Solar Energy Interactions with Wildlife and Their Habitats

A Summary of Research Results and Priority Questions

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This summary reviews publicly available information about the adverse impacts and potential benefits of ground-mounted large scale - PV solar power on wildlife in North America, and the status of our knowledge regarding how to mitigate adverse impacts and enhance beneficial impacts.

REWI

Renewable Energy Wildlife Institute

About REWI

The Renewable Energy Wildlife Institute is a partnership of leaders in the renewable industry, wildlife management agencies, and conservation and science organizations 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

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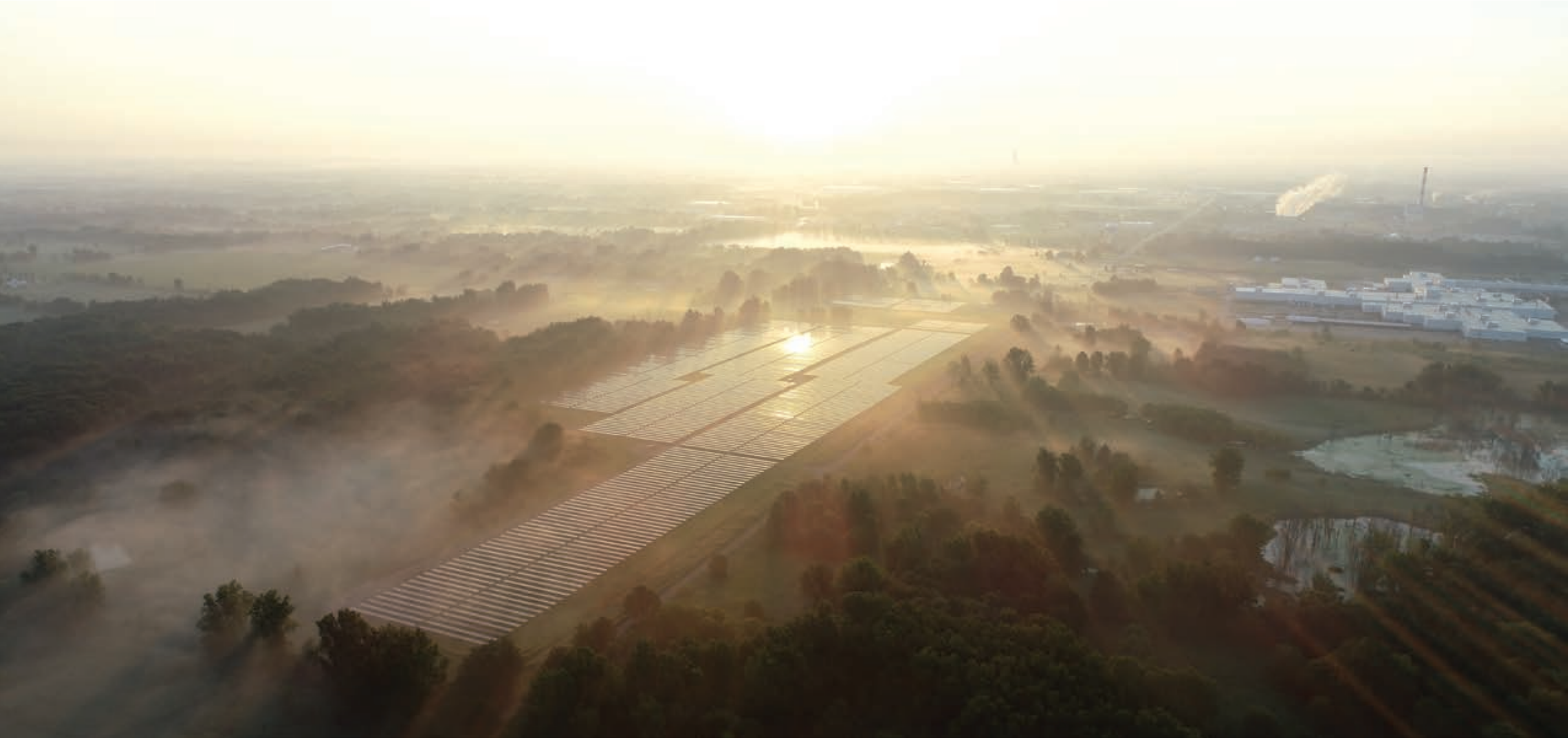
BACKGROUND: AURORA CHICAGO, ENEL • INSET, L-R: SHEEP GRAZING ON A SOLAR FARM, LIGHTSOURCE BP • AURORA ANNANDALE, ENEL • GREATER SAGE-GROUSE, USFWS, FLICKR



ALTAVISTA,VA, APEX

INTRODUCTION

Solar-generated electricity is rapidly growing in the United States and emerging as a key technology in our nation's strategy to mitigate climate change. Solar-generated electricity is projected to contribute as much as 40% and 45% of the United States' total electricity generation capacity by 2035 and 2050, respectively (DOE 2021a). Accompanying this rapid growth of utility-scale solar facilities (also referred to as large-scale solar facilities) within the landscape are solar-wildlife challenges related to increased land conversion into solar facilities. For example, the Department of Energy (DOE) estimated that 10.3 million acres are needed for solar-energy conversion to meet the decarbonization goals of the United States (DOE 2021a), and this increase in land conversion may bring solar-wildlife challenges and opportunities to the forefront of conservation research.

ENEL_AURORA ANNANDALE

There are two main solar technologies, photovoltaic (PV) and concentrating solar-thermal power (CSP), deployed at the utility scale. However, the exceptional growth of solar-generated electricity is unequal between the two solar technologies with the expansion of PV greatly outpacing CSP (Mendelsohn et al. 2012; MIT 2015). Although PV solar and CSP are often grouped collectively as solar energy, the associated wildlife and habitat challenges may be dissimilar. For example, reported wildlife impacts related to infrastructure (i.e., panels vs power towers) are often greater at CSP, in particularly power tower systems, than PV facilities (see Smallwood 2022), and the wildlife and ecosystem enhancements related to vegetation management and restoration of solar energy sites (e.g., pollinator habitat) will occur regionally and likely not in areas appropriate for CSP development (i.e., desert southwest).

The Renewable Energy Wildlife Institute (REWI) will focus primarily on the effects of utility-scale PV solar energy facilities (henceforth, PV facilities or PV solar) on natural resources within this summary. Other forms of PV solar (e.g., rooftops, distributed, and community-scale) will undoubtedly contribute to the goal of net-zero emissions by 2050; however, to meet this goal it is anticipated that more than 80% of the solar capacity will be utility-scale facilities.[1]

In this summary, REWI evaluates the interactions between PV facilities and natural resources, including wildlife, their habitats, and ecosystem function and services. We view these interactions in the framework of considering PV solar developments and operations as ecosystems with biotic and abiotic interactions both within the footprint of the facility and within the surrounding landscape. For example, these facilities might change how species use and traverse the landscape surrounding the footprint, potentially altering other wildlife and ecological interactions at various scales (REWI 2023). We argue that viewing PV facilities as ecosystems provides a heuristic approach to organizing research and unites concerns about impacts on species, habitat loss, and species interactions with the growing interest in ecosystem function and services of solar facilities. This approach differs from the species-focused paradigm of wind-wildlife challenges and

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

PV solar energy, unlike other renewable technologies, is deployed at various scales and settings, such as rooftops, community, and utility. The installed capacity of PV solar energy continues to grow in the United States at all scales, and collectively, the total capacity will exceed 143,000 megawatts (MW) by the middle of 2023. Over the past decade, the annual growth of solar energy has averaged 33% and has been driven largely by utility-scale PV solar installations. At the utility scale, PV solar energy accounts for 3.0% of electricity generated in the United States but substantially less than that produced by natural gas (38.3%), coal (21.8%), nuclear power (18.9%), wind power (9.2%), or hydropower (6.3%). There are two broad types of solar technologies – CSP and PV; however, the growth is not equivalent across the solar technologies, with PV solar energy representing approximately 90% of the installed solar capacity in the United States. Solar energy's footprint is land-use intensive (km^2/TWhr) relative to other renewable and traditional forms of energy (Trainor et al. 2016) and may require between six to eight acres per MW (DOE 2021a). Within the fenced perimeter, a utility-scale PV solar facility may encompass thousands of acres. Current solar market information can be found at the American Clean Power Association, Solar Energy Industry Association and U.S. Energy Information Administration.

SOLAR SNOW, BY KAREN AND BRAD EMERSON, FLICKR

its concern for collision fatalities, which, if adopted for solar-wildlife interactions, will limit our full understanding of the complex ecological and environmental challenges and enhancements to natural resources of PV development. In this construct, we review publicly available information about the known effects of PV facilities on wildlife, wildlife habitat and communities, and ecosystems, and the status of our knowledge regarding how to avoid and minimize adverse effects and enhance beneficial effects.

The information and conclusions within this summary largely focus on peer-reviewed publications and reports that have undergone expert, technical review. We attempt to limit our summary to North American wildlife and habitats; however, given the paucity of information publicly available, we include pertinent research from other regions of the globe. Stakeholders have diverse interests and concerns regarding the siting of PV solar, and many of these are outside the scope of REWI's focus on renewable energy and wildlife. Here, we focus on assessing risk and mitigating impacts on wildlife and wildlife habitats, land management, and related water resource management.

PV facilities, much like other human infrastructure, may pose risks to some wildlife and their habitats (Lovich and Ennen 2011; Hernandez et al. 2014; Moore-O'Leary et al. 2017; Agha et al. 2020). Peer-reviewed research evaluating these risks has not kept pace with the rapid deployment of PV facilities over the past decade, and researchers have raised many questions about the risks to wildlife and their habitats. Effects might occur at multiple ecological scales (species, population, metapopulations, communities, and ecosystems; Moore-O'Leary et al. 2017) and potentially affect complex ecosystem processes at local and regional scales. The direct and indirect impacts of PV solar development might affect non-volant and volant wildlife from myriad taxonomic groups.

This summary has undergone expert review and will be updated annually. Literature citations supporting the information presented are denoted in parentheses; full citations can be found online at LINK.

Organization of This Summary

This summary organizes what is known and what remains unknown or uncertain regarding the ecological and environmental effects of PV solar energy on wildlife within the following categories:

- Habitats and Landscapes
- Fatality Impacts
- Mitigation,[2] Enhancing Benefits, and On-site Management

We further organize this summary by developing questions to reflect stakeholder interests related to solar-wildlife and environmental challenges. We used surveys and interviews with various stakeholders and leveraged the contributions of the planning committees and subcommittees for REWI's Solar Power and Wildlife/Natural Resources Symposium (REWI Solar Symposium 2021). REWI recognizes that these questions are not all-encompassing of the environmental concerns around solar energy development. REWI's focus and mission are related to wildlife and their habitats, and the categories and questions of this summary reflect this focus.

Within each category, questions are not organized in a particular order of importance or level of certainty. Because of the paucity and geographic limitations of peer-reviewed scientific works, most questions will have a low level of certainty. A single study, although informative, or several studies with limited geographic representation, are usually insufficient for drawing broad conclusions.

[2] The mitigation hierarchy is to avoid impacts; then minimize impacts that are unavoidable; and finally, offset or compensate for unavoidable impacts (REWI 2022).

HABITAT AND LANDSCAPE CHALLENGES

PV facilities, if built to capacity to meet United States' energy goals, will transform millions of acres (*sensu* Diffendorfer and Compton 2014). Habitat loss and degradation are well-studied phenomena globally and widely considered a major threat to biodiversity, exacerbated by a rapidly warming climate (Newbold et al. 2015; Tilman et al. 2017). Although there is little information quantifying the habitat and landscape impacts caused by PV facilities, these impacts (e.g., Pocewicz et al. 2011; Inman et al. 2013; McClung et al. 2019; McCoshum and Geber 2020; Sawyer et al. 2022; Smallwood 2022) may be comparable to other anthropogenic developments on the landscape.

PV facilities have biotic and abiotic components that interact within the footprint and the surrounding landscape—a basic tenet of the ecosystem concept (Tansley 1935), and these facilities alter these biotic and abiotic conditions and their interactions due to construction, operation, and infrastructure relative to natural ecosystems (Hobbs et al. 2006; 2009). There is value in an ecosystem framework to guide and synthesize research because PV facilities are already viewed within the ecosystem concept, in terms of ecosystem function and service. Furthermore, pollinator-friendly solar, other on-site habitat mitigation, and even turfgrass, which could enhance ecosystem function and services relative to pre-construction land-use (if sited on disturbed lands), can create suitable habitats that attract and support wildlife to these ecosystems.

All putative benefits and enhancements (i.e., habitat and ecosystem services) are either poorly understood or involve the conversion of degraded or agricultural lands and are related to on-site vegetation management. The conversion of natural habitats dominated by woody shrubs and trees might adversely affect carbon storage potential and other ecosystem functions for not just the life of the PV facility but well beyond (Mori and Tabata 2020).

This section outlines and summarizes what is currently known and where there is remaining uncertainty about habitat and landscape impacts and indirect effects. We do not summarize the impacts or the benefits of replacing agricultural production with native grasses or pollinator habitats (e.g., Sanaullah et al. 2020; Meena et al. 2020), but focus on what is known about PV solar. We discuss ecosystem function because it is intrinsically linked to biodiversity (e.g., wildlife and habitat quality) through soil-plant interactions, nutrient cycles, and the water cycle. Our questions include the extent to which PV solar impacts differ from other anthropogenic development activities, and how we minimize the effects and maximize the enhancements provided by vegetation management consistent with the restrictions inherent in power plant operation.

SHEEP GRAZING AT AURORA LAWRENCE CREEK, ENEL

PV Facilities as Ecosystems

What are the types of effects on wildlife that result from habitat and ecosystem function alterations within PV facilities?

Much has been learned about adverse effects of anthropogenic developments on wildlife habitat and ecosystem function. It is not known how transferable this understanding is to the development and operation of PV facilities due to their unique infrastructure and opportunities for restoration and vegetation management. We consider PV facilities as ecosystems due to biotic (i.e., species composition including invasive species) and abiotic (e.g., temperature, hydrology, and albedo) conditions that are interacting within the footprint and in context to the larger landscape. Additionally, evidence suggests that PV facilities alter biotic and abiotic conditions related to construction and the presence of infrastructure. Construction and operation activities (Field et al. 2010; Macknick et al. 2013; Beatty et al. 2017; Choi et al. 2020) and the alteration of microclimates (Millstein and Mennon 2011; Barron-Gafford et al. 2016; Adeh et al. 2018; Choi et al. 2020; Tanner et al. 2020, 2021; Hernandez et al. 2020; Vervloesem et al. 2022) can alter soil-plant interactions, thus changing habitat quality and ecosystem function, and affecting the wildlife dependent on those site attributes. Further, soil disturbance and microclimate alterations could increase the abundance of invasive species, with potential, but as yet undetermined impacts on adjacent agricultural production (Uldrijan et al. 2021).

SOLAR PANEL CONSTRUCTION IN ALTAVISTA, VA, APEX

Soils. — Any soil disturbance, such as grading and vegetation removal during construction, can degrade soil properties and vegetative communities for extended periods (Field et al. 2010; Choi et al. 2020), release stored carbon dioxide from the soil altering terrestrial carbon cycling (i.e., carbon sequestration and storage; Rastogi et al. 2002; Moore-O'Leary et al. 2017), adversely affect insect abundance and community composition relative to natural controls (Saul-Gershenz et al. 2018), and emit dust that can adversely affect plant species (Piechota et al. 2004; Sarver et al. 2013).

Microclimate. — The local climate is important in predicting plant responses and regulating terrestrial nutrient cycles. The microclimates of a PV facility can affect on-site wildlife habitats by altering plant-specific responses (negative or positive) with potentially population-level consequences (Tanner et al. 2020, 2021; Hernandez et al. 2020) and alter ecosystem function. For example, the species composition of vegetation and bloom timing is different under panels when compared to other portions of the PV facility (Uldrijan et al. 2021; Graham et al. 2021). The direction and magnitude of the responses depend upon the region, vegetative community, and design of the facility (Armstrong et al. 2014, 2016; Liu et al. 2019; Guoqing et al. 2021; Vervloesem et al. 2022). It is hypothesized, but remains untested at PV facilities, that microclimates in PV facilities could influence ecological interactions, such as predator-prey dynamics and competitive outcomes (Grodsky et al. 2017; Moore-O'Leary et al. 2017; Sinha et al. 2018a; Nordberg et al. 2021).

Our understanding of what ecosystem functions will be enhanced by PV facilities also is low, and in some instances, ecosystem services will be negatively affected (Grodsky and Hernandez 2020). These enhancements are dependent upon restoration efforts, vegetation management decisions, and pre-construction land use, and are not necessarily associated with the PV facility's infrastructure. Restored facilities and vegetative management may enhance habitat and ecosystem function for wildlife species relative to the previous land use — for example in the conversion of agricultural lands (e.g., Montag et al. 2016; Sinha et al. 2018a; Walston et al. 2018; Randle-Boggis et al. 2020; Walston et al. 2021).

Most studies do not compare outcomes against natural or offsite restored habitats, which would isolate and fully address wildlife habitat and ecosystem function changes, if any, related to the PV facility's presence on the landscape. For example, the conversion of grassland habitats into a PV facility with restored grassland still had diminished soil nutrient cycling and carbon sequestration seven years post-construction (Choi et al. 2020), suggesting the infrastructure or construction affected habitat and ecosystem processes. Lambert et al. (2021) found that carbon and nitrogen content, basal respiration, and microbial biomass were lower at PV facilities relevant to various adjacent land cover types.

Although the ecosystem enhancements (e.g., pollinator abundance, carbon and nutrient cycling, and water and soil retention) of habitat restoration, including pollinator habitat, have plenty of support in the literature (Wratten et al. 2012; Blaauw and Isaacs 2014; Garibaldi et al. 2014; Randle-Boggis et al. 2020; Blaydes et al. 2021; Walston et al. 2021), much remains unknown about the enhancements in wildlife habitat and ecosystem function at the local and landscape level as a consequence of vegetation management strategies at PV facilities (Uldrijan et al. 2021). Moreover, ecosystem enhancements at PV facilities will depend on the region of the United States; persistence of long-term adverse effects of solar development on ecosystem function of natural lands, such as desert-shrub lands and forest habitats is worthy of study (see also mitigation below).


POLLINATORS WITH SOLAR PANELS, LIGHTSOURCE BP


SOLAR PLANT AND MOUNTAINS, PANCHOE VALLEY, CA, RUSS PARMAN, FLICKR

Fragmentation and Disturbance

How do PV facilities alter the movements of game animals and other wildlife?

Much remains unknown about the impacts of PV facilities on wildlife movement at different spatial scales and within different geographic regions. Habitat loss and perimeter fencing associated with PV facilities could reduce landscape permeability and impede the movement of game animals and other wildlife. There are three studies investigating the impacts of fragmentation and barrier effects related to PV facilities – pronghorn in Wyoming (Sawyer et al. 2022), Florida panthers (Leskova et al. 2020), and desert tortoises (Dutcher et al. 2020). These studies highlight connectivity reduction between suitable habitats or populations by PV facilities at the landscape level. However, at the local level, areas surrounding PV facilities managed or left as wildlife corridors can facilitate movement through the landscape by ungulates (Sinha et al. 2018a; Cypher et al. 2021) and potentially by desert tortoises (Hromada et al. 2020). Linear features, such as roads and utility corridors, will accompany PV facilities, and multiple studies, albeit not solar energy-related, report adverse impacts of linear features on various volant and non-volant species (Andrews 1990; Fahrig and Rytwinski 2009; Benítez-López et al. 2010; Hromada et al. 2020) including ungulates (Hebblewhite 2011).

What wildlife species display avoidance behaviors within the landscape near the PV facility's footprint?

Much remains unknown about what species display avoidance behaviors towards PV facilities, but the potential avoidance of PV facilities by wildlife, particularly big game, within the landscape is a growing concern. For game species, avoidance of PV facilities remains understudied or is extrapolated from research related to the oil and gas industries (Wyckoff et al. 2018, Green et al. 2016, Sawyer et al. 2010), although extrapolation may not be appropriate. For example, greater sage-grouse, known for avoiding oil and gas infrastructure (Doherty et al. 2008; Carpenter et al. 2010; Fedy et al. 2014), were observed foraging within a PV facility in Wyoming (Gerringer et al. 2022). It remains unknown if pronghorn exhibits avoidance behaviors towards this Wyoming PV facility (Sawyer et al. 2022), but some evidence suggests that PV facilities have little impact on elk behavior if properly sited (Mohr 2020). There is no evidence that raptors avoid PV facilities, and some raptors forage and nest in surrounding habitats (Cypher et al. 2019).

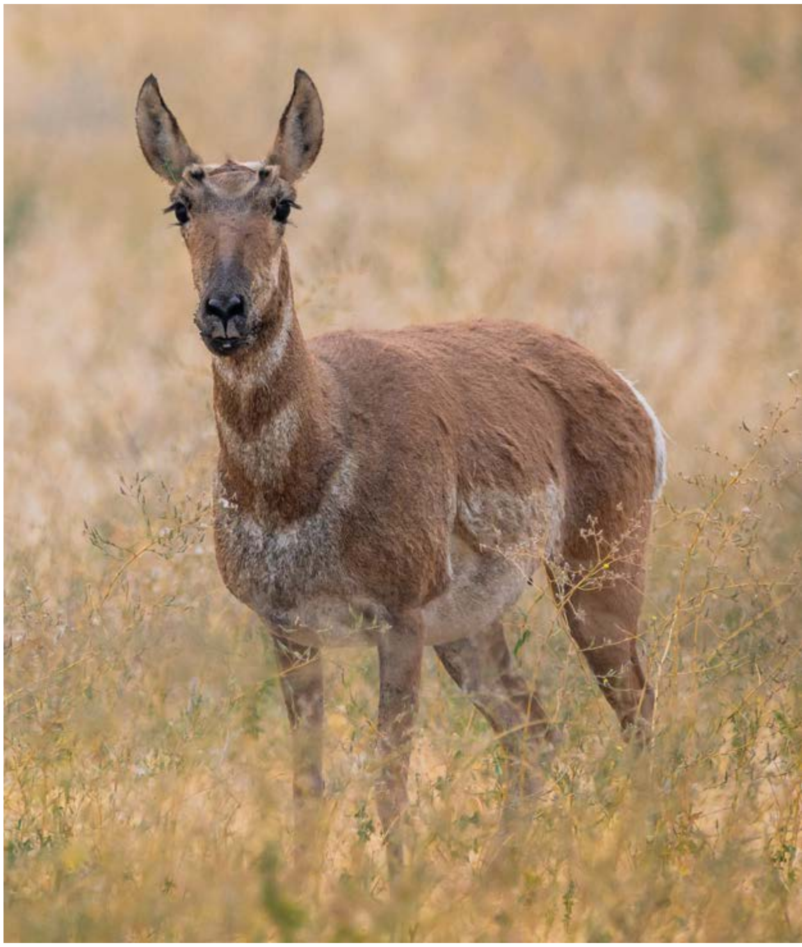
Habitat Concerns

How does wildlife fatality risk interact with vegetation management of PV facilities?

Only long-term demographic studies can determine if this occupation is maladaptive and creates an ecological trap (i.e., negative feedback loop), and it remains unknown if these facilities are sources or sinks at the meta-population level. Wildlife can occupy PV facilities with a variety of ground cover and adjacent land uses (e.g., DeVault et al. 2014; Beatty et al. 2017; Sinha et al. 2018a; Walston et al. 2018; Cypher et al. 2021; Kosciuch et al. 2021; Walston et al. 2021; Gerringer et al. 2022). Identifying which species will commonly occupy PV facilities will aid in our understanding of fatality risks and mitigation as they relate to vegetation management.

What impacts on aquatic wildlife and habitats are expected from PV facilities?

Very few studies have quantified the impacts on water resources caused by PV facilities, and no research has linked adverse impacts on aquatic wildlife to PV facilities. PV facilities have reduced water holding capacity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and water content or redistribution of soil moisture relative to natural habitats and agricultural lands (Lambert et al. 2021; Yavari et al. 2022). Concerns exist at PV facilities about water and soil retention (e.g., erosion), stormwater management, and the potential for adverse effects to water quality and the physiology of aquatic wildlife (e.g., Singh et al. 2003; Piechota et al. 2004; Belnap et al. 2011; Hoorman 2011). Simulations of hydrologic responses at PV facilities suggest that vegetative ground cover will increase water and soil retention and limit on-site chemical substances (e.g., dust depressants, fertilizers, herbicides, and oil and grease from vehicles) and sedimentation from entering the surface and groundwaters (Cook and McCuen 2013). In general, much remains unknown about impacts related to runoff and erosion as patterns are unclear at PV facilities (Yavari et al. 2022), but some results suggest soil erosion prevention and water infiltration increase at PV facilities with vegetation restoration (Beatty et al. 2017; Uldrijan et al. 2021).

However, much remains unknown about whether adverse effects on non-protected intermittent water features, such as desert washes and ephemeral streams, could be modified by PV facilities resulting in significant cumulative impacts on hydrology and watersheds (O'Connor et al. 2014; Grippo et al. 2015) and vegetation (Schwinning et al. 2011). Additionally, the interaction between the decoupled desert hydrology and altered microclimate down gradient (e.g., heat island) from the PV facility could adversely affect off-site vegetative communities (Devitt et al. 2022).

How can damaged and decommissioned panels increase contamination risks to wildlife?

Our understanding and certainty related to risk and exposure of wildlife to contaminants at PV facilities are low. Although there are concerns related to heavy metal leachate from damaged and disposed of panels, there is little evidence of a significant contamination risk to wildlife or habitat (Robinson and Meindl 2019), and most information focuses on human risks (Sinha et al. 2018b, 2019).

FATALITY IMPACTS

The uncertainty regarding our understanding of fatality impacts is exceptionally high, and broad generalizations of patterns and mechanisms currently are infeasible. Wildlife fatality impacts should be viewed in the context of the ecosystem concept and investigated in relation to biotic and abiotic conditions and their interactions. This approach deviates from merely calculating fatality rates per facility and standardizing rates by MW per year (i.e., the wind-wildlife paradigm) without the proper context of onsite and the surrounding landscape factors. REWI believes the ecosystem concept will unify how researchers and stakeholders view fatality impacts to further research toward understanding trends and mechanisms explaining wildlife risks. Some researchers have already placed fatalities in the context of the surrounding landscape (e.g., Kosciuch et al. 2021).

Wildlife remains, characterized as fatalities, have been reported at PV facilities and their associated infrastructure. We lack the data to evaluate the extent or magnitude of these fatalities beyond the southwestern United States, where most of the publicly available data focusing primarily on avian species have been collected (Kagan et al. 2014; Walston et al. 2016; Kosciuch et al. 2020; Kosciuch et al. 2021; Smallwood 2022). In turn, the causes of most fatalities reported within PV facilities

SOLAR PLANT IN THE PHOENIX DESERT, JERRY FERGUSON, FLICKR are largely unknown but may result from myriad causes, including panel and vehicle collisions, entanglement and entrapment in infrastructure, drowning, predation events, and electrocution. The available data are restricted to the southwest because these PV facilities were located on public lands and triggered the National Environmental Policy Act process. We know virtually nothing about fatality impacts on non-volant species or the cumulative impacts at the population level for any wildlife species.

Given that most causes of death remain uncertain, our understanding of how PV facilities influence direct and indirect fatalities is unknown. We know fatalities directly associated with infrastructure occur, but fatalities found in PV facilities may involve complex but unknown interactions among on-site management decisions (i.e., vegetation management and restoration) that attract wildlife, preconstruction land use (i.e., natural vs disturbed), and adjacent landscape types. Therefore, viewing solar-wildlife fatalities under the ecosystem concept is pivotal to understanding these potentially complex interactions. Reporting fatalities estimates without proper context will fail to identify trends and mechanisms.

SOLAR PANELS BESIDE A HIGHWAY, PORTLAND GENERAL ELECTRIC, FLICKR

This section provides fundamental questions related to solar-wildlife fatalities and summarizes what is currently known and where there is remaining uncertainty about fatality impacts, specifically the influence of on-site and landscape variables.

What species' remains have been found at PV facilities across regions of North America?

Our understanding of what wildlife species are dying at PV facilities is very limited taxonomically and geographically. Available data are largely restricted to birds in the desert southwest (see Walston et al. 2016; Kosciuch et al. 2020; Kosciuch et al. 2021; Smallwood 2022). Most reported fatalities have been small-bodied bird species, and the most common fatalities are of regionally abundant species that share similar ecological traits (Kosciuch et al. 2020), including ground-dwelling species and species commonly found in open, disturbed habitats. Interestingly, common bird species reported as fatalities at PV facilities are also common species reported as fatalities at wind facilities (AWWI 2020). In the southwestern U.S., remains of aquatic habitat birds are reported at PV facilities but at much lower numbers than songbirds (Kosciuch et al. 2020; Kosciuch et al. 2021). Other wildlife remains reported at PV facilities have included rabbits, rodents, snakes, lizards, medium-sized mammals, and frogs (Smallwood 2022). However, no study has evaluated causes of death for these wildlife groups, or changes in fatality rates relative to the surrounding landscape. Known bat remains at PV facilities include pallid bats, Townsend's big-eared bats, western mastiff bats, and Mexican free-tailed bats (Smallwood 2022). We discuss fatality rate estimates below.

How are fatality data collected and fatality rates estimated at PV facilities?

Post-construction monitoring, if conducted, consists of walking transects and searching for animal remains within the PV facilities. There is no standardized data collection procedure and protocols (e.g., number of years, the total percent of project sampled, transect length and width, survey type, searcher efficiency, and frequency of sampling) among solar sites/projects (Reyes et al. 2016; Smallwood 2022). These raw counts are adjusted using common fatality estimators, largely developed for wind energy facilities, to estimate bird,

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and to a lesser degree bat, fatalities at PV facilities; however, each estimator is different (e.g., assumptions and accounting for detectability variation) and may yield different fatality estimates (see Rabie et al. 2021). For example, three studies calculated different fatality estimates (i.e., 8.97 to 16.17 bird fatalities/MW/year) using the same bird fatality dataset from a PV facility (Walston et al. 2016; Kosciuch et al. 2020; Smallwood 2022). Therefore, any conclusions drawn from comparisons or aggregation of fatality estimates among studies should be done with caution.

What information do we have about fatality rate estimates at PV facilities?

There are wildlife fatality rate estimates from 15 PV facilities in the desert southwest of the U.S.—California and Nevada, and these are typically reported in a manner similar to fatality estimates from wind energy facilities. We report these numbers here, but as we have discussed, the utility of evaluating impacts to birds and bats in this manner is questionable without the context of onsite and landscape factors.

In the southwestern U.S., mean bird fatality rate estimates range from 2.49 to 11.6 fatalities/MW/year within the solar field (Walston et al. 2016; Kosciuch et al. 2020; Smallwood 2022) but increase on average by 5.9 fatalities/MW/year when all features (e.g., generation tie-ins, fencing, and overhead lines) are considered (Smallwood 2022). Site-specific estimated bird fatality rates varied considerably among solar facilities (Kosciuch et al. 2020; Smallwood 2022), suggesting site-specific and landscape factors potentially affect fatality rates. Time of year might be another factor influencing bird fatalities (Kosciuch et al. 2020). Therefore, without the proper contexts, such as onsite and landscape biotic and abiotic conditions and their interactions, we cannot yet explain the exceptional variation in bird fatality rates among facilities.

There is very little empirical information on avian-solar fatality outside the southwestern U.S., so it's uncertain whether the above-mentioned fatality estimates are applicable across the entire U.S. solar industry. Furthermore, there's little fatality information for other wildlife across the U.S. solar industry. Our understanding of bat fatality estimates is limited to one PV facility in the desert southwest of the U.S., where mortality was estimated to be 0.46 fatalities/MW/year (Smallwood 2022). There are no fatality estimates for non-volant wildlife species. In general, fatality data are too limited geographically and lack context, and extrapolation of these data to other facilities and regions is inappropriate.

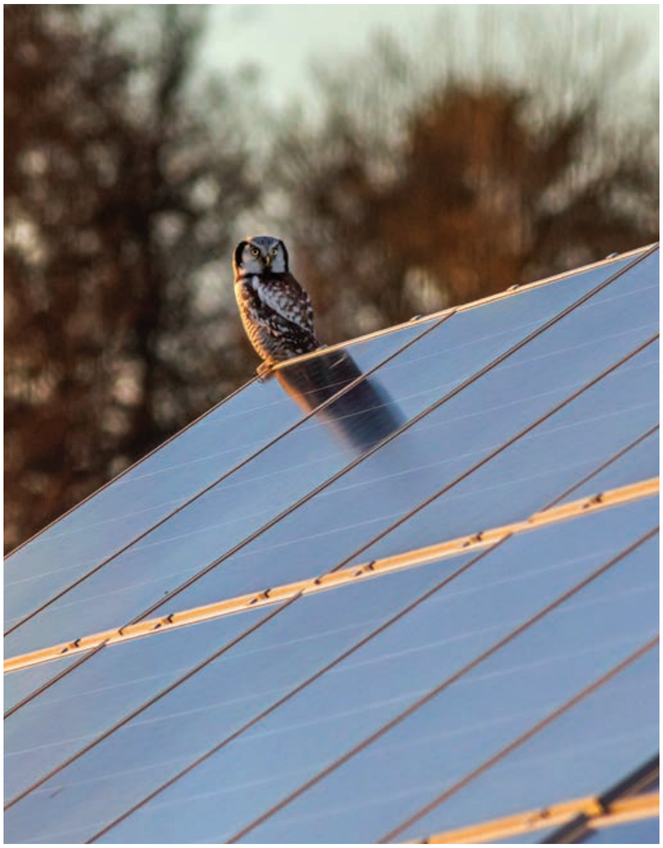
How does facility-related mortality compare to mortality in the surrounding landscape?

Background mortality is any natural wildlife mortality (i.e., biotic interaction) not related to PV solar infrastructure. Our understanding and level of certainty on background mortality is low as studies typically do not collect the data necessary to estimate mortality near PV facilities or in natural areas (see Kosciuch et al. 2020; Kosciuch et al. 2021; Smallwood 2022). When fatality monitoring does occur at PV facilities, the cause of death is usually unknown for birds (61%) and bats (89%), and what remains uncertain is the contribution of infrastructure-related mortality to these unknown fatalities (Kosciuch et al. 2020; Smallwood 2022). Furthermore, we lack an understanding of how PV solar facilities influence predator-prey dynamics (i.e., biotic interactions) onsite and within the landscape. For example, Cypher et al. (2019) reported no fatalities within the PV facility's footprint of San Joaquin kit foxes and six fatalities — one attributed to golden eagle predation — in the surrounding landscape.

Incorporating monitoring of background fatalities would provide more accurate estimates of the effect of the presence of the solar facility on survival and deaths of wildlife using the facility. However, the proximity of adjacent reference plots could introduce biases of counting facility-injured or killed wildlife in the background mortality (Smallwood 2022) or facility-altered fatalities (i.e., altered predator-prey dynamics) in the surrounding landscape perceived as natural. Before-After-Control-Impact studies are the best option to remove bias, understand background mortality, and establish a pre-construction baseline, but they are substantially more expensive than standard monitoring practices.

Are birds and insects attracted to PV facility's infrastructure?

Our understanding and certainty of wildlife being attracted to PV panels is limited, and largely restricted to birds and insects. Some early reports detected carcasses of aquatic bird species at PV facilities in the desert southwest, thus driving interest in the *Lake Effect* hypothesis (LEH), which posits that these bird species may perceive PV facilities as bodies of water (Kosciuch et al. 2020). By viewing fatalities in the context of the surrounding landscape, Kosciuch et al. (2021) reported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water-obligate species fatalities within PV facilities in desert-scrub, agricultural, and grassland landscapes, although in limited numbers, and not within the desert-scrub or grassland reference sites (Kosciuch et al. 2021). A recent study comparing fatality numbers at active PV facilities to background mortality at reference sites revealed no difference in estimated fatalities among PV facilities and reference sites, and no diurnal maladaptive behaviors of aquatic birds near PV facilities in the desert southwest (Kosciuch et al. 2021). However, preliminary experimental results suggest songbirds may perceive PV panels as water bodies due to emitted polarized light (REWI Solar Symposium 2021). In general, there is little evidence supporting the LEH significantly driving bird fatalities in the desert southwest and in other regions; however, progress is being made by various stakeholder groups (e.g., Avian Solar Working Group) in understanding the mechanism(s) (e.g., sensory and behavioral ecology) that could explain the LEH.

Aquatic insects are attracted to panels by the emittance of polarized light (Horváth et al. 2009; Horváth et al.

2010). For example, male dragonflies were observed interacting (e.g., territory defense behaviors) with PV panels, but females were not observed ovipositing on the panels (Langan and Green 2013). Some panel collisions of volant wildlife could be from predator-prey interactions with aquatic insects (Smallwood 2022); however, much remains unknown about these ecological interactions at PV facilities.

Are wildlife fatalities numerous enough to adversely affect populations or have cumulative impacts?

Our understanding is limited to two demographic modeling studies combining solar technologies (PV and CSP) in the western United States (Katzner et al. 2020; Conkling et al. 2022). In general, the studies suggest that if fatalities are additive and pass certain thresholds (e.g., species-specific fatalities exceed 1,000 or 5,000 individuals), which include non-solar, anthropogenic sources of fatalities, then PV facility buildout on the landscape could adversely impact local and regional populations of some species (Katzner et al. 2020; Conkling et al 2022). The likelihood of PV solar-related fatalities per species reaching these levels annually remains unknown. Additionally, 92% of avian tissues included in the study were from three CSP facilities in Conkling et al. (2022) and reported estimates of CSP bird fatalities are substantially higher than PV-related estimates (Ho 2016; Smallwood 2022). More wildlife studies are warranted to assess local and cumulative impacts of PV facilities because the development of PV facilities will continue to outpace CSP developments on the landscape. Additionally, more studies assessing the local and cumulative impacts of PV facilities on groups of species that are long-lived with low fecundity are needed.

MITIGATION, ENHANCING BENEFITS, AND ON-SITE MANAGEMENT

The mitigation hierarchy includes avoiding, minimizing, and compensating for impacts to wildlife resulting from the construction and operation of PV facilities. In general, our understanding of mitigation measures' effectiveness is in its infancy at PV facilities, but these measures could include avoidance via siting, co-location, fatality mitigation, wildlife-friendly fencing or spacing, and various vegetation management strategies. Using the mitigation hierarchy, we can begin to evaluate and understand net biodiversity and ecosystem effects (impacts and benefits) at PV facilities through siting on degraded or marginal agricultural lands and on-site vegetation restoration.

Avoidance is a powerful mitigation action, and many resources have been developed to guide PV facility siting to avoid sensitive species and habitats (see Cameron et al. 2012; Hernandez et al. 2015a, 2015b; Phillips and Cypher 2019; Curtis et al. 2020; DOE 2021b; RE-Powering Mapper 2022; Solar Mapper 2022). Avoidance through proper siting is critical in protecting lands for wildlife and ensuring net biodiversity and ecosystem benefits. For example, co-location of PV facilities on abandoned, degraded (e.g., brownfields or grayfields), or agricultural lands is an often-cited strategy to meet energy demands while simultaneously sparing natural habitats (Adelaja et al. 2010; Dupraz et al. 2011; Macknick et al. 2014; Adeh et al. 2018; ACP 2022; Hall et al. 2022) and improving biodiversity and ecosystem benefits if paired with on-site vegetation restoration. However, all these co-location strategies present challenges (e.g., additional costs and liabilities) to the developer (see ACP 2022).

Minimization will come in two forms — on-site habitat restoration and fatality reduction. On-site habitat restoration has garnered much attention in the PV solar industry in the form of pollinator-friendly solar or native grassland restoration to minimize habitat loss within the footprint. The benefits of vegetation restoration in solar facilities include enhanced wildlife habitat and ecosystem function, and a variety of ecosystem services, such as pollinator services, agrivoltaics, and soil and water retention. However, native vegetation restoration at PV facilities is a relatively new practice, and more research on the degree and magnitude of habitat quality and ecosystem function outcomes related to the various vegetation management strategies (e.g., grazing, mowing, seed mixes) is needed by region.

SOLAR PANELS WITH FENCING, PHOENIX SOLAR, PATTERN

What is lacking is a comprehensive understanding of solar-wildlife fatality risks across geographies and the tested minimization practices (i.e., physical, operational, and abatement controls) to reduce fatalities at operational PV facilities. There is a wealth of information about the effectiveness of fatality minimization in other human-altered settings. However, before effective mitigation can occur, more research is needed to identify the causes and magnitude of fatalities and types of habitat impacts caused by PV facilities and associated infrastructure.

How can solar facilities be sited and designed to maximize permeability and decrease fragmentation on the landscape?

Minimizing fragmentation and barrier effects while maximizing the permeability of PV facilities is of interest to stakeholders, especially for large mammals at the landscape level (DOE 2021b; Leskova et al. 2022; Sawyer et al. 2022), but permeability concerns (i.e., wildlife-friendly fencing) exist at the local level for other wildlife as well (DOE 2021b). Avoidance through low-risk siting is the best strategy to minimize fragmentation, and many resources and tools exist related to siting (see DOE 2021b; RE-Powering Mapper 2022; Solar Mapper 2022) and some specifically address fragmentation (e.g., TNC 2019a - NC Solar Siting Webmap). In general, research on the effects of PV facilities on wildlife movement ecology, especially for migratory species and species with large home ranges, is limited. Broad generalizations about fragmentation outcomes currently are inappropriate, and more research is warranted.

At the local level, design features have improved onsite and adjacent landscape permeability. Appropriate micro-siting that avoided critical features, such as hibernacula, burrows and dens, and suitable habitat, reduced impacts and increased onsite permeability for various wildlife (e.g., San Joaquin kit foxes and kangaroo rats) (Cypher et al. 2021). Similarly, design considerations, such as many small blocks of PV panel arrays dispersed in the landscape instead of a single large block, can increase landscape permeability by accommodating migratory routes, important winter grounds of ungulates (e.g., pronghorn and elk), and water courses (i.e., Sinha et al. 2018; Cypher et al. 2021).

Wildlife-friendly fencing[3] is not a novel mitigation strategy within the conservation community, although its implementation at PV facilities is rare. Fencing surrounding facilities (i.e., at least 2.1 meters in height) is required by the National Electric and National Electrical Safety Codes and also by the local Authority Having Jurisdiction. Few studies have studied the effectiveness of wildlife-friendly fencing relative to traditional fencing at PV facilities. However, wildlife-friendly fencing allowed the passage of medium to small vertebrate species at PV facilities (Sinha et al. 2018a; TNC 2019b; Cypher et al. 2021), thereby increasing local permeability.

[3] Wildlife-friendly fencing can include a wide variety designs, features, and materials. We refer the reader to Paige et al. (2012).

What fatality minimization measures have been evaluated at PV facilities?

The type and value of specific mitigation will depend on the affected species and the predominant fatality mechanism. Potential mitigation measures for fatalities could include ultrasonic and acoustic deterrents (Walston et al. 2015; Smallwood 2022), vehicle management plans (Lovich and Ennen 2011), micro-siting roads and infrastructure to avoid high-density wildlife areas (Cypher et al. 2021), various fencing modifications (Murph and Pettie 2015), panel borders and coating (Horváth et al. 2010; Black and Robertson 2020; Fitz et al. 2020), enhancing exclusion and escape structures in ponds (Jeal et al. 2019), and translocation of wildlife (Brand et a. 2016; Dickson et al. 2019). Additionally, soil compaction mitigation measures include soil ripping (i.e., subsoiling or tilling), composting (i.e., adding organic matter), air spading or aeration, low-pressure tires for vehicles, and tracked vehicles (MPCA 2021, Chamen et al. 2015). The latter two examples could minimize burrow and tunnel collapses that might cause entrapment fatalities during operation activities (e.g., maintenance and vegetation management). All these mitigation measures are largely untested at PV facilities, and their on-site effectiveness needs further research.

What are the effects of on-site vegetation management practices to wildlife habitat?

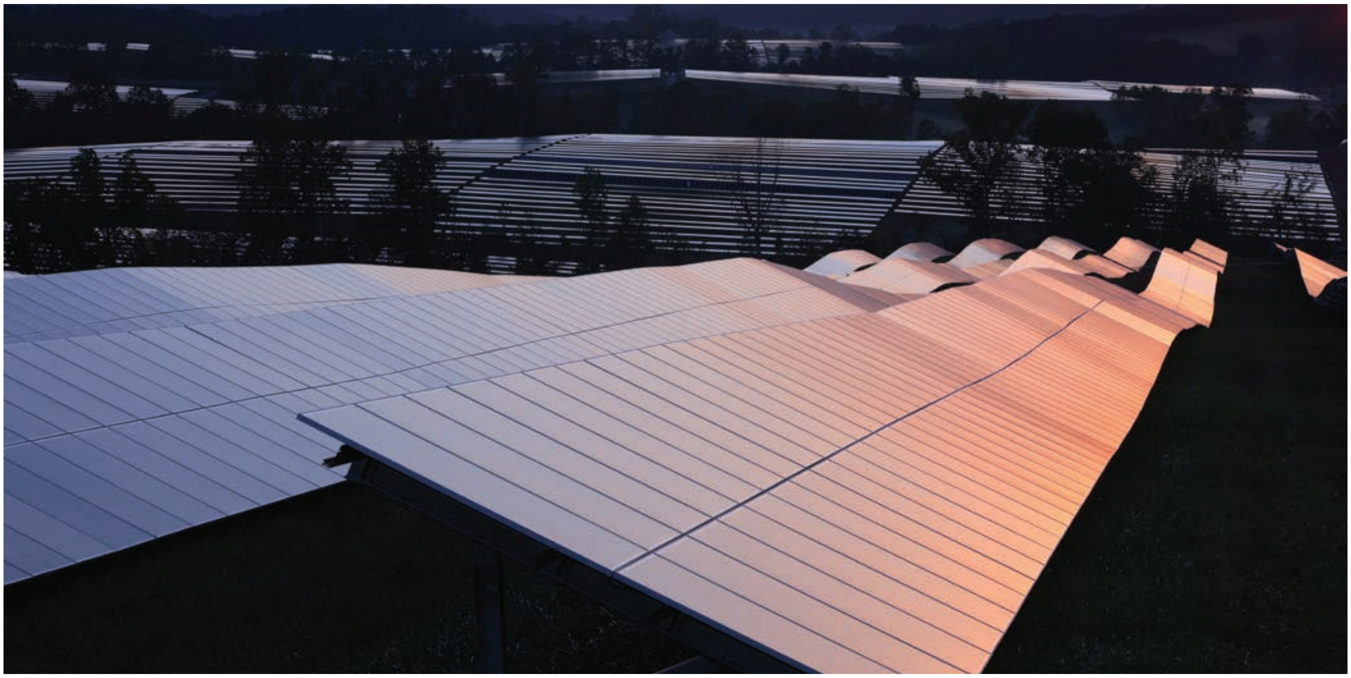
Depending on the region of the United States, there will be various ground covers and vegetation management practices, such as bare soil, graveled, turfgrass, native vegetation restoration (e.g., solar-pollinator habitat), or a combination of these. Regardless of ground cover type or vegetation management practice, regular maintenance is required to prevent vegetative shading of panels and control of invasive plant species, and the various decisions related to vegetation and ground cover (e.g., maintenance and vegetation type [native, turfgrass, or a combination]) will affect wildlife differently (e.g., Bollinger 1995; Washburn and Seamans 2007; Graitson et al. 2020; Filazzola et al. 2020; Blaydes et al. 2021; Walston et al. 2021).

Best management practices proposed for vegetation management of turfgrass and solar-native habitat restoration include lower frequency and intensity of mechanical mowing/cutting, avoiding summer mowing/cutting and ground-nesting season, replacing mowing/cutting with low-intensity grazing, and planting native vegetation and hedgerows in undeveloped areas (BRE 2014; M'Gonigle et al. 2015; Graham et al. 2018; Blaydes et al. 2021). Both turfgrass and native habitat restoration could require herbicide applications.

Livestock grazing at PV facilities may also be used to manage vegetation and could enrich soils and reduce mechanical mowing and cutting (Blaydes et al. 2021). However, the intensity and timing of the grazing could have impacts on pollinators, ground-nesting species, and their habitats. For a more detailed discussion on agrivoltaics, including grazing, we refer the reader to review papers (e.g., Dinesh and Pearce 2016; Mamun et al. 2022; Walston et al. 2022).

The creation of artificial refuges is a mitigation strategy (or best practice) deployed to minimize habitat loss and degradation (Cowan et al. 2021). Artificial refuges can include nest boxes, dens, burrows, and generated crevices (log, rock and stone piles) (BRE 2014; Cowan et al. 2021). This mitigation strategy is rarely deployed at PV facilities in North America, and its effectiveness has not been tested at these types of facilities.

POLLINATORS WITH SOLAR PANELS, AURORA CHICAGO, ENEL



SUNSET REFLECTED, ALTAVISTA, VA, APEX

Which species will benefit from vegetation restoration and the ecosystem created by PV facilities?

Many studies report that restored vegetation at PV facilities, including pollinator-friendly solar, will support pollinators and insects (e.g., Parker and McQueen 2013; Montag et al. 2016; Walston et al. 2018; Blaydes et al. 2021; Walston et al. 2021) and other wildlife species (e.g., Peschel 2010; Montag et al. 2016; Wilbert et al. 2015; Sinha et al. 2018a; Cypher et al. 2021; Kosciuch et al. 2021; Gerringer et al. 2022). For pollinators, restored facilities could provide foraging and reproductive resources and improve landscape connectivity (see Blaydes et al 2022). However, much remains unknown due to a lack of empirical evidence related to the effects of PV facilities on pollinator diversity and abundance in the United States (Dolezal et al. 2021). Another concern is whether native seed availability is able to keep up with ecological restoration demands (Pedrini et al. 2020). What remains unclear is if the removal of woody debris from facilities limits the re-establishment of some native bees and other insects, which need woody debris of various decomposition stages for nesting and refugia.

PV infrastructure could provide perches, nesting opportunities, and thermal refugia for some bird species (Peschel 2010; Beatty et al. 2017; Gerringer et al. 2022) and provide some habitat value (e.g., perching) even in the absence of native vegetative restoration (see DeVault et al. 2014). However, much remains unknown about the enhancements, if any, of infrastructure on priority and sensitive species and other wildlife. For example, no study has tested whether restored vegetation (e.g., native and turfgrass) at PV facilities offers the same quality of habitat as natural habitats, nor has a study quantified changes in predation-prey dynamics due to the perching availability provided by PV facilities. In general, grassland and motile species that can adapt to the infrastructure and the modified abiotic and biotic conditions (i.e., ecosystem) will be more likely to occupy PV facilities, and depending on pre-construction land use and adjacent habitat, we should expect species composition shifts. However, there is a lack of long-term data related to adverse impacts and source/sink dynamics for these wildlife species attracted to PV facilities.

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