR "solar panel$" OR "solar plant$" OR "solar park$" OR "solar array$" OR "solar power" OR "solar installation$" OR conservoltaic OR agrivoltaic) AND (evaluat* OR solution$ OR mitigat* OR assess* OR option$ OR measur* OR priorit* OR reduc* OR avoid* OR compensat* OR minimiz* OR adapt* OR interven* OR action$ OR manag* OR protect* OR manipulat* OR counteract* OR removal OR engineer* OR plan* OR strateg* OR offset* OR "flight divert*" OR "attract* remov*" OR "m?cro-siting" OR deterr* OR "habitat restoration$" OR "habitat enhancement$" OR "habitat creation$" OR "ecological engineering" OR "site selection$" OR "displacement$" OR "buffer zone$") AND (impact* OR effect* OR collision$ OR behavio*r OR aversion$ OR repulsion$ OR disturb* OR mortalit* OR fatalit* OR carcass* OR "glass reflection" OR "reflective surface$" OR "light pollution"OR "population size$" OR "population densit*" OR abundance OR occurrence OR "habitat loss*" OR "habitat fragmentation$" OR "habitat degradation$" OR "breeding success" OR nesting OR reproduct* OR "site fidelit*" OR richness OR composition OR surviv*))

All search equations used for each query of search engines, bibliographic databases, and specialized websites are given in Appendix II.

Shortcuts and limitations

Only terms in English were included in the search queries. However, selected publications were either in English or in French, in accordance with the team's language skills. No restrictions on the date or geographic area were applied to database searches.

Literature sources

Only one bibliographic database was queried using the search equations given above: the Web of Science Core Collection database, which was available to the authors of this review via the French National Research Institute for Sustainable Development (IRD). Searches were carried out in the following citation indexes: SCIEXPANDED, SSCI, AHCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, and IC.

Four additional searches were carried out in:

- Google Scholar (https://scholar.google.com/). We used the Publish or Perish (v6) software to retrieve citations. Because of restrictions on the number of characters, the search equations were simplified. Moreover, we prioritized academic publications, limiting each sub-search to the first 50 results, as it has been shown document relevance decreases rapidly after that (Haddaway et al., 2015).

- Bielefeld Academic Search Engine (BASE) (http://www.base-search.net). As with Google Scholar, because of restrictions on the maximum number of characters, the search equations were simplified.

We manually searched the following five websites for relevant technical documentation:

- The International Renewable Energy Agency (IRENA): https://www.irena.org/
- The International Energy Agency (IEA): https://www.iea.org/
- The US Office of Energy Efficiency and Renewable Energy: https://www.energy.gov/eere/office-energy-efficiency-and-renewable-energy
- La Libraire «Énergies renouvelables, réseaux et stockage», Agence de la Transition Écologique (ADEME) https://librairie.ademe.fr/2889-energies-renouvelables-reseaux-et-stockage
- La page «Documentation et rapports», France Renouvelables : https://www.france-renouvelables.fr/documentation-et-rapports/

As we expected the total number of articles to be relatively low, we also examined "by hand" the references from three recent systematic review papers:

- 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.
- Gómez-Catasús, J., Morales, M. B., Giralt, D., del Portillo, D. G., Manzano-Rubio, R., Solé-Bujalance, L., Sardà-Palomera, F., Traba, J., & Bota, G. (2024). Solar photovoltaic energy development and biodiversity conservation: Current knowledge and research gaps. *Conservation Letters*, 17(4), e13025.
- Lafitte, A., Sordello, R., Ouédraogo, D. Y., Thierry, C., Marx, G., Froidevaux, J., Schatz B., Kerbiriou C., Gourdain P.& Reyjol, Y. (2023). Existing evidence on the effects of photovoltaic panels on biodiversity: a systematic map with critical appraisal of study validity. *Environmental Evidence*, *12*(1), 25.

In addition, we explored grey literature (brochures, technical reports, institutional guidebooks and documents) to identify potential sources of scientific information or practical experience on measures for mitigating the impact of ground-mounted PV installations on biodiversity. Several recent documents in French were examined:

- Kraaijenbrink, M., & Dixon, R. (2024). Photovoltaïque & biodiversité : Concilier accélération et préservation [Brochure]. France Renouvelables.
- I Care & Consult & Biotope. (2020). Photovoltaïque et biodiversité : exploitation et valorisation de données issues de parcs photovoltaïques en France. Rapport final.
- Bodez, J., Bourgogne, P., Cerqueus, D., Dupin, A., Renier, S., Neveux, G., Fraix, J., & Ziadi, C. (2023). Programme « Photovoltaïque et Biodiversité « : Identification des questions scientifiques à adresser et estimation des moyens pour y répondre. 51 p.
- Agence de la transition écologique (ADEME) & Office français de la biodiversité (OFB). (2023). Photovoltaïque, sol et biodiversité : Enjeux et bonnes pratiques [Brochure]. ADEME Éditions.
- UICN Comité français. (2023). Améliorer la prise en compte de la biodiversité dans la planification et la conception des projets éoliens et photovoltaïques : retours d'expériences et identification de bonnes pratiques en France métropolitaine.
- Marx, G. (2022). Centrales photovoltaïques et biodiversité : synthèse des connaissances sur les impacts et les moyens de les atténuer. LPO, Pôle Protection de la Nature.

These documents, whose purpose is mainly to raise awareness and disseminate good practice, combine general knowledge and practical experience. In some cases, examples of sites are given, however, descriptions of the methods and results are generally insufficient to include these in our analysis (lack of quantified data, no quantitative indicators, effects described from a combination of measures so that it is not possible to determine the effect of a specific measure).
An additional search was carried out to try to identify technical reports or monitoring studies associated with these examples. However, we could not find any report that was sufficiently documented within the deadline for our review.

Estimate of search exhaustivity

To ensure the relevance of the search and a certain level of exhaustivity, an iterative process was carried out to "calibrate" the search equation to a predetermined list of 6 reference articles (hereafter, the "test list"). This "test list" comprised articles from relevant scientific journals previously identified by the team. We tested different keyword combinations and checked that the reference articles were retrieved. If articles from the "test list" were missing, keywords were added to improve search sensitivity until all articles were retrieved.

Criteria for article eligibility and study selection

Screening was carried out over two stages: 1) from "titles and abstracts", and 2) from "full texts". We assessed the relevance of retrieved articles using a set of inclusion and exclusion criteria (Table 2). When selecting from titles and abstracts, if the presence of an inclusion criterion was in doubt (or if the information was missing), the article in question would automatically be included in the next stage of the selection process. The documents that were retrieved manually from specific websites or systematic review papers were assessed solely from the full text. To ensure the consistency and reproducibility of these decisions, the reliability of agreement between the different raters was compared using a Kappa test at the start of each selection stage (APPENDIX III).

Table 2. List of eligibility criteria used for the selection of documents from "titles/abstracts" and "full texts".

PICO Criteria		Description	Definition(s)
Inclusion criteria	Eligible populations	All vertebrates and invertebrates (i.e. all species of small and large terrestrial and flying mammals, birds, terrestrial and flying insects, reptiles, amphibians, gastropods) affected by ground-mounted PV installations.	Wild species – i.e. species freely occurring in natural environments (*in situ*) or wild species used in laboratories (*ex situ*). All non-domesticated species.
	Eligible interventions	Mitigation measures to avoid, minimize and compensate the impacts of ground-mounted PV installations on wildlife.	Mitigation solutions for minimizing the negative impacts of ground-mounted PV installations on wildlife.
	Eligible comparators	Studies that have spatial or temporal comparisons.	"Before/after", "control/intervention", and "before/after/control/intervention" studies
	Eligible effects and measures	All relevant measures and results showing the effect of a mitigation measure.	Quantification of: variation in population size or density (e.g. abundance, species richness, activity indices); mortality or collision (e.g. carcass counts, collision frequency); behavioural changes (e.g. site avoidance, changes in flight activity, altered flyways or spatial occupation); functional or physiological responses (e.g. reproductive success, stress, feeding); effects on habitat connectivity or habitat use (e.g. crossings, corridor use, occupation of compensatory habitats).
Exclusion criteria	Ineligible populations	Flora	Plant species are not included in this review.
	Ineligible interventions	Measures not focused on the avoidance, reduction or compensation of negative impacts.	Any intervention that does not aim to minimize the negative impacts of ground-mounted PV installations on populations, either through actions put in place directly at the solar farm, or by measures taken before, after, or in parallel of their operation.

	Ineligible results	Studies that do not study abundance, species diversity, mortality, collisions, behaviour, etc.	All non-relevant results that do not allow interpretation of decreased abundance or diversity, mortality, collisions, avoidance, etc.

Critical appraisal: assessing study validity

We carried out the critical appraisal of both internal (i.e. the risk of bias[6] linked to different factors) and external (i.e. relevance and generalizability (Haddaway *et al.*, 2020)) validity. A series of criteria were predefined using the CEE's Critical Appraisal Tool. Each study was ranked for each criterion as having a "weak", "moderate" or "strong" risk of bias. Each criterion was weighted ("weak" = 1, "moderate" = 0.5, "strong" = 0) in order to calculate a global risk of bias coefficient, which allowed studies to be classified according to their global risk of bias rating ("very weak", "weak", "moderate", "strong", "very strong"). Before doing the full critical appraisal, "test phases" were carried out to check that criteria were understood and interpreted in the same way by our different raters (AQ, JL and LD). For each research article, we assessed its robustness, notably in terms of the method for site selection, the number of replicates (and pseudo-replicates), and the sampling and analysis methods (see Appendix IV for more details). When the objective assessment of a given criterion was not possible due to a lack of information, the risk of bias was automatically rated as "strong".

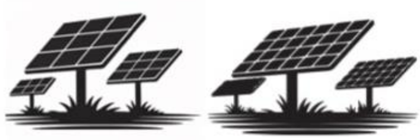
Narrative synthesis

To analyse and visualize the trends in the literature, data was extracted in a standard way from the selected documents. References were examined to identify the case studies in each. Following the methodology for systematic mapping of environmental sciences (see James *et al.*, 2016), a case study represented a single result associated with a single intervention (i.e. a mitigation measure) from a single population (i.e. a single species or a group of species). When multiple case studies were extracted from the same article, each was recorded as a unique entry in the Excel spreadsheet with the corresponding metadata. Crossing these key variables of the metadata (e.g. taxonomic group x solutions x results), the figures and tables of the synthesis were produced to identify research gaps (sub-themes that need additional primary research). Thus, the distribution and frequency of the studies on mitigation measures were described, for example using heatmaps.

After the production of figures to visualize the metadata of interest, we produced a written report summarizing, for each type of measure, each available study including their main results and context. Each section ends with a brief general summary, highlighting the trends we observed. The qualitative descriptions of the studies, their methods, limitations, and specific contributions, provide context for the quantitative results shown in the figures. They contribute to a better understanding of the conditions under which measures may be effective, potentially mixed results depending on the context, and points of convergence or divergence between the studies. This section is followed by a general discussion of the results, highlighting the main trends, knowledge gaps and potential biases in this set of publications. It also explores how these observations can guide future research and the formulation of operational recommendations.

[6] **Risk of bias** is the likelihood that certain characteristics of a study influence the results in a systematic way, leading to conclusions that deviate from the truth. Bias can arise from methods for data gathering and site selection, or from analyses that are not completely impartial or rigorous. Risk of bias can affect the validity and reliability of results in a study.

Table 3. The different types of comparators used during the extraction of metadata. Created with free images from Vecteezy.

Type d'étude de comparaison	Exemple illustré		Exemples d'études comparatives
	Groupe contrôle	Groupe intervention	
Amélioration habitat – mesures en faveur de la biodiversité			• Implantation de prairies fleuries • Ajout de haies, de bosquets, d'arbres, … • Restauration de sols dégradés
Gestion de la végétation – pâturage			• Pâturage par moutons et ânes
Traitements surfaciques des panneaux visant à limiter l'effet « miroir/lac »			• Ajout de différents motifs de grillage • Ajout de verres antireflets mats • Ajout de revêtements polymères microtexturés
Modification de la conception des infrastructures			• Panneaux à suivi solaire
Dissuasion acoustique			• Emission de sons durant la journée

APPENDIX II: SEARCH EQUATIONS USED IN THE LITERATURE SEARCHES

Full search equations used with the Web of Science Core Collection (WOSCC):

• *Aerofauna search equation:*
TS= ((insect$ OR invertebrate$ OR butterfl* OR moth$ OR lepidoptera OR dragonfl* OR odonata OR avifauna OR aves OR avian OR bird$ OR passerine$ OR raptor$ OR vulture$ OR owl$ OR piciforme$ OR columbiforme$ OR passeriforme$ OR falconiforme$ OR bat$ OR chiroptera) AND (photovoltaic$ OR "solar energ*" OR "solar farm$"OR "solar panel$" OR "solar plant$" OR "solar park$" OR "solar array$" OR "solar power" OR "solar installation$" OR conservoltaic OR agrivoltaic) AND (evaluat* OR solution$ OR mitigat* OR assess* OR option$ OR measur* OR priorit* OR reduc* OR avoid* OR compensat* OR minimiz* OR adapt* OR interven* OR action$ OR manag* OR protect* OR manipulat* OR counteract* OR removal OR engineer* OR plan* OR strateg* OR offset* OR "flight divert*" OR "attract* remov*" OR "m?cro-siting" OR deterr* OR "habitat restoration$" OR "habitat enhancement$" OR "habitat creation$" OR "ecological engineering" OR "site selection$" OR "displacement$" OR "buffer zone$") AND (impact* OR effect* OR collision$ OR behavio*r OR aversion$ OR repulsion$ OR disturb* OR mortalit* OR fatalit* OR carcass* OR "glass reflection" OR "reflective surface$" OR "light pollution"OR "population size$" OR "population densit*" OR abundance OR occurrence OR "habitat loss*" OR "habitat fragmentation$" OR "habitat degradation$" OR "breeding success" OR nesting OR reproduct* OR "site fidelit*" OR richness OR composition OR surviv*))

•*Terrestrial fauna search equation:*
TS= ((reptiles$ OR amphibian$ OR frog$ OR arthropod$ OR arachnid$ OR gastropod$ OR mammal$ OR rodent$ OR lagomorph$ OR hedgehog$ OR ungulate$ OR carnivore$ OR canid$ OR felid$)
AND (photovoltaic$ OR "solar energ*" OR "solar farm$"OR "solar panel$" OR "solar plant$" OR "solar park$" OR "solar array$" OR "solar power" OR "solar installation$" OR conservoltaic OR agrivoltaic)
AND (evaluat* OR solution$ OR mitigat* OR assess* OR option$ OR measur* OR priorit* OR reduc* OR avoid* OR compensat* OR minimiz* OR adapt* OR interven* OR action$ OR manag* OR protect* OR manipulat* OR counteract* OR removal OR engineer* OR plan* OR strateg* OR offset* OR "flight divert*" OR "attract* remov*" OR "m?cro-siting" OR deterr* OR "habitat restoration$" OR "habitat enhancement$" OR "habitat creation$" OR "ecological engineering" OR "site selection$" OR "displacement$" OR "buffer zone$") AND (impact* OR effect* OR collision$ OR behavio*r OR aversion$ OR repulsion$ OR disturb* OR mortalit* OR fatalit* OR carcass* OR "glass reflection" OR "reflective surface$" OR "light pollution"OR "population size$" OR "population densit*" OR abundance OR occurrence OR "habitat loss*" OR "habitat fragmentation$" OR "habitat degradation$" OR "breeding success" OR nesting OR reproduct* OR "site fidelit*" OR richness OR composition OR surviv*))

Simplified search equations derived from the initial full search equation, used with the Bielefeld Academic Search Engine (BASE):

• *Aerofauna search equation:*
(insect OR invertebrate OR bird OR passerine OR raptor OR waterbird OR bat OR chiroptera) AND (photovoltaic OR "solar farm" OR "solar energy" OR "solar panel" OR "solar power" OR agrivoltaic) AND (deterrent OR strategy OR management OR intervention OR evaluation OR solution OR mitigation OR assessment OR measure OR reduce OR avoid OR compensate OR minimize OR offset) AND (impact OR effect OR collision OR behaviour OR aversion OR mortality OR "glass reflection" OR "light pollution" OR abundance OR "habitat loss" OR reproduction OR survival)

• *Terrestrial fauna search equation:*
(reptile OR amphibian OR frog OR arthropod OR arachnid OR gastropod OR mammal OR rodent OR lagomorph OR hedgehog OR ungulate OR carnivore OR canid OR felid)
AND (photovoltaic OR "solar farm" OR "solar energy" OR "solar panel" OR "solar power" OR agrivoltaic) AND (deterrent OR strategy OR management OR intervention OR evaluation OR solution OR mitigation OR assessment OR measure OR reduce OR avoid OR compensate OR minimize OR offset) AND (impact OR effect OR collision OR behaviour OR aversion OR mortality OR "glass reflection" OR "light pollution" OR abundance OR "habitat loss" OR reproduction OR survival)

Simplified and broken up search equations derived from the initial full search equation, used with Google Scholar

Aerofauna search equations:

• (insect OR invertebrate) AND (photovoltaic OR "solar energ*" OR "solar panel" OR "solar power") AND (evaluat* OR solution OR mitigat* OR assess* OR measur* OR reduc* OR avoid* OR compensat* OR minimiz* OR offset*) AND (impact* OR effect* OR collision OR behavio*r OR aversion OR mortalit*)

• (insect OR invertebrate) AND (photovoltaic OR "solar energ*" OR "solar panel" OR "solar power") AND (evaluat* OR solution OR mitigat* OR assess* OR measur* OR reduc* OR avoid* OR compensat* OR minimiz* OR offset*) AND ("glass reflection" OR "light pollution" OR abundance OR "habitat loss*")

• (insect OR invertebrate) AND (photovoltaic OR "solar energ*" OR "solar panel" OR "solar power") AND (evaluat* OR solution OR mitigat* OR assess* OR measur* OR reduc* OR avoid* OR compensat* OR minimiz* OR offset*) AND (reproduct* OR surviv*)

• (bird OR passerine OR raptor OR waterbird) AND (photovoltaic OR "solar energ*" OR "solar panel" OR "solar power") AND (evaluat* OR solution OR mitigat* OR assess* OR measur* OR reduc* OR avoid* OR compensat* OR minimiz* OR offset*) AND (impact* OR effect* OR collision OR behavio*r OR aversion)

• (bird OR passerine OR raptor OR waterbird) AND (photovoltaic OR "solar energ*" OR "solar panel" OR "solar power") AND (evaluat* OR solution OR mitigat* OR assess* OR measur* OR reduc* OR avoid* OR compensat* OR minimiz* OR offset*) AND (mortalit* OR "glass reflection" OR "light pollution")

• (bird OR passerine OR raptor OR waterbird) AND (photovoltaic OR "solar energ*" OR "solar panel" OR "solar power") AND (evaluat* OR solution OR mitigat* OR assess* OR measur* OR reduc* OR avoid* OR compensat* OR minimiz* OR offset*) AND (abundance OR "habitat loss*" OR reproduct* OR surviv*)

• (bat OR chiroptera) AND (photovoltaic OR "solar energ*" OR "solar panel" OR "solar power") AND (evaluat* OR solution OR mitigat* OR assess* OR measur* OR reduc* OR avoid* OR compensat* OR minimiz* OR offset*) AND (impact* OR effect* OR collision OR behavio*r OR aversion OR mortalit*)

• (bat OR chiroptera) AND (photovoltaic OR "solar energ*" OR "solar panel" OR "solar power") AND (evaluat* OR solution OR mitigat* OR assess* OR measur* OR reduc* OR avoid* OR compensat* OR minimiz* OR offset*) AND ("glass reflection" OR "light pollution" OR abundance OR "habitat loss*" OR reproduct*)

• (bat OR chiroptera) AND (photovoltaic OR "solar energ*" OR "solar panel" OR "solar power") AND (evaluat* OR solution OR mitigat* OR assess* OR measur* OR reduc* OR avoid* OR compensat* OR minimiz* OR offset*) AND (surviv*)

Terrestrial fauna search equations:

•(reptile OR amphibian OR mammal) AND (photovoltaic OR "solar energ*" OR "solar panel" OR "solar power") AND (evaluat* OR solution OR mitigat* OR assess* OR measur* OR reduc* OR avoid* OR compensat* OR minimiz* OR offset*) AND (impact* OR effect* OR collision OR behavio*r OR aversion)

•(reptile OR amphibian OR mammal) AND (photovoltaic OR "solar energ*" OR "solar panel" OR "solar power") AND (evaluat* OR solution OR mitigat* OR assess* OR measur* OR reduc* OR avoid* OR compensat* OR minimiz* OR offset*) AND (mortalit* OR "glass reflection" OR "light pollution")

•(reptile OR amphibian OR mammal) AND (photovoltaic OR "solar energ*" OR "solar panel" OR "solar power") AND (evaluat* OR solution OR mitigat* OR assess* OR measur* OR reduc* OR avoid* OR compensat* OR minimiz* OR offset*) AND (abundance OR "habitat loss*" OR reproduct* OR surviv*)

APPENDIX III: ASSESSING THE CONFORMITY TO ELIGIBILITY CRITERA WITH RANDOLPH'S KAPPA TEST

Randolph's Kappa test on title + abstract ratings:

- This test was carried out by two independent raters on a list of 193 bibliographic references, after initial calibration also using 10 references to harmonize the selection decisions. Randolph's Kappa test was chosen here as it is more adapted to analyses with two raters than Fleiss' Kappa test, which is designed for more than two raters.

- Results: *Kappa = 0.95*
  z = 4.22
  p-value < 0,001

Results show high agreement between raters at each stage of the selection process. ~~Whether selection was carried out on titles + abstracts (Kappa = 0.72) or full texts (Kappa = 0.80),~~ The Kappa value indicates that rater decisions were highly congruent and reproducible. This congruence guarantees the reliability and robustness of the assessment of eligibility criteria during the entire selection process.

For various reasons (time constraints, unavailability of one of the raters), we did not carry out a second inter-rater agreement test during the full text screening stage. Doing this test would have resulted in further delays that were incompatible with the project's deadline. However, this decision can be justified by:

- the very high level of agreement on title + abstract ratings (Randolph's Kappa = 0.948) indicating that inclusion/exclusion criteria were applied consistently,
- the experience acquired from previous reports (on onshore and offshore wind power), which reinforces our confidence in the rigour of our screening of full texts.

APPENDIX IV: CRITERIA FOR THE RISK OF BIAS ASSESSMENT

External validity:

- Has the exposure/intervention taken place *in situ* (at a site with PV panels)?

Confounding factors:

- Are there potential confounding factors that can influence the intervention and/or the result? If yes, have the authors identified, then analysed/controlled these factors, and did they take them into account in their analysis?

Selection bias:

- Was the selection of subjects or locations after the intervention or exposure random or systematic, and could we assume that before and after groups are interchangeable?

Detection bias:

- Could result measurements be influenced by knowledge of the exposure, intervention, subjects or locations, or by wanting a certain result?

Result assessment:

- Could there be mistakes or were inappropriate methods used in the statistical analyses (including: were the hypotheses of the statistical inference methods used violated)?

Conflicts of interest:

- Have the authors disclosed funding sources and potential conflicts of interest?