REWI

Renewable Energy Wildlife Institute

National Solar Wildlife Research Plan

2023-2025

Prepared by
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May 31, 2023

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For Release May 2023

REWI is a partnership of leaders in the wind and solar industry, science and conservation organizations, and wildlife management agencies who collaborate on a shared mission: through science and collaboration, accelerate responsible deployment of renewable energy to mitigate climate change and protect wildlife and ecosystems.

Find this document online at (Link)

Acknowledgments

This document was made possible by the generous support of REWI's Partners and Friends. Thank you to those who reviewed and provided insightful feedback during the development of this document. The information contained in this document does not necessarily reflect the opinion of REWI's Partners and Friends or those who served as reviewers.

Suggested Citation Format

Renewable Energy Wildlife Institute (REWI). 2023. National Solar Wildlife Research Plan 2023-2025. Washington, DC. Available at www.rewi.org.

Contents

Executive Summary

The growth of solar-generated electricity continues to accelerate in the United States. Renewable energy electricity generation is forecasted to increase 26% in 2024, with two-thirds attributed to new photovoltaic (PV) solar developments, and, in many areas globally, PV solar has become the least expensive form of electricity. The shift towards renewable energy, including large-scale photovoltaic solar (also referred to as utility-scale), supports efforts to reduce global carbon emissions and lessen future climate change impacts on wildlife, their habitats, and the ecosystems on which wildlife depends. As utility-scale PV solar facilities become more commonplace within the landscape, solar-wildlife stakeholders including the industry, government, academics, and the conservation/science community are leading efforts to understand these facilities' adverse and beneficial effects on wildlife and other natural resources.

The Renewable Energy Wildlife Institute (REWI) is developing a solar-wildlife program. To guide this Program, we have developed this National Solar Wildlife Research Plan (Plan) outlining REWI's strategic priorities and approach to solar-wildlife challenges and opportunities. The conceptual basis of our Plan is that solar facilities represent ecosystems with altered ecological (biotic) and environmental (abiotic) processes, both adversely and, in some instances, beneficially. With this view, we have concluded that focusing attention solely on describing the adverse impacts, such as direct impacts (on birds, large game, or desert tortoises) or loss of habitat at the species level, will limit our full understanding of the complex ecological and environmental challenges and benefits associated with these facilities.

The Plan aims to identify and prioritize key areas where additional, strategically targeted research investments will advance our understanding of these environmental challenges and benefits. We first summarize the state of the science on selected topics based on a literature review, outline specific topics where research is needed, and highlight REWI's focus and the anticipated outcomes over the next three to five years. These topics are selected to target key scientific research priorities that are appropriate to the pace and scale of utility-scale solar deployment over the next 10-20 years, and ultimately to advance research that maximizes beneficial effects and minimizes wildlife and ecosystem impacts.

Priority research questions outlined in this Plan focus on topics related to habitat and landscape challenges, risks to wildlife, ecosystem-level benefits, and mitigation[a] and enhancing benefits where: 1) sufficient interest exists regarding the levels of impact and benefit but corroborating data are needed; 2) Data are needed to address siting and permitting issues; 3) Research can be structured to promote data pooling to address patterns and mechanisms and increase the rate at which results are incorporated into best practices; and 4) Substantial progress can be made in three to five years with current resources.

REWI's specific priorities leverage REWI's expertise, resources, and extensive network of partnerships, and will support research on impacts and identify and evaluate management practices resulting in improved siting and minimization strategies.

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a USFWS (2023) defines mitigation to include avoiding the impact altogether by not taking a certain action or parts of an action; minimizing impacts by limiting the degree or magnitude of the action and its implementation; rectifying the impact by repairing, rehabilitating, or restoring the affected environment; reducing or eliminating the impact over time by preservation and maintenance operations during the life of the action; and compensating for the impact by replacing or providing substitute resources or environments. (Link)

Introduction

The rapidly changing climate is a major threat to biodiversity, ecosystems, and our communities, people, and economy.[1] As atmospheric carbon dioxide (CO_2) and other greenhouse gases continue to increase as the result of human activities, our planet's climate is experiencing warmer temperatures, more intense and frequent prolonged droughts and rainstorm events, and rising sea-levels, which will affect humans and many wildlife species.[1]

The challenge in mitigating climate change is meeting electricity generation demands and reducing CO_2 emissions simultaneously. National energy electricity consumption grew by 3% in 2022 and is predicted to remain stable in 2023 and grow by 3% in 2024.[2] The Biden-Harris administration has set ambitious goals for carbon reduction in the United States energy sector, targeting 50-52% reduction in greenhouse gas emissions by 2030 and reaching net-zero emissions by 2050.[3] Renewable energy, in particular solar energy, is a key part of the strategy to achieve this national goal.[4]

Solar energy production is poised to increase significantly due to progressive energy policies and standards set by federal and state governments, incentives, and higher efficiencies and price reductions of solar technology. In the United States, renewable energy electricity generation is forecasted to increase 26% in 2024, with two-thirds attributed to new photovoltaic (PV) solar developments,[2] and, in many areas globally, PV solar has become the least expensive form of electricity.[4]

Over the past two decades, the solar energy industry has largely deployed new PV solar facilities instead of concentrating solar-thermal power (CSP),[5] and by 2014, PV solar represented approximately 90% of the installed solar capacity in the United States.[6] Although other forms of PV solar (e.g., residential and commercial rooftops, and community-scale) will undoubtedly contribute to the United States' solar capacity to meet net-zero emissions by 2050, over 80% of the solar capacity is anticipated to be utility-scale facilities.[b,4] Utility-scale PV solar-generated electricity is a leading component of the national strategy for **reducing the impacts of climate change on wildlife and their habitat.**

In this National Solar Research Plan (Plan), the Renewable Energy Wildlife Institute (REWI[c]) describes a strategy for evaluating interactions between utility-scale PV solar projects and wildlife[d] by considering solar energy developments and operations as ecosystems within a larger landscape (Box 1). In this construct, we evaluate the effects (positive and negative) of PV solar facilities on the ecological community (e.g., biodiversity, species interactions, behavior, movements, and population-level effects), habitat loss and fragmentation, and ecosystem function, including soil function, nutrient and water cycles, and other ecosystem services, on-site and within the surrounding landscape. All this information will inform responsible siting on how best to avoid and minimize effects on wildlife, their habitats[e], and the ecosystem, and also highlight beneficial opportunities for biodiversity and ecosystems enhancements on-site.

Studying PV facility's effects (positive and negative) on ecosystem function, many of these functions form the base of the food web and influence primary productivity, is important in understanding on-site habitat impacts and beneficial opportunities for wildlife. REWI believes it is necessary to study these aspects to fully understand solar-wildlife interactions, particularly bottom-up and indirect effects that will influence higher trophic levels (i.e., wildlife). By ignoring soil health and other ecosystem functions, our understanding of mechanistic drivers responsible for habitat quality would be incomplete.

This framework aligns with broader ecological concepts within population (demography and

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b According to DOE's Solar Futures Study, "Utility-scale renewable energy projects are typically defined as those 10 megawatts or larger." (**Link**)

c In 2022, the American Wind Wildlife Institute (AWWI) rebranded as the Renewable Energy Wildlife Institute (REWI).

d The Wildlife Society (TWS) and United States Code defines "wildlife" as any member of the animal kingdom (**Link** 1, **Link** 2)

e REWI refers to "habitat" as being specific to species and not related to land cover or ecological communities (e.g., grassland habitat) metapopulation), community (species interactions), landscape, and ecosystem ecology (biotic and abiotic interactions) and includes studying ecological processes within and adjacent to solar facilities (i.e., ecotones and edge effects in a larger landscape). We propose this conceptual basis as an alternative to applying the paradigm guiding wind energy-wildlife research, such as evaluating avian and bat collision fatalities or habitat loss and fragmentation as a feature solely of the technology and in isolation from the surrounding landscape. We reinterpret the wildlife impacts of PV solar facilities as demographic processes (e.g., births, deaths, immigration, and emigration) within and in lands surrounding PV solar facilities while recognizing that these impacts have implications for the permitting, compliance, and regulatory processes for developing PV facilities and direct on-site management applications. REWI's research interests reflect these considerations and will include evaluating how to mitigate (avoid, minimize and/or compensate) adverse impacts to further the sustainable development of renewable energy on the landscape.

In applying the ecosystem framework, we identify research opportunities to determine how the presence of the PV facility alters ecological and environmental processes at various spatial and temporal scales and trophic levels. PV facilities affect biotic (e.g., wildlife) and abiotic (e.g., microclimates) components and their interactions (e.g., soil-plant interactions) within the footprint[7,8,9,] and other associated infrastructure (e.g., fencing and linear features, such as electrical lines) change how species use and traverse the landscape.[10] Much remains unknown about the wildlife interactions, species' demography (e.g., reproduction and

Box 1

What is an ecosystem?

Tansley (1935) coined the term "ecosystem" and developed the concept. An ecosystem is defined as a dynamic system of biotic communities and their abiotic environment "interacting as a functional unit" (United Nations Convention on Biological Diversity (CBD 1992)). Over the years, how to delineate individual ecosystems has been debated (Blew 1996; Fitzsimmons 1996). Ecological boundaries, including those of ecosystems, are fundamentally defined by humans as conceptual or tangible constructs, and defined based on numerous attributes, such as origin, maintenance, spatial structure, function, and change over time (Strayer et al. 2003). The ecosystem concept is applied at various spatial scales (e.g., from patches to ecoregions to the biosphere) if the spatial extent is explicit and the biotic and abiotic components interact within the boundaries (Pickett and Cadenasso 2002).

Justification for the ecosystem approach

REWI is viewing PV solar within an ecosystem framework for various reasons. First, we argue that PV solar facilities satisfy most ecosystem attributes described by Strayer et al. (2003), and boundaries can be explicitly defined at different spatial scales. True to the original definition of an ecosystem, these facilities have biotic and abiotic components interacting within a defined boundary, such as the facilities' footprint or broader. These facilities, through construction activities and the presence of infrastructure, will modify biotic and abiotic conditions within the footprint and depend upon pre-construction land use (see main text). Moreover, PV solar facilities will interact with the surrounding landscape to influence biotic (e.g., migratory big game; Sawyer et al. 2022) and abiotic conditions (e.g., heat or cool islands; Barron-Gafford et al. 2016; Guoqing et al. 2021). Second, the ecosystem concept is already applied in other anthropogenically disturbed systems, such as urban systems, and the influence of humans on the natural environment was deliberately mentioned in the original ecosystem definition (Tansley 1935; Pickett and Cadenasso 2002). Third, PV solar facilities are already viewed within the ecosystem concept, in terms of ecosystem function and services (see Armstrong et al. 2016; Walston et al. 2021; Grodsky and Hernandez 2020).

An ecosystem framework provides a heuristic approach to unite research and priorities related to solar-natural resource challenges, such as fatalities, habitat loss, and interactions, with an interest in ecosystem function and service and biodiversity enhancements.

mortality patterns and mechanisms), wildlife habitats, and ecosystem function within the facility and as it relates to the larger landscape surrounding the PV facility.

An estimated 10.3 million acres of solar facilities are needed to meet the decarbonization goals of the United States;[4] however, the actual land conversion of natural habitats is likely smaller due to siting and permitting constraints, and some level of development in degraded or agricultural lands. Still, the conversion of large amounts of land to accommodate solar energy may bring solar-wildlife challenges to the forefront of conservation concerns including siting, evaluating and mitigating impacts on wildlife and their habitat, population-level dynamics, land management and wildlife compatibility, water resource management, and solar life cycle and natural resource considerations. For example, avoidance through proper siting is critical in protecting lands with important natural resources, sensitive species and plant communities, and natural lands needed for climate solutions and carbon sequestration.[11]

Vegetation management and restoration within PV facilities may provide ecosystem-level enhancements (e.g., biodiversity, pollinator supply, carbon storage, and soil and water retention) and provide wildlife habitat relative to the surrounding landscape (i.e., agrarian landscapes) and pre-construction land use (e.g., brownfields). These potential ecosystem enhancements may be achieved primarily through siting solar facilities on already disturbed, degraded, and marginal agricultural lands with the accompanying on-site vegetation restoration resulting in enhanced carbon storage potential and sediment and water retention.[12] Also, biodiversity enhancement may be achieved as various wildlife species are reported occupying facilities,[13,14] and much effort has also focused on evaluating the benefits to pollinator biodiversity. However, most native vegetation restoration (e.g., solar-pollinator habitat) is restricted to small PV facilities (e.g., less than 5 MW). The scaling feasibility of on-site native vegetation restoration activities to large, utility-scale PV facilities remains unknown, especially with concerns about native seed availability.[15]

To prepare this Plan, REWI used the surveys and interviews of solar-wildlife stakeholders conducted an exhaustive literature search available in REWI's Solar Resource Library.[16] In 2022, REWI surveyed and interviewed **industry, government, academic, and nonprofit stakeholders to further our understanding of the concern regarding solar energy's potential impacts and benefits to wildlife and ecosystem function.** Additionally, REWI hosted the 2021 Solar Power and Wildlife/Natural Resources Symposium,[17] which provided a platform for a diverse range of experts to share the state of the science on important topics and identify key areas of research to address wildlife and environmental challenges and benefits. This endeavor was supported by REWI's conservation science and industry partners. Building upon the symposium, REWI has prepared this Plan to support the timely and responsible growth of utility-scale solar energy development while protecting wildlife and ecosystem function, and to understand the status of efforts to avoid, minimize, and compensate when appropriate (defined as mitigation from this point forward). Because of the potentially rapid growth of utility-scale PV solar, the goal of REWI's Plan is to identify and prioritize key areas where additional, strategically targeted research investments are needed to advance:

- Our understanding of land conversion trends and impacts, and cumulative impacts to wildlife habitat and movement.
- Our understanding of how wildlife interacts, including demographic, metapopulation, and wildlife community considerations, within PV facilities and identifying changes to these interactions and mitigation opportunities at various scales.
- Our understanding of how ecosystem functions are affected within PV facilities across regions.
- The development and evaluation of strategies to avoid, minimize, and compensate for adverse impacts when necessary to conserve healthy wildlife populations and ecosystems.

Solar Energy State of the Science Summary

The following summary is a synopsis of REWI's "Solar Energy Interactions with Wildlife and Their Habitats," which is available online (**Link**). This report highlights the paucity of scientific research, which impedes our understanding of impacts and the decision-making needed to mitigate solar-wildlife conflicts. Compared to wind-wildlife interactions, the information on wildlife impacts by solar developments and operations is nascent but poised to increase dramatically over the next decade due to the projected increases in solar development. Studies are emerging or just underway, including projects funded by the Department of Energy[16] and the Renewable Energy Wildlife Research Fund (REWRF[17]), that evaluate potential effects on wildlife and wildlife habitat while also examining potential effects on ecosystem services. A more detailed summary of the state of knowledge of solar energy-wildlife interactions is included in **Appendix A**.

To date, the solar-wildlife community's approach to understanding solar-wildlife impacts has reflected what REWI describes as the wind-wildlife paradigm, which focuses on impacts to individual species or groups of species. Fatality estimates are the primary metric to determine wind impacts on wildlife, and all bird remains (e.g., carcasses or spot feathers) are assumed related to wind-energy production. For example, the discovery of bird carcasses at solar facilities has resulted in substantial efforts to estimate fatalities, in a manner analogous to bird collision fatalities at wind facilities, and then asking whether bats die at solar facilities. Recent papers provide estimates on a per megawatt (MW) basis and extrapolate to regional fatality estimates.[18,19,20] We describe elsewhere in this plan why we think this approach is limiting and possibly misplaced without landscape context.

Remains of various wildlife species have been found at PV solar facilities. Most studies focus on avian species in the desert southwest,[20,21,22,21] but the remains of bats, rabbits, rodents, snakes, lizards, medium-sized mammals, and frogs also have been found on-site of these facilities.[22] The causes of fatalities at PV facilities are largely unknown for wildlife, but studies have generally found that the combination of other less prominent infrastructure (e.g., fencing and overhead lines) were associated with more fatalities than apparent panel collisions.[20] One explanation for avian remains detected at PV facilities, especially water-associated and -obligate species, is the Lake Effect hypothesis, which posits certain avian species are attracted to PV facilities due to some species perceiving facilities as bodies of water. There is little published evidence supporting the Lake Effect hypothesis as a significant fatality mechanism in birds;[21] though preliminary experimental results suggest birds may perceive PV panels as water bodies due to emitted polarized light and are attracted to them in some ecological contexts (e.g., arid deserts), potentially increasing mortality above background rates.[16] Although there is limited published literature, stakeholder groups are making progress in understanding mechanism(s) (e.g., sensory and behavioral) and population-level impacts as it relates to avian fatalities.

Few studies have investigated population-level or cumulative effects of PV facilities on wildlife. Evidence suggests potential adverse population-level and cumulative impacts could occur for some avian species[22,22] if all solar technologies (i.e., concentrated solar power and PV) and other anthropogenic causes of fatalities combined increases direct avian mortality above background levels or through habitat loss (e.g., eliminating breeding, foraging, shelter, and migratory habitats).

Also of concern is whether and to what extent PV solar facilities contribute to habitat loss but also whether and to what extent they provide on-site wildlife habitat and support ecosystem services. PV solar build-out could affect wildlife habitat at various spatial scales (e.g., site-specific and landscape). At the landscape level, several studies report direct habitat loss,[10] modeled habitat loss,[23,24,25] and habitat fragmentation[10,26] associated with solar facility developments. It remains unknown if species will exhibit avoidance behaviors towards PV facility footprints,[10] but greater sage-grouse, a species known for avoiding energy infrastructure, has been observed within a PV facility,[27] suggesting potential habitat value (e.g., shade, especially in arid environments) on-site as well. Little is known about the energetic costs related to avoidance behavior from habitat loss and disturbance from PV facilities and associated infrastructure on wildlife, especially big game.

At the local scale, PV facilities alter vegetation, soil, and microclimate, which can influence habitat quality and ecosystem function[28] and shift species-specific responses to the environment.[7,8,9] Various wildlife species (e.g., mammals, birds, insects, and reptiles) appear to inhabit PV facilities suggesting some degree of habitat value (i.e., suitable habitat) within these facilities, especially within facilities with established vegetation. What remains to be understood is if these facilities are ecological sources or sinks (i.e., ecological trap) by creating and maintaining wildlife habitats within these facilities through time.

Solar developments may also provide potential enhancements to ecosystem function following the conversion of degraded lands accompanied by on-site vegetation restoration and management.[12,29] These benefits (e.g., carbon storage, pollinator supply, biodiversity enhancements, and soil and water retention) may vary regionally and are likely less pronounced or non-existent in desert ecosystems (e.g., harsh environmental conditions).[30] We know little beyond these studies, especially regarding the impacts on ecosystem function from converting natural or restored vegetative habitats (e.g., forested, shrublands, or grasslands) into PV facilities.[31] Further, very few studies have quantified the effects of PV facilities on water resources. Studies suggest both potential adverse (e.g., disruption of surface hydrology)[31,32,33,34] and beneficial effects[35] on water resources. The latter study is a computer simulation demonstrating the benefits of on-site vegetation with the retention and infiltration of water thus benefiting stormwater management. However, much remains unknown and long-term studies on the ecosystem function impacts of utility-scale solar operations are lacking.

There is no evidence of a significant contamination risk (i.e., heavy metal leachate) for wildlife or their habitat (i.e., soil, air, and groundwater)[36],[37] by damaged panels from deconstruction, decommissioning, or extreme weather events (e.g., hail). However, little data are available on the decommissioning of PV facilities.

The ability to effectively mitigate solar-wildlife adverse impacts is currently limited by our lack of understanding of the wildlife, habitat, and landscape impacts of PV facilities and associated infrastructure. However, many siting resources are available to avoid sensitive species and habitats, including Mojave fringe-toed lizards, tortoises, Mojave ground squirrels, grassland birds, and bats to name a few,[38] and co-location on abandoned, degraded, and marginal agricultural lands is a common strategy to spare undisturbed or natural habitats.[39,40,41] To our knowledge, there is no study assessing the effectiveness of mitigation measures or identifying what fatality mitigation measures at PV facilities are warranted. Most of our mitigation understanding is focused on establishing on-site vegetation (i.e., pollinator habitat, turfgrasses, or a combination of both) and comparing outcomes to the preconstruction land use (largely agricultural lands). Other mitigation strategies, such as mitigation-driven translocation and the effectiveness of compensatory mitigation, are still in need of studies. For example, some studies report high mortality rates associated with translocation for some long-lived species.[42]

National Solar-Wildlife Research Priorities – REWI's Focus

The priorities described below are where REWI will focus over the next three to five years. These areas of research have been selected to target scientific research priorities that are appropriate to the pace and scale of solar development over the next 10-20 years. For each research area and specific topic, we identify additional, focused research investments needed to fill knowledge gaps and highlight REWI's research focus and the anticipated outcomes. In addition, REWI will examine the uncertainties surrounding the impacts and benefits due to data deficiencies. Priorities could shift in the event of unforeseen impacts as utility-scale solar energy expands, including the implications of cumulative impacts related to solar in combination with other anthropogenic impacts on the landscape.

As described above, we conducted a review of the existing literature, reviewed the results of recent priority-setting exercises of various stakeholders, and through a third party, asked solar-energy stakeholders from state and federal agencies, the solar industry, academia, and non-governmental organizations about the solar-wildlife challenges of greatest concern and potential benefits of PV solar facilities to wildlife and the environment. For each challenge, we asked how well we understand its relative significance for species persistence, the underlying risk factors, and ways to avoid or minimize the challenges. For each benefit, we further asked about the extrapolation to other regions of the United States and the importance of the benefit. The common themes that arose from all the stakeholder reviews, surveys, and interview processes included challenges focused on wildlife fatalities, habitat and landscape processes, mitigation, and ecosystem function.

Research on these priorities will involve **collaboration with our solar-wildlife partners**, including state and federal agencies, conservation and science organizations, academic scientists, and the solar industry. By leveraging these relationships, REWI will accomplish our national research objectives, which, in turn, may be used to transform research results into sound policies and practices to inform decision-makers and achieve a balance between mitigating climate change impacts while simultaneously minimizing adverse impacts and maximizing benefits to wildlife, their habitats, and ecosystems from PV facilities in the United States.

In developing our list of research priorities, we applied the following **guidelines**:

- Research supported by REWI should focus on the ecosystem approach and investigate topics where:
    - Sufficient interest exists regarding the levels of impact and benefit, but corroborating data are needed
    - Data are needed to address siting and permitting issues
- Substantial progress can be made on a research topic in three to five years and with the resources available to REWI and its collaborating organizations
- Research can be structured to promote data pooling to:
    - Increase the rate at which results are incorporated into best practices
    - Address patterns and mechanisms related to impacts and benefits

Approach

REWI research priorities are based on an ecosystem approach to investigate species interactions with infrastructure, identify the potential for on-site wildlife habitat provided by the solar facility, evaluate the risks associated with species occupying these mesohabitats within the footprint of the facility, and understand the effects of facilities within the landscape. Furthermore, REWI's priorities investigate patterns of habitat value and ecosystem function provided by various vegetation management strategies across regions with the recognition that each region may have a different set of environmental challenges and benefits. Some priorities listed below might be most appropriately led by organizations other than REWI, although we would welcome the opportunity to contribute to these efforts as appropriate. Many of these topics will be supported through collaboration with a variety of stakeholders including the REWRF.

Ecological Interactions

Challenge: There is a need to increase our understanding of how PV facilities interact with wildlife within the footprint of the facility and the surrounding landscape, as well as how they influence occupancy, demography (births, deaths, immigration, and emigration), behavior (e.g., avoidance and sensory), ecological interactions (i.e., competition and predator-prey dynamics), and habitat loss and fragmentation (i.e., movement ecology). For example, the presence of a PV facility and other associated infrastructure is assumed to cause habitat loss and reduce permeability for wildlife, especially big game and other wildlife of concern (e.g., desert and gopher tortoises and grassland birds) within the landscape. Vegetation management and restoration (e.g., non-native, native, or a combination of vegetation types) within these facilities can create wildlife habitat that attracts wildlife from various trophic levels. A paradox exists between creating wildlife habitat within a facility with the potential risks of wildlife occupying PV facilities (i.e., ecological trap). Future research should focus on the risks and benefits of occupying PV facilities, how species and communities interact with the on-site wildlife habitats, microclimates, and infrastructure within the footprint, and how wildlife interact with the PV facility in the larger landscape context. Our increased understanding of the solar-wildlife interactions and outcomes will inform future mitigation measures, especially avoidance through proper siting.

Ecological Interactions Objectives	Outcomes
Conduct long-term monitoring to understand interactions among wildlife and facilities design, infrastructure, and vegetation management strategies	1. Improved understanding of the long-term, population, and cumulative effects, if any, of wildlife occupying PV facilities at the local and regional scale 2. Improved understanding of the effects of microclimate, soil-plant interaction alterations, and vegetation management strategies on wildlife and their habitats 3. Improve understanding of effects of stormwater and erosion control measures on wildlife and their habitats onsite and within the surrounding landscape
Develop standardized data collection of wildlife occupancy and demography at PV facilities and the surrounding landscape	1. Improved understanding of what wildlife is living and dying within PV facilities and the mechanisms among sites and regions 2. Improved understanding of habitat and ecological value within PV facilities
Evaluate the movement and behavioral ecology of wildlife within the PV facilities and the surrounding landscape	1. Improved understanding of landscape permeability for wildlife movements (e.g., big game) and avoidance in context of PV facilities siting and designs (e.g., corridors) 2. Identification of species sensitive to habitat loss and fragmentation caused by PV facilities in various regions and landscapes 3. Understanding of what wildlife use the area within and around the footprint of PV facilities and factors affecting the permeability of PV solar in different landscapes

Ecosystem Function

Challenge: There is a need to understand site-level ecosystem function as it relates to the effect of various on-site vegetation management strategies (e.g., turfgrasses, native vegetation, combination of native and non-native vegetation, or lack of vegetation, and grazing versus mechanical mowing) and construction activities compared to natural, agricultural, and degraded landscapes (e.g., brownfields and brightfields). These ecosystem functions include carbon storage and sequestration, water and soil retention, and a variety of functions provided by soil-plant interactions. Many of these functions may have implications for the quality and use of wildlife habitats. Some effects also correspond with the solar industry's requirements for stormwater management and erosion control plans.

Ecological Functions Objectives	Outcomes
Conduct studies, including BACI studies, investigating the effects of on-site and landscape factors related to ecosystem services and function in various regions of the United States	1. Improved understanding of on-site microclimates and management decisions (e.g., vegetation and stormwater) that affects, if any, ecosystem function on-site and within the surrounding landscape across regions 2. Improved understanding of solar facility effects in the context of the landscape, native vegetative communities, and regional factors
Develop standardized approaches in collecting abiotic and biotic variables to assess variation in impacts and benefits on ecosystem function across regions	Improved data sharing across sites and regions to elucidate broad patterns of ecosystem benefits and impacts

Mitigation

Challenge: Mitigation includes avoiding, minimizing, and compensating, and all are of interest to all stakeholders working on renewable energy and wildlife. Appropriate project siting is the most effective strategy to avoid or minimize impacts to wildlife, their habitat, and ecosystem function. The lack of understanding and the high level of uncertainty related to adverse impact to wildlife, their habitats, and ecosystems at PV facilities inhibit the development and evaluation of mitigation measures, including avoidance through improved siting. Future research should focus on technologies that monitor wildlife interactions within PV facilities that will inform mitigation measures. With more information, effective mitigation strategies can be implemented and tested, such as wildlife translocations and compensatory actions.

Mitigation Objective	Outcomes
Support the development and evaluate measures to mitigate wildlife risks at PV facilities	1. Improve understanding of various mitigation measures to reduce risk and offsetting impacts to wildlife inhabiting PV facilities, facility-wildlife interactions within the landscape, wildlife habitats, and ecosystems 2. Improve understanding of where and how compensatory mitigation is necessary and effective

Synthesis

Challenge: The solar industry is facing permitting challenges that may delay the development of proposed facilities. The rapid pace of development needed over the next decade will require access to the best available information about risks to wildlife, natural resources, and ecosystems. Future efforts should focus on effective ways to share, disseminate, and synthesize data collected at PV solar facilities to enhance collaboration across regions, assist decision-makers on proper siting, and streamline permitting.

Synthesis Objectives	Outcomes
Create a solar-wildlife database that incorporates natural resource data driven by stakeholder engagement and needs	1. Improve data-sharing among stakeholders to elucidate larger patterns and mechanisms related to solar-wildlife challenges and benefits
Plan and facilitate two future solar symposia (2023 and 2025)	1. Proceedings of the symposia that advance our understanding and address key challenges informed by a planning committee of utility-scale PV solar on the landscape 2. Exchange of ideas among stakeholders that advance research, policy, and best practices at PV solar facilities

Conclusion

This Plan outlines REWI's solar-wildlife strategy and priorities over the next three to five years. In general, our understanding of the impacts on wildlife associated with PV solar development is limited — both taxonomically and geographically. These limitations prevent us from making broad generalizations of patterns and mechanisms related to risks and benefits, and thus underscore the need for more research and funding of all priorities. Our progress in addressing this Plan's suite of priorities will increase our understanding and provide a catalyst for synthesis and collaboration to overcome the challenges associated with the rapid deployment of PV solar across the United States.

In this Plan, we have described a strategy for evaluating utility-scale PV solar facilities as an ecosystem with biotic and abiotic conditions interacting to affect wildlife and wildlife habitat, both negatively and positively, and not primarily as a source of increased wildlife mortality. This approach differs from the species-focused paradigm and is needed to understand the complex ecological and environmental interactions associated with these facilities at various spatial scales.

Our priorities are ambitious but necessary to inform the rapid deployment of PV solar energy to mitigate the effects of climate change and promote conservation of ecosystems. REWI recognizes that successful implementation of these priorities can only be achieved through considerable investment of financial and human resources and the continued collaboration with our partners in the solar industry, state and federal government agencies, researchers, and conservation and science organizations. Utility-scale PV solar is a necessity in decarbonizing the electric grid to mitigate climate change, and this Plan's priorities will, ultimately, facilitate timely and responsible solar deployment on the landscape while protecting natural resources.

Appendix A: State of the Science on Utility-Scale Solar-Wildlife Adverse and Beneficial Impacts

Although significant amounts of research are being conducted currently,[16,18,19] the adverse ecological consequences and potential benefits of utility-scale solar developments remain relatively unknown and understudied, and few before-after-control-impact studies have been conducted.[43] This Plan broadly groups solar-wildlife impacts into habitat and landscape and fatalities effects and how to mitigate these effects. We discuss ecosystem function within habitat and landscape effects because it is intrinsically linked to biodiversity (e.g., wildlife and habitat quality) through soil-plant interactions, nutrient cycles, and the hydrologic cycle. The state of the science largely focuses on utility-scale PV solar (i.e., greater or equal to 10 MW); however, much of the information related to agrivoltaics, including solar-pollinator habitat and other native vegetation restoration, is limited to smaller, community and distributed PV facilities. For more details on each of the following impacts and benefits, we refer the reader to REWI's Solar Energy Interactions with Wildlife and Their Habitats (Link).

Habitat and Landscape Processes

PV facilities, if built to capacity to meet United States' energy goals, will transform millions of acres of agricultural, degraded, abandoned lands, and natural habitats.[44] Several studies have investigated habitat loss associated with PV facilities[10,22,25,26,27] and potential population-level impacts to wildlife is a concern.[22] Assuming PV facilities will provide no habitat value and a total loss of breeding habitat, one study estimated the combined impact of bird fatalities and on-site habitat loss (in terms of bird nesting densities reported in the literature) might adversely affect some bird species populations (e.g., burrowing owls[22]). PV facilities are thought to, albeit with little published evidence, alter on-site biotic and abiotic conditions, cause habitat loss, fragmentation, and disturbances, and may provide habitat and ecosystem service benefits in certain landscape settings. Much remains unknown, and what we have learned is taxonomically and geographically limited. Thus, any broad generalizations of trends are inappropriate at this time. We organize this habitat and landscape impacts section into three categories related to fragmentation and disturbances, on-site habitat, and general habitat concerns.

Fragmentation and Disturbance. — PV facilities' infrastructure (including perimeter fencing) and associated linear features (e.g., roads, transmission lines, and utility corridors) have the potential to decrease landscape permeability and inhibit wildlife movement[10,28] that may impede or alter daily or seasonal migration patterns. Although anthropogenic disturbances can cause wildlife avoidance, much remains unknown about the avoidance behavior of ungulates[10] and wildlife, in general, towards PV facilities. For example, PV facilities with restored native vegetation may provide usable habitat for greater sage-grouse[29] — a species known for avoiding anthropogenic structures. On-site and adjacent vegetative management decisions and spacing of solar panel arrays could maintain landscape permeability for ungulates and other sensitive species at PV facilities.[13,14]

On-site Habitat. — PV facilities represent a modified ecosystems relative to more natural habitats due to construction and infrastructure altering vegetation and microclimate.[7,8,9,30,41,45] Soil disturbance can degrade soil properties and vegetative communities for extended periods[30,35] and adversely affect insects.[46] Much remains unknown about the influence of PV facilities' altered microclimates on species-specific responses, population-level consequences, ecological interactions, and ecosystem function, and what is known is geographically restricted to the Western United States.[7,8,9,35,47,47,48] There is interest in evaluating potential ecosystem function benefits linked to on-site restoration efforts and pre-construction land use that include pollinator supply, carbon storage and cycle, and sediment and water retention (nutrient cycling).[12,31,37]

Habitat Concerns. — Various habitat concerns were expressed by stakeholders, including hazardous material contamination risk, water resources, and habitat quality. There are no studies investigating contamination risk to wildlife or wildlife habitat from damaged or decommissioned panels, and the risk to humans is low.[38,39] Few studies have quantified the effects of PV facilities on water resources, including aquatic organisms. At the landscape level, modifications to non-protected intermittent water features in the southwest United States could cause cumulative impacts on hydrology and watersheds.[36] In a simulated study of a PV facility, panels influenced hydrologic responses very little compared to on-site ground cover.[37] Vegetative ground cover, relative to gravel, pavement, and bare ground, reduces peak discharge and erosion and increases water infiltration.[37] Various wildlife species have been documented within PV facilities suggesting some on-site habitat value.[13,14,20,21,22,23,49,50] Given fatality risks and concerns (see below), wildlife occupation might be maladaptive and create a negative feedback loop (i.e., ecological trap) affecting population level dynamics. However, it remains to be seen whether these facilities are meta-population sources or sinks.

Wildlife Fatalities

The discovery of bird remains in utility scale PV solar facilities has led to the concern that these facilities and their associated infrastructure pose a fatality risk to wildlife, although the fatality mechanisms for individual species are unclear,[20,21,51] and we lack the data to evaluate the extent of risk beyond the southwestern United States.[20,21,22,23] We organize this fatality section into three categories related to species, mechanisms, and population-level impacts.

What species are dying? – A variety of wildlife species have been reported as dead at PV facilities in North America.[20,21,22,23] These on-site fatalities include birds, bats, several rabbit species, rodents, snakes, lizards, medium-sized mammals, and frog species.[22] Wildlife fatalities may occur from a variety of sources, including panel and vehicle collisions, entanglement and entrapment (e.g., fencing and netting), drowning (e.g., retention ponds), electrocution, and predation events (e.g., background mortality).

What are the mechanisms? – The cause of death is largely unknown for wildlife, especially for birds and bats, at PV facilities, limiting our understanding of the mechanisms.[20,21,22] There is little evidence supporting the Lake Effect hypothesis significantly driving bird fatalities,[20,21] and other infrastructures (e.g., lines, fencing, and buildings) cause similar fatality rates as panels.[20] Most non-volant fatalities were caused by vehicle collisions, accidental drownings, or were unknown.[22] Other causes of non-volant fatalities were classified as abandoned, construction, entangled, exposure, probable predation, and starvation.

Are there population-level impacts? – Any population-level or cumulative impacts from fatalities and habitat loss remain understudied. No study has quantified population-level effects on wildlife due to PV facilities related fatalities, but one study has considered both solar technologies in combination with other anthropogenic sources of fatalities.[24] Fatality estimates are limited to only a few studies from the desert southwest,[20,21,22,23] and the lack of pre-construction data and information on the change in mortality associated with PV infrastructure relative to the landscape (i.e., background mortality) makes it difficult to assess population-level and cumulative effects for PV solar.

In general, more research is needed to understand the impacts on populations and demographics in a variety of landscapes including potential population-level effects on wildlife species. Several issues impede robust assessments and predictions related to effects of PV facilities on mortality:

- There is a lack of standardization in data collection procedures and protocols across studies, which limits the ability to quantify or accurately assess changes to species' mortality within or across solar facilities.[22]
- Various data collection protocols and fatality estimates may yield different conclusions.[20,21,22,23,52]
- Our understanding of causes of death of wildlife at PV facilities is low.[20,21,22]

Mitigation, Enhancing Benefits, and On-site Management

Mitigation includes avoiding, minimizing, and compensating. Appropriate project siting is the most-effective strategy to avoid or minimize impacts to wildlife, their habitat, and ecosystem function. Many resources and tools exist to promote responsible siting relative to natural resources,[40] and co-location of PV facilities on abandoned, degraded, or agricultural lands is an often-cited strategy to spare wildlife habitat conversion.[41,42,43] Strategic siting could also involve micro-siting to avoid critical wildlife features, such as hibernacula, burrows and dens, roosting trees, and desert washes.[13] Other design considerations, such as wildlife-friendly fencing and breaking up the facility's footprint to accommodate ungulate migratory routes, wildlife movements, and water courses[13,14,53] will additionally improve landscape permeability. However, all these strategies present unique challenges to the developer. It is important to understand that the siting process involves other considerations (e.g., distance to transmission lines, local permitting constraints and fees, Not-In-My-Backyard issues, interconnection costs, slope, available land for lease, and cultural resources) beyond wildlife. Additionally, developers must follow fencing regulations (i.e., PV facilities must have at least 2.1-meter fence) from the National Electrical Code and National Electrical Safety Code and also compliance with the local Authority Having Jurisdiction. Developers must balance these considerations (see above) and regulations (e.g., fencing) with avoidance and minimization measures to make the project financially feasible.

Before effective fatality minimization can occur, more research is needed to identify the degree and magnitude of fatalities, specific mechanisms for wildlife fatalities, and in general, we lack tested minimization practices (i.e., physical, operational, and abatement controls) that reduce fatalities attributable to PV facilities. There are studies investigating possible mitigation measures for wildlife fatalities that could apply to PV facilities:

- Ultrasonic and acoustic deterrents;[22,54]
- Vehicle management plans;[55]
- Micro-siting roads and infrastructure to avoid high-density wildlife areas;[13]
- Various fencing modifications;[56]
- Panel borders and coating;[57,58,59]
- Enhancing exclusion and escape structures in ponds;[60]
- Translocation;[44,61,62] and
- Soil ripping, composting, air spading or aeration, low-pressure tires for vehicles, and tracked vehicles to reduce soil compaction.[63,64]

If vegetation is present, regular vegetation maintenance is required regardless of vegetation type at PV facilities for safe and efficient operation of the PV facility. Our understanding of the wildlife implications of these various management options at PV facilities is limited, and much of our knowledge of wildlife responses is inferred from studies at non-solar facilities.[31,65,66,67] Possible vegetation management measures that benefit wildlife include:[31,68,69,70]

- Lower frequency and intensity of mechanical mowing/cutting;
- Avoiding spring/summer mowing/cutting;
- Planting native vegetation and hedgerows in undeveloped areas (e.g., setback areas);
- Replacing mowing/cutting with low intensity grazing.

Known benefits of livestock grazing include selective foraging, soil enrichment, and reduction of mechanical mowing and cutting.[31] However, the intensity and timing of the grazing could have impacts on pollinators and habitats, and not all livestock are compatible with PV infrastructure for site grazing. For a more detailed discussion on agrivoltaics, including grazing, we refer the reader to review papers.[71,72]

[1] International Panel on Climate Change 2022 (Link)
[2] United States Energy Information Administration 2023 (Link)
[3] The Department of Energy (DOE). 2022a. The Inflation Reduction Act drives significant emissions reduction and positions America to reach our climate goals (Link)
[4] The Department of Energy (DOE). 2021a. Solar Future Study (Link)
[5] Mendelsohn, M., T. Lowder, and B. Canavan. 2012. Utility-scale concentrating solar power and photovoltaics projects: a technology and market overview. NREL Technical Report NREL/TP-6A20-51137, National Renewable Energy Laboratory, Golden, CO. pp 65. (Link)
[6] Massachusetts Institute of Technology (MIT). 2015. The future of solar energy: an interdisciplinary MIT study. Massachusetts Institute of Technology, Boston, MA. pp. 356. (Link)
[7] Tanner, K.E., K.A. Moore-O'Leary, I.M. Parker, B.M. Pawlik, and R.R. Hernandez. 2020. Simulated solar panels created altered microhabitats in desert landforms. Ecosphere 44:e03089. DOI:10.1002/ecs2.3089
[8] Tanner, K.E., K.A. Moore-O'Leary, I.M. Parker, B.M. Pawlik, S. Haji, and R.R. Hernandez. 2021. Microhabitats associated with solar energy development alter demography of two desert annuals. Ecological Applications 31:e02349. DOI:10.1002/eap.2349
[9] Hernandez, R.R., K.E. Tanner, S. Haji, I.M. Parker, B.M. Pavlik, and K.A. Moore-O'Leary. 2020. Simulated photovoltaic solar panels alter the seed bank survival of two desert annual plant species. Plants 9:1125. DOI: 10.3390/plants9091125
[10] Sawyer, H., N.M. Korfanta, M.J. Kauffman, B.S. Robb, A.C. Telander, and T. Mattson. 2022. Trade-offs between utility-scale solar development and ungulates on western rangelands. Frontiers in Ecology and the Environment (early view) DOI:10.1002/fee.2498
[11] Bateman, B.L., J. Grand, J.X. Wu, S.P. Saunders, C.B. Wilsey, and C. Koseff. 2021. Natural climate solutions report: maintaining and restoring natural habitats to help mitigate climate change. National Audubon Society: New York. (Link)
[12] Walston, L.J., Y. Li, H.M. Hartmann, J. Macknick, A. Hanson, C. Nootenboom, E. Lonsdorf, and J. Hellmann. 2021. Modeling the ecosystem services of native vegetation management practices at solar energy facilities in the Midwest United States. Ecosystem Services 47: 101227. DOI:10.1016/j.ecoser.2020.101227
[13] Cypher, B.L., B.B. Boroski, R.K. Burton, D.E. Meade, S.E. Phillips, P. Leitner, E.C. Kelly, T.L. Westall. And J. Dart. 2021. Photovoltaic solar farms in California: can we have reviewable electricity and our species, too? California Fish and Wildlife 107:231-248. DOI: 10.51492/cfwj.hwisi.6
[14] Sinha, P., H. Hoffman, J. Sakers, and L. Althouse. 2018. Best practices in responsible land use for improving biodiversity at a utility-scale solar facility. Case Studies in the Environment 2:1-12. DOI:10.1525/cse.2018.001123
[15] Pedrini, S., P. Gibson-Roy, C. Trivedi, C. Gálvez-Ramírez, K. Hardwick, N. Shaw, S. Frischie, G. Laverack, and K. Dixon. 2020. Collection and production of native seeds for ecological restoration. Restoration Ecology 28:S228-S238. DOI: 10.1111/rec.13190
[16] Solar Resource Library (Link)
[17] REWI Solar Symposium. 2021. Proceedings of the 1st Solar Power and Wildlife/Natural Resources Symposium. December 1-3, 2021. Prepared by the Renewable Energy Wildlife Institute, Washington D.C., Susan Savitt Schwartz and Justin Fischer, ed. 102 pp. (Link)
[18] Department of Energy (DOE). 2022b. DOE invests $14 million to enhance environmental and wildlife benefits from solar energy infrastructure. (Link)
[19] Renewable Energy Wildlife Research Fund (Link)
[20] Kosciuch, K., D. Riser-Espinoza, M. Gerringer, and W. Erickson. 2020. A summary of bird mortality at photovoltaic utility scale solar facilities in the Southwestern U.S. PLoS ONE 15(4): e0232034. DOI: 10.1371/journal.pone.0232034
[21] Kosciuch, K., D. Riser-Espinoza, C. Moqtaderi, and W. Erickson. 2021. Aquatic habitat bird occurrences at photovoltaic solar energy development in Southern California, USA. Diversity 13:524. DOI:10.3390/d13110524
[22] Smallwood, K. S. 2022. Utility-scale solar impacts to volant wildlife. The Journal of Wildlife Management 86: e22216. DOI: 10.1002/jwmg.22216
[23] Walston Jr., L.J., K.E. Rollins, K.E. LaGory, K.P. Smith, and S.A. Meyers. 2016. A preliminary assessment of avian mortality at utility-scale solar energy facilities in the United States. Renewable Energy 92:405-414. DOI: 10.1016/j.renene.2016.02.041
[24] Conkling, T.J., H.B. Vander Zanden, T.D. Allison, J.E. Diffendorfer, T.V. Dietsch, A.E. Duerr, A.L. Fesnock, R.R. Hernandez, S.R. Loss, D.M. Nelson, P. M. Sanzenbacher, J.L. Yee, and T.E. Katzner. 2022. Vulnerability of avian populations to renewable energy production. Royal Society Open Science 9: 911558. DOI: 10.1098/rsos.211558
[25] Pocewicz, A., H. Copeland, and J. Kiesecker. 2011. Potential impacts of energy development on shrublands in Western North America. Natural Resources and Environmental Issues 17: 105-109. (Link)
[26] Inman, R.D., T.C. Esque, K.E. Nussear, P. Leitner, M.D. Matocq, P.J. Weisberg, T.E. Dilts, and A.G. Vandergast. 2013. Is there room for all of us? Renewable energy and *Xerospermophilus mohavensis*. Endangered Species Research 20:1-18. DOI:10.3354/esr00487
[27] McCoshum, S.M., and M.A. Geber. 2020. Land conversion for solar facilities and urban sprawl in southwest deserts causes different amounts of habitat loss for Ashmeadiella bees. Journal of the Kansas Entomological Society 92:468-478. DOI:10.2317/0022-8567-92.2.468
[28] Leskova, O.V., R.A. Frakes, and S.H. Markwith. 2022. Impacting habitat connectivity of the endangered Florida panther for the transition to utility-scale solar energy. Journal of Applied Ecology 59:822-834. DOI:10.1111/1365-2664.14098
[29] Gerringer, M.B., K.T. Smith, and K.L. Kosciuch. 2022. Observations of greater sage-grouse at a solar energy facility in Wyoming. Western North American Naturalist 82:196-200. (Link)
[30] Choi, C.S., A.E. Cagle, J. Macknick, D.E. Bloom, J.S. Caplan, and S. Ravi. 2020. Effects of revegetation on soil physical and chemical properties in solar photovoltaic infrastructure. Frontiers in Environmental Science 8:140. DOI: 10.3389/fenvs.2020.00140
[31] Blaydes, H., S.G. Potts, J.D. Whyatt, and A. Armstrong. 2021. Opportunities to enhance pollinator biodiversity in solar parks. Renewable and Sustainable Energy Reviews 145:111065. DOI: 10.1016/j.rser.2021.111065

[32] Whisenant, S.G. 1995. Landscape dynamics and arid land restoration. In Proceedings: wildland shrub and arid land restoration symposium (eds. B.A. Roundy, E.D. McArthur, J.S. Haley, and D.K. Mann). 1993 October 19-21, Las Vegas, Nevada (Link)
[33] Piechota, T., J. van Ee, J. Batista, K. Stave, and D. James (eds). 2004. Potential environmental impacts of dust suppressants: "avoiding another Times Beach". Report No. EPA/600/R-04/031, US Environmental Protection Agency. (Link)
[34] Sarver, T., A. Al-Qaraghuli, and L.L. Kazmerski. 2013. A comprehensive review of the impact of dust on the use of solar energy: history, investigations, results, literature, and mitigation approaches. Renewable and Sustainable Energy Reviews 22:698-733. DOI:10.1016/j.rser.2012.12.065
[35] Field, J.P., J. Belnap, D.D. Breshears, J.C. Neff, G.S. Okin, J.J. Whitaker, T.H. Painter, S. Ravi, M.C. Reheis, and R.L. Reynolds. 2010. The ecology of dust. Frontiers in Ecology and the Environment 8:365-430. DOI:10.1890/090050
[36] Grippo, M., J.W. Hayse, and B.L. O'Connor. 2015. Solar energy development and aquatic ecosystems in the Southwestern United States: potential impacts, mitigation, and research needs. Environmental Assessment 55:244-256. DOI:10.1007/s00267-014-0384-x
[37] Cook, L.M., and R.H. McCuen. 2013. Hydrologic response of solar farms. Journal of Hydrologic Engineering 18:536-541. DOI:10.1061/(ASCE)HE.1943-5584.0000530
[38] Sinha, P., G. Heath, A. Wade, and K. Komoto. 2018. Human health risk assessment methods for PV, Part 1: fire risks. International Energy Agency (IEA) PVPS Task 12, Report T12-14:2018, pp 54. (Link)
[39] Sinha, P., G. Heath, A. Wade, and K. Komoto. 2019. Human health risk assessment methods for PV, Part 3: module disposal risks. International Energy Agency PVPS Task 12, Report T12-16:2020, pp 50. (Link)
[40] Department of Energy (DOE). 2021b. Solar impacts on wildlife and ecosystems. Request for information response summary. Washington, D.C. pp 47. (Link)
[41] Adeh, E.H., J.S. Selker, and C.W. Higgins. 2018. Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. PLoS ONE 13(11):e0203256. DOI:10.7267/N9W37T8D
[42] Adelaja, S., J. Shaw, W. Beyea, and J.D.C. McKeown. 2010. Renewable energy potential on brownfield sites: a case study of Michigan. Energy Policy 38: 7021-7030. DOI: 10.1016/j.enpol.2010.07.021
[43] American Clean Power (ACP). 2022. Solar power siting. Washington, DC. (Link)
[44] Mack, J.S., and K.H. Berry. 2023. Drivers of survival of translocated tortoises. Journal of Wildlife Management 87:e22352. DOI:10.1002/jwmg.22352
[45] Agha, M., J.E. Lovich, J.R. Ennen, and B.D. Todd. 2020. Wind, sun, and wildlife: do wind and solar energy development 'short-circuit' conservation in the western United States? Environmental Research Letters 15:075004. DOI: 10.1088/1748-9326/ab8846
[46] Diffendorfer, J.E., and R.W. Compton. 2014. Land cover and topography affect the land transformation caused by wind facilities. PLoS ONE 9:e88914. DOI:10.1371/journal.pone.0088914
[47] Beatty, B., J. Macknick, J. Mccall, G. Braus, and D. Buckner. 2017. Native vegetation performance under a solar PV array at the National Wind Technology Center. Technical Report No. NREL/TP-1900-66218. US Department of Energy, Washington DC. DOI:10.2172/1357887
[48] Saul-Gershenz, L., L. Kimsey, N.M. Williams, T. Zavortink, R. Thorp, J. Ascher, D. Yanega, and R. Hernandez. 2018. Characterization of the impact on native bees from utility scale solar development in the desert (BLM Grant 2015-2016). Report Grant No. L15AC00185, Bureau of Land Management. Pp 35. (Link)
[49] Moore-O'Leary, R.R. Hernandez, D.S. Johnston, S.R. Abella, K.E. Tanner, A.C. Swanson, J. Kreitler, and J.E. Lovich. 2017. Sustainability of utility-scale solar energy - critical ecological concepts. Frontiers in Ecology and the Environment 15:385-394. DOI: 10.1002/fee.1517
[50] Nordberg, E.J., M.J. Caley, and L. Schwarzkopf. 2021. Designing solar farms for synergistic commercial and conservation outcomes. Solar Energy 228:586-593. DOI:10.1016/j.solener.2021.09.090
[51] DeVault, T.L., T.W. Seamans, J.A. Schmidt, J.L. Belant, B.F. Blackwell, N. Mooers, L.A. Tyson, and L. Van Pelt. 2014. Bird use of solar photovoltaic installations at US airports: implications for aviation safety. Landscape and Urban Planning 122:122-128. DOI:10.1016/j.landurbplan.2013.11.017
[52] Walston, L.J., S.K. Mishra, H.M. Hartmann, I. Hlohowskyj, J. McCall, and J. Macknick. 2018. Examining the potential for agricultural benefits from pollinator habitat at solar facilities in the United States. Environmental Science and Technology 52:7566-7576. DOI: 10.1021/acs.est.8b00020
[53] Loss, S.R., M.A. Dorning, and J.E. Diffendorfer. 2019. Biases in the literature on direct wildlife mortality from energy development. BioScience 69:348-359. DOI: 10.1093/biosci/biz026
[54] Rabie, P.A., D. Riser-Espinoza, J. Studyvin, D. Dalthorp, and M. Huso. 2021. AWWI technical report: performance of the GenEst mortality estimator compared to the Huso and Shoenfeld estimators. Washington, DC. (Link)
[55] The Nature Conservancy (TNC). 2019. Making solar wildlife-friendly: creating solutions to maximize conservation benefit from solar production. The Nature Conservancy, Washington DC. (Link)
[56] Walston Jr., L.J., K.E. Rollins, K.P. Smith, K.E. LaGory, K. Sinclair, C. Turchi, T. Wendelin, and H. Souder. 2015. A review of avian monitoring and mitigation information at existing utility-scale solar facilities. Prepared for U.S. Department of Energy, SunShot Initiative, ANL/EVS-15/2. (Link)
[57] Lovich, J.E. and J.R. Ennen. 2011. Wildlife conservation and solar energy development in the Desert Southwest, United States. BioScience 61:982-992. DOI:10.1525/bio.2011.61.12.8
[58] Murph, R., and C. Pettie. 2015. Fence visual markers to reduce wildlife collisions or entanglement. Range Technical Note 39:1-4. (Link)
[59] Horváth, G., M. Blahó, A. Egri, G. Kriska, I. Seres, and B. Robertson. 2010. Reducing the maladaptive attractiveness of solar panels to polarotactic insects. Conservation Biology 24: 1644-1653. DOI: 10.1111/j.1523-1739.2010.01518.x
[60] Black, T.V. and B.A. Robertson. 2020. How to disguise evolutionary traps created by solar panels. Journal of Insect Conservation 24:241-247. DOI: 10.1007/s10841-019-00191-5
[61] Fitz, B., G. Horváth, R. Hünig, A. Pereszlényi, A. Egri, M. Guttmann, M. Schneider, U. Lemmer, G. Kriska, and G. Gomard. 2020. Bioreplicated coatings for photovoltaics solar panels nearly eliminate light pollution that harms polarotactic insects. PLoS ONE 15:e0243296. DOI: 10.1371/journal.pone.0243296

[62] Jeal, C., V. Perold, S. Ralston-Paton, and P.G. Ryan. 2019. Impacts of a concentrated solar power trough facility on birds and other wildlife in South Africa. Ostrich: Journal of African Ornithology 90:129-137. DOI: 10.2989/00306525.2019.1581296
[63] Brand, L.A., M.L. Fransworth, J. Meyers, B.G. Dickson, C. Grouios, A.F. Scheib, and R.D. Scherer. 2016. Mitigation-driven translocation effects on temperature, condition, growth, and mortality of Mojave Desert tortoises (*Gopherus agassizii*) in the face of solar energy development. Biological Conservation 200:104-111. DOI: 10.1016/j.biocon.2016.05.032
[64] Dickson, B.G., R.D. Scherer, A.M. Kissel, B.P. Wallace, K.M. Langin, M.E. Gray, A.F. Scheib, and B. Weise. 2019. Multiyear monitoring of survival following mitigation-driven translocation of a long-lived threatened reptile. Conservation Biology 33:1094-1105. DOI:10.1111/cobi.13301
[65] Minnesota Pollution Control Agency (MPCA). 2021. Minnesota Stormwater Manual. "Alleviating compaction from construction activities". St. Paul, MN. (Link)
[66] Chamen, W.C.T., A.P. Moxey, W. Towers, B. Balana, and P.D. Hallet. 2015. Mitigating arable soil compaction: a review and analysis of available cost and benefit data. Soil and Tillage Research 146:10-25. DOI: 10.1016/j.still.2014.09.011
[67] Bollinger, E.K. 1995. Successional changes and habitat selection in hayfields bird communities. The Auk 112:720-730. DOI:10.1093/auk/112.3.720
[68] Washburn, B.E., and T.W. Seamans. 2007. Wildlife responses to vegetation height management in cool-season grasslands. Rangeland Ecology and Management 60:319-323. DOI:10.2111/1551-5028(2007)60[319:WRTVHM]2.0.CO;2
[69] Filazzola, A., C. Brown, M.A. Dettlaff, A. Batbaatar, J. Grenke, T. Bao, I.P. Heida, and J.F. Cahill Jr. 2020. The effects of livestock grazing and biodiversity are multi-trophic: a meta-analysis. Ecology Letters 23:1298-1309. DOI:10.1111/ele.13527
[70] BRE. 2014. Biodiversity guidance for solar developments. Eds. G.E. Parker and L. Greene. (Link)
[71] M'Gonigle, L.K., L.C. Ponisio, K. Cutler, and C. Kremen. 2015. Habitat restoration promotes pollinator persistence and colonization in intensively managed agriculture. Ecological Applications 25:1557-1665. DOI:10.1890/14-1863.1
[72] Graham, L., R. Gaulton, F. Gerard, and J.T. Staley. 2018. The influence of hedgerow structural condition on wildlife habitat provision in farmed landscapes. Biological Conservation 220: 122-131. DOI:10.1016/j.biocon.2018.02.017
[73] Dinesh, H., and J.M. Pearce. 2016. The potential of agrivoltaic system. Renewable and Sustainable Energy Reviews 54:299-308. DOI:10.1016/j.rser.2015.10.024
[74] Mamun, M.A.A., P. Dargusch, D. Wadley, N.A. Zulkarnian, and A.A. Aziz. 2022. A review of research on agrivoltaic systems. Renewable and Sustainable Energy Reviews 161: 112351. DOI:10.1016/j.rser.2022.112351

Box 1 Citations

Armstrong, A., N.J. Ostle, and J. Whitaker. 2016. Solar park microclimate and vegetation management effects on grassland carbon cycling. Environmental Research Letters 11:074016. DOI:10.1088/1748-9326/11/7/074016
Barron-Gafford, G.A., R.L. Minor, N.A. Allen, A.D. Cronin, A.E. Brooks, and M.A. Pavao-Zuckerman. 2016. The photovoltaic heat island effect: larger solar power plants increase local temperatures. Scientific Reports 6:35070. DOI:10.1038/srep35070
Blew, R.D. 1996. On the definition of ecosystem. Bulletin of the Ecological Society of America 77:171-173. DOI: 10.2307/20168067
Convention on Biological Diversity (CBD) 1992. Article 2. Use of Terms. (Link)
Fitzsimmons, A.K. 1996. Stop the parade. BioScience 46:78-79. DOI:10.2307/1312808
Grodsky, S.M. and R.R. Hernandez. 2020. Reduced ecosystem services of desert plants from ground-mounted solar energy development. Nature Sustainability 3:1036-1043. DOI:10.1038/s41893-020-0574-x
Guoqing, L., R.R. Hernandez, G.A. Blackburn, G. Davies, M. Hunt, J.D. Whyatt, and A. Armstrong. 2021. Ground-mounted photovoltaic solar parks promote land surface cool islands in arid ecosystems. Renewable and Sustainable Energy Transition 1:10008. DOI:10.1016/j.rset.2021.100008
Pickett, S.T.A., and M.L. Cadenasso. 2002. The ecosystem as a multidimensional concept: meaning, model, and metaphor. Ecosystems 5:1-10. DOI:10.1007/s10021-001-0051-y
Sawyer, H., N.M. Korfanta, M.J. Kauffman, B.S. Robb, A.C. Telander, and T. Mattson. 2022. Trade-offs between utility-scale solar development and ungulates on western rangelands. Frontiers in Ecology and the Environment (early view) DOI:10.1002/fee.2498
Strayer, D.L., M.E. Power, W.F. Fagan, S.T.A. Pickett, and J. Belnap. 2003. A classification of ecological boundaries. BioScience 53:723-729. DOI: 10.1641/0006-3568(2003)053[0723:ACOEB]2.0.CO;2
Tansley, A.G. 1935. The use and abuse of vegetational concepts and terms. Ecology 16:284-307. DOI:10.2307/1930070
Walston, L.J., Y. Li, H.M. Hartmann, J. Macknick, A. Hanson, C. Nootenboom, E. Lonsdorf, and J. Hellmann. 2021. Modeling the ecosystem services of native vegetation management practices at solar energy facilities in the Midwest United States. Ecosystem Services 47:101227. DOI:10.1016/j.ecoser.2020.101227