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Review

Assessing the Impact of Solar Farms on Waterbirds: A Literature Review of Ecological Interactions and Habitat Alterations

Crystal M. Anderson, Andrew P. Hopkins and James T. Anderson *

James C. Kennedy Waterfowl and Wetlands Conservation Center, Belle W. Baruch Institute of Coastal Ecology and Forest Science, Clemson University, Georgetown, SC 29442, USA; crhode2@clemson.edu (C.M.A.)
* Correspondence: jta6@clemson.edu; Tel.: +1-(304)-276-8956

Abstract: Given the threat of climate change caused by greenhouse gas emissions, climate-safe alternatives are receiving more attention. One of the most widespread solutions is the implementation of solar-powered technologies. These technologies, once implemented, do not increase emissions and provide safe, clean energy sources. However, large-scale solar farms require large amounts of land space in areas that receive increased sunlight to operate successfully. As such, there have been proposals to establish solar farms adjacent to or encroaching on wetland habitats. Currently, little is known about the interactions between wildlife, specifically waterbirds, and solar installations in wild areas, specifically wetland environments. In this article, we examine the current knowledge base of wildlife interactions with solar infrastructure in natural environments. We highlight a significant need for more information on wetland ecosystems and the responses of migratory waterfowl that are dependent on these ecosystems. Finally, we present methods of mitigation to reduce the occurrence of these interactions and future considerations for research. While solar facilities represent an opportunity to decrease the reliance on fossil fuels, care must be taken so that their installation does not harm local ecosystems.

Keywords: solar; wetlands; waterbirds; wildlife; waterfowl

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1. Introduction

Climate change is a major force impacting both the environment and ecosystems globally. Greenhouse gases are a leading cause of climate change, with energy production being a major contributor to this, with ~1500 metric tons of CO_2 released globally [1]. Because of this, there has been a strong push toward renewable resources, with solar being a leading source. Solar energy can provide environmental, financial, and human health benefits through improved air quality and reduced payback time, making it a valuable alternative to fossil fuels and helping us reach sustainability goals [2,3]. Since its invention, solar energy generation has quickly spread and seen rapid growth and advancements.

In 1986, the world's largest solar facility was built in Kramer Junction, California, USA, to generate electricity using mirrors that focused sunlight into pipes with heat transfer fluid that produced steam to drive the turbines [4]. As of 2023, the United States Photovoltaic Database detailed a total of 4185 solar power facilities spread across 47 states and the District of Columbia, contributing to 4% of the nation's electricity generation [5,6]. It is projected that in the United States, solar power generation will grow 75% between 2023 and 2025, making it one of the fastest-growing clean energy options [7,8]. With the effects of global climate change becoming more evident, the push for alternatives to fossil fuels and carbon emissions is on the rise. The pursuit of carbon emission neutrality is motivating many nations to intensify their green renewable energy portfolio [2,9–13].

Reducing carbon emissions can mitigate climate change and alleviate negative impacts on wildlife; however, the installation of renewable energy infrastructure may also pose direct and indirect threats to local abiotic factors and wildlife populations, requiring the careful planning of infrastructure to ensure robust ecological and wildlife safeguarding [14]. Solar panels mounted to the ground have the greatest chance of creating direct and indirect habitat alterations, demonstrating the need to understand their impacts at the regional scale [15,16]. Green infrastructure, though beneficial, may adversely affect adjacent natural areas due to its proximity to protected ecosystems, the physical footprint of the infrastructure, and associated environmental impacts, including the loss of ecosystem services and potential risks to wildlife [1,17–20]. Despite growing support for green energy initiatives, local communities may oppose green energy projects and developments due to a range of factors [17,18,20–23]. There is a growing need to address concerns proactively to ensure green energy projects can be developed with the support of local communities, contributing to a sustainable and clean energy future.

Climate change is increasingly impacting wildlife through changes in migration patterns, mating behavior, access to food, and extinction events [15,24–29]. Waterbirds are a vital part of wetland ecosystems, serving as herbivores, vectors for seed, invertebrate, and nutrient dispersal, pest control, and biodiversity maintenance [30–33]. Due to these factors, waterfowl and other waterbirds represent a crucial component of wetlands, and building projects that may impact their biological capacity should be carefully investigated. Currently, there is a lack of information on the interactions between waterbirds and solar infrastructure in or around wetlands.

The objectives of this study were to conduct a comprehensive global literature review to determine the impacts of solar farms on waterbirds with a focus on waterfowl to gain an understanding of the interactions between anthropogenic effects of solar farms and other artificial infrastructure on habitat variables and wildlife. To do this, we conducted a literature review focusing on the impacts of solar infrastructure on natural systems. This paper aims to give insight into (1) how solar farms impact abiotic factors such as the potential for environmental contamination, microclimate, and land use; (2) the ways solar farms affect wildlife interactions through changes in migration, mating behavior, food web dynamics, species interactions, and resource availability; and (3) ways to minimize the negative impacts of solar farm installation on abiotic factors and wildlife, with a focus on migratory waterfowl, and provide insights that can inform the careful planning and implementation of renewable energy infrastructure to balance ecological protection with the need to reduce carbon emissions.

2. Materials and Methods

We conducted a comprehensive global literature review to identify reoccurring themes on the impacts of solar energy farms on habitat alteration, including soil structure, vegetation changes, hydrology, microclimate, land fragmentation, and food availability. Specifically for waterbirds, we looked at overall ecology, behavioral patterns, species richness, diversity, and abundance and assessed community concern on impacts on waterfowl populations regarding behaviors of nesting and breeding of migratory waterfowl populations. We conducted the literature review using the following methods:

1. Databases: Google Scholar, Web of Science, Scopus;
2. Detailed search terms, including Boolean queries, dates, and databases: Appendix A;
3. Listserv inquiries: ECOLOG-L, TWS Wetland Working Group, and Afton Waterfowl;
4. Individual communications with green energy, wetlands, and waterfowl scientists from around the world to collect both published and unpublished data;

5. Deduplication to determine the total number of papers included in the literature review; and
6. From these papers, we further narrowed the results by focusing on papers that referenced solar or photovoltaic and wildlife species. Then, we narrowed these results further by searching for avian or waterfowl-focused papers.

3. Results

Using the databases outlined in the methods and Boolean queries described in Appendix A, we searched for solar and wildlife interactions and found 472 papers. Deduplication removed 39 copies from the total number of papers we retrieved, bringing the total number to 433. From there, we narrowed our search to any paper that contained any reference to solar or photovoltaic and had a term that referenced any wildlife species, excluding a further 388 records. From the remaining 45 records, we looked specifically at solar and any reference to avian, waterfowl, or duck, leaving 19 records. Our database query found no papers that directly investigate the impacts of solar infrastructure on waterfowl species (Figure 1).

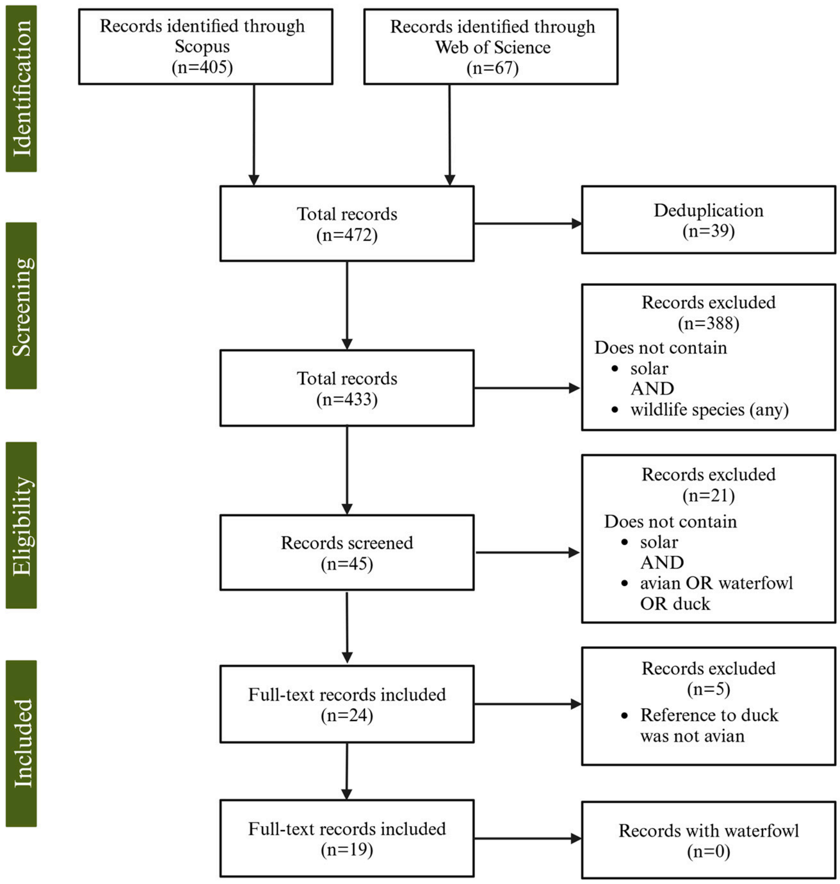

Figure 1. Scopus and Web of Science search results for the impacts of solar infrastructure on waterbirds.

The final articles used for this paper from the full literature review incorporated a total of 141 sources, identified through a combination of Boolean database searches from the Web of Science and Scopus as previously described, listserv requests, personal communications, and Google Scholar queries. After filtering for studies that specifically addressed interactions between solar energy infrastructure and any wildlife species, 29 relevant records were retained. Narrowing the focus to interactions between solar energy and avian species reduced the dataset to 25 records. Of these, a detailed examination of references to waterfowl species resulted in the identification of five relevant sources from a global search (Figure 2).

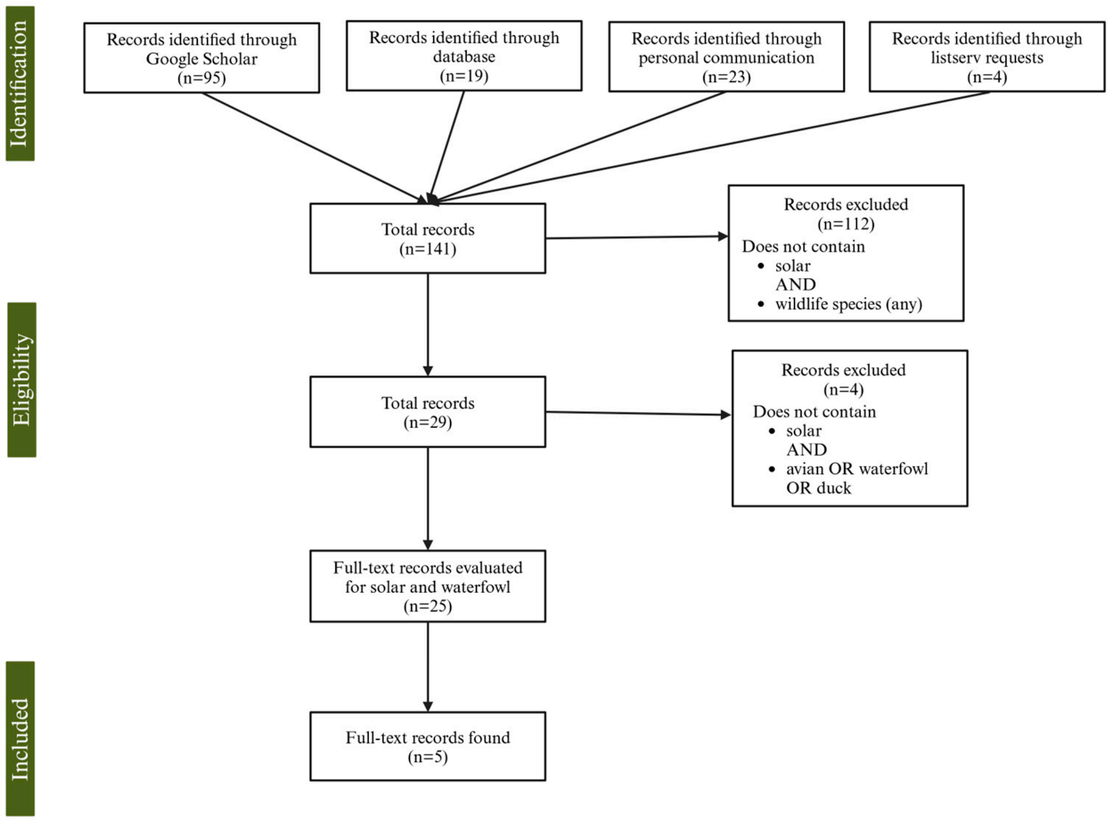

Figure 2. Papers included in the review by source, number, and relevance.

We broke down the literature review into relevant information in several key areas detailing the potential impacts of solar infrastructure on natural habitats and wildlife. These areas are environmental contamination, microclimate, land use, and wildlife interactions (Figure 3). We found no current studies that have examined the potential for contamination from the materials in aged or damaged panels. For aspects related to microclimate, we found ~25 papers focusing on the impacts of local climate impact. However, none of these papers focused on wetland environments and predominantly focused on arid and urbanized systems. There were roughly nine papers that addressed the impact of solar systems and the surrounding land use, and their focus centered on arid landscapes and grasslands, similar to other reviews of existing literature. Finally, in our review of the interactions with wildlife, we found six papers that directly mentioned or worked with waterbirds. Furthermore, despite the focus on waterbirds, the papers predominantly focused on arid environments and grasslands.

Our literature review revealed that existing research on solar installations is concentrated predominantly within a specific ecological niche, primarily focusing on arid, xeric environments. This geographic and climatic focus limits the generalizability of findings, providing insufficient insights into the potential impacts of solar infrastructure on diverse taxonomic groups across other ecological systems. Our findings substantiated an emerging discourse within the scientific community, highlighting a significant research gap concerning the environmental impacts of solar energy installations within biodiversity hotspots. Specifically, while these regions are critically important for sustaining species diversity, there is a notable gap in understanding how solar installations may affect different taxonomic groups in temperate, tropical, and coastal habitats, where environmental variables, species compositions, and ecosystem processes differ substantially from those in arid regions. Expanding research to include these varied systems is crucial for developing a comprehensive understanding of the ecological consequences of solar infrastructure on biodiversity across broader environmental gradients. The lack of extensive scientific research on complex ecological systems constrains the development of evidence-based management strategies essential for effective ecological conservation. Robust, system-level insights are necessary to inform targeted interventions, assess potential trade-offs, and optimize conservation outcomes across diverse and interconnected environmental contexts.

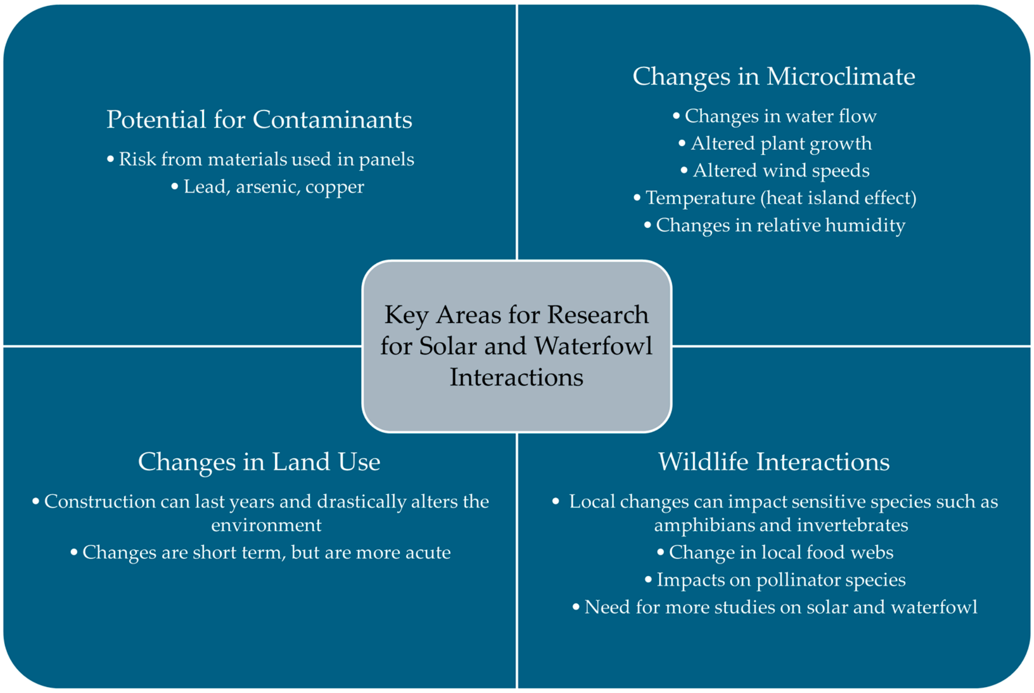

Figure 3. Focal areas of solar impacts identified from literature review.

4. Discussion

Through the literature review, we identified several key interactions with solar installations that have the potential to impact waterbirds and waterfowl. There is a lack of information on how solar influences factors such as environmental contaminants, microclimate, land use, and interactions between species and how these would play out in wetland environments. Here, we discuss how these interactions can influence wetland environments and the avian groups (waterbirds and waterfowl) that are dependent on wetland environments as part of their life histories.

4.1. Environmental Contaminants

Currently, two generations of photovoltaic panels are widely installed. The first, monocrystalline and polycrystalline silicon, contain hazardous chemicals such as lead, ethylene vinyl acetate (EVA), chlorofluorocarbons (CFCs), and poly/brominated flame retardants [34–36]. Second-generation photovoltaic panels are made from cadmium telluride, copper indium gallium diselenide, and other heavy metal-containing materials. The main concern about these components comes from their potential to leach into the surrounding environments when damaged or at the end of life (25–30 years), thus creating a significant environmental hazard. Studies have found that when using the Toxicity Characteristic Leaching Procedure, the leachate from broken/damaged polycrystalline panels can reach between 6.6 mg/L (lead) and 43.9 mg/L (copper), exceeding the 5 mg/L regulatory standard [37,38]. Studies have shown that the occurrence of acid rain can lead to increased leeching of the contaminants into surrounding areas [39]. A third generation of nanomaterial and dye-based solar panels is seeing increased use and contains fewer of the key toxic components than first- and second-generation panels; however, they still contain several critical toxic components [40,41]. While solar may not have the CO_2 emissions of coal and other technologies, it is still closely associated with toxic chemicals, and as such, these potential impacts should be considered before their installation in or around wetlands.

4.2. Microclimate

Solar farms can alter microclimates, influencing water distribution, plant growth, and microorganisms (Table 1) [42–46]. The height and angle of solar panels can alter microclimatic variables such as temperature, wind speed and direction, relative humidity, soil moisture, vegetation dynamics, and water usage [47,48]. Studies have produced conflicting findings regarding the potential for solar farms to induce a heat island effect as a result of changes in albedo [49–52]. The use of vegetation in solar installations contributes to reduced wind speeds and narrower diurnal variations in soil temperature than non-vegetated solar sites [53]. Microclimate changes are correlated to local climate and landscape characteristics, with larger farms producing stronger effects [52].

Solar farms can influence water infiltration and runoff patterns through altered land surface characteristics and changes in vegetative cover [47,54–57]. Photovoltaic panels create uneven precipitation distribution, increased soil water fluctuations, reduced drought, and higher soil water availability due to lower evaporation rates and concentrated water at panel edges [47,55–57]. The integration of solar arrays with vegetation homogenizes soil moisture distribution and buffers against extreme soil temperatures, with vegetated solar sites maintaining higher soil moisture compared to bare soil solar sites [53,58]. Water runoff is more significantly influenced by the extent of vegetation cover than by the presence of solar panels themselves [59]. Simulations at varying slopes measured runoff with different rainfall intensities, and panel configurations showed that solar panels increase peak discharge 11 times over a reference slope, but a moderate positive impact was seen when slope-aligned panel placement was used [54]. The actual effects of solar farms may not be fully known because they are often assessed without accounting for the absorptive properties of impervious surfaces, leading to inaccurate estimates of water infiltration and an overestimation of runoff [60]. There are potential mitigation techniques that can minimize impacts on hydrological processes and soil erosion, but further investigation into these techniques is needed to determine whether the measures currently used are sufficient [61].

Table 1. Potential impacts of solar farms on microclimate in wetlands.

Factor	Effect	References
Water and hydrology	Altered soil moisture, humidity, water usage, and runoff patterns	[47,55–57]
Vegetation	Potential to mitigate issues such as altered temperatures and water flow	[53,58]
Temperature	Potential to create heat islands and alter local area albedo	[49–52]

In agricultural regions, the implementation of well-designed solar farms can potentially enhance biodiversity by substituting monocultural practices with more diverse ecosystems [62,63]. Still, little science exists on how solar installations may impact biodiversity hotspots such as wetlands. Most research on impacts on microclimates and wildlife has been performed in arid regions, which are a stark contrast to the high biodiversity found in wetland environments [64]. Solar farms have more recently been included in the push towards green energy, and few have been studied outside of the Southwest, providing limited data on solar impacts on avian species in forested or wetland systems [65–67].

4.3. Land Use

The initial construction of solar farms can last anywhere between 2 and 3 years. During this time, the machinery needed for the construction of solar farms can impact numerous aspects of wetlands, including, but not limited to, excessive loud noise and loss of habitat [68,69]. This disturbance's impacts can lead to the exclusion of native species and create unsuitable environments or stopover points for migratory species. Additionally, the effects of construction equipment and processes can lead to alterations in water quality through soil disturbances and the runoff of pollutants such as lubricants and hydraulic fluids [68]. While modifications in microclimate, hydrology, soils, and vegetation have a cascading effect on wildlife, land conversion leading to habitat fragmentation is a major threat to biodiversity, as it limits resources, increases species isolation, and undermines population size and genetic diversity essential for wildlife conservation [70–73]. Solar farms are often sited in undeveloped rural areas that frequently serve as critical wildlife movement corridors, potentially altering the biogeography of rare, at-risk, or endangered species [74]. Wetlands are no exception, providing high biodiversity and many vital ecosystem services that benefit both the environment and anthropogenic concerns. The amount of land used to create solar farms can create significant barriers for wildlife species, disrupting movement patterns critical to life cycles and ecological needs [75].

When built with anthropogenic land cover types, as opposed to semi-natural environments, solar farm construction can result in a decline in both soil physical and chemical quality [58]. However, ecologically focused strategic placement of photovoltaic panels can positively influence several soil properties, including enhanced soil aggregate stability, increased microbial communities, and elevated organic matter content [76]. Soil properties and vegetative diversity are interconnected, with their interactions influenced by geographic and climatic variables [52,77]. In grasslands, photovoltaic panels contribute to the enhancement of beneficial microbial communities and increase plant diversity [78]. Solar installations impact plant communities by altering soil conditions but also through changes in light availability, often benefiting shade-tolerant species while limiting heliophilic species [52]. Early successional plant communities do not show lasting impacts on solar farm installation, but this may be a result of their rapid growth, resource allocation, and greater tolerance to harsh conditions [58]. The potential impacts of solar installations in and around natural environments have exhibited varied impacts of habitat alteration, with some studies showing degradation and others showing increased refuge for biodiversity [79]. However, more studies must be conducted in this area, as the lack of research leads to uncertainty.

4.4. Wildlife Interactions

The direct impacts of solar farm installations on wildlife are varied, encompassing both beneficial and detrimental effects (Table 2). Solar farms can modify the natural behavioral patterns of wildlife species [75,80]. Species may experience altered home ranges when their range overlaps with solar arrays [75]. Projects that incorporate evaporative cooling ponds or artificial wetlands may attract insects, foraging birds, amphibians, and waterfowl populations [69,81]. Pollinator species seem to have the most to gain from solar installations, with research demonstrating that the inclusion of pollinator plants can increase pollinator abundance threefold over 5 years [82]. Solar farms potentially impact multiple levels of local food webs in the environments where they are installed [83]. Habitat fragmentation has a top–down impact on food webs due to the inability of smaller isolated patches of land to support larger predator species, creating a non-proportional loss of large carnivore communities [72]. The installation of solar farms near open water and agricultural fields can create benefits for certain wildlife species based on the method of site development but can increase avian mortality, demonstrating the need for project planners to evaluate the presence of protected, threatened, and endangered species [29,84].

The location and size of solar energy projects, along with the type of technology used, can greatly influence their impact on bird habitats, with larger projects and those located in sensitive areas creating larger disturbances [67,85]. Wildlife mortalities from solar farms are reported from a range of causes, including solar flux, impact, electrocution, and entrapment, with avian species disproportionately affected compared to other taxa [86–90]. One source of mortality affecting birds at a higher rate is heliostat or concentrated solar projects. Solar facilities of this design feature unique mortalities apart from the typical collision that is seen elsewhere. Concentrated solar facilities see birds suffer from extreme heat flux, where they fly into the concentrated solar beam, leading to severe burns and singed feathers. These facilities use an array of mirrors to focus solar energy into a central tower, which generates electrical power. Feather properties have been used to assess the angle of focusing mirrors to reduce solar flux impacts on avian species [91,92]. Bird fatalities at solar energy sites may increase due to birds being attracted to the area by artificial habitats, insects, and glare from the projects, leading to a higher risk of collisions with structures [83]. Extrapolated avian mortality counts have shown that solar farms are responsible for 37,000–138,000 avian mortality cases annually across the United States [85]. These mortalities fall into either collision-related mortalities or the aforementioned solar flux singeing. A study examining avian mortalities in the Southwestern U.S. noted the relative percentages of different species and groups and found that Mourning doves (*Zenaida macroura*) were the most commonly found (12.92%), followed by Horned lark (*Eremophilia alpestris*) (11.93%), and House finch (*Haemorhous mexicanus*) (8.41%) [66]. The most commonly identified waterbirds were American coots (*Fulica americana*) (2.87%) [66]. While these data do provide some representation of the breakdown of different species occurrence and densities, these results are difficult to extrapolate to other systems. Solar installations can disrupt nesting sites for certain avian species, potentially leading to adverse effects on population size [93]. The installation of solar infrastructure around wetlands has the potential to lead to altered foraging, nesting, and habitat fragmentation for many different wetland species.

Despite the negative impacts produced on avian species, some studies have found that solar farms support higher bird species richness, diversity, and abundance, particularly for invertebrate eaters and ground foragers, likely due to their increased structural diversity; however, these increases may be more related to the surrounding landscape [89,94,95]. The distinct bird community composition within solar parks suggests that these areas could enhance overall diversity in specific landscapes, with the potential for even greater positive impacts if managed with a stronger focus on wildlife [14,94]. Birds prefer different successional stages of ecosystem development based on their breeding and foraging characteristics, which can make solar farms a preferred habitat for birds that like open space with some natural elements but are not good for species that require other systems for successful life functions [96,97]. Resource-limited agricultural areas often experience enhanced avian biodiversity, as do arid environments when ground-covering vegetation is used, but there is limited research on the impacts on forest and wetland-associated species [94]. However, while there may be an increase in diversity, studies have yet to examine the effects of wetlands on the functional diversity of avian species in these environments. As mentioned previously, there has been an initial increase in invertebrate specialists and ground foragers, but there is also the potential loss of other niche specialists. While the initial construction of solar farms in undisturbed areas may cause habitat disturbance with adverse ecological effects, these installations can also offer beneficial habitats for rare or endangered bird species under appropriate management conditions [98].

Table 2. Potential effects of solar farms on wildlife interactions in wetlands.

Interaction	Effect	Reference
Altered movement patterns	Potential for habitat fracturing and altered home ranges	[75,80]
Mortality	Mortality events due to "lake effect" collisions or solar flux	[67,85–90]
Altered species composition	Changes in both species diversity and functional diversity for regions	[94,96–98]

While the data for avian and solar farm interactions are limited, studies have examined other forms of human disturbance and bird interactions. Bird–window collisions are an increasingly common occurrence in the United States, with an estimated 100 million to upwards of 1 billion deaths/year [99]. Birds are not able to recognize the reflective and transparent glass surfaces as barriers to their movement, leading to collisions [100]. While these window collisions occur ubiquitously across species, different groups are more susceptible than others due to differences in migration patterns or behaviors. Species that migrate during the night have been shown to be especially at risk for window collisions [100–102]. Due to limited knowledge of effects, particularly on bird species, solar site selection should be carefully considered, followed by continuous monitoring, and consideration should be given to future impacts from plant deconstruction [103]. Birds serve as sensitive indicators of landscape alterations, and solar parks influence habitat utilization, breeding behavior, foraging patterns, and interspecies competition among avian populations, demonstrating the need for careful planning and management of solar installations to mitigate these ecological impacts [104].

4.5. Relevance to Wetlands

The poorly understood impact of solar farms in heavily forested and wetlands areas necessitates evaluating their potential adverse effects on migratory birds and waterfowl in coastal regions, as large-scale solar installation may increase avian mortality [105]. Migratory waterfowl may confuse a large farm of photovoltaic panels for waterbodies through the "lake effect hypothesis," increasing their risk of injury or death [83,105,106]. A recent study found that while the lake effect may not lead to significant increases in bird mortality events, diversity at sites with adjacent photovoltaic panels was lower compared to nearby natural wetlands [66]. Furthermore, many of the studies involved in our review did not find strong evidence to support the "lake effect hypothesis." These results suggest that while direct mortality events could be lower than expected, the installation of photovoltaic panels could alter migratory routes. Waterfowl and other wetland-dependent species that are nocturnal migrants accounted for almost half of the avian deaths at solar facilities [106]. The surrounding landscapes utilized by avian species may play a role in species mortality composition and numbers [106].

There is limited literature on the interactions between waterbirds and solar installations, and what information exists focuses on mortality. Our literature review found five articles that examined the interactions between waterbirds and solar infrastructure [64,66,83,84,107]. Of these, all five focused on the mortality rates of waterbirds and other species. Waterbird species have been noted among avian mortalities in studies examining solar infrastructure in the Southwest. Kosciuch et al. (2020) [66] examined the rates of mortality of avian species in and around solar facilities in the Southwest and described the occurrence of several waterbird species.

Waterbird mortality varies seasonally, with the majority of events happening during peak migration periods [64]. However, these studies predominantly focused on arid environments; given the limited research on solar farms located near wetland systems and their effects on waterfowl, mortality is unlikely to be the only ecological impact. Initial development and construction of facilities could lead to an increase in noise, which could ward off migratory species. Waterfowl utilize wetlands as habitat, but the conversion of these areas to solar infrastructure can lead to a reduction in species richness and biodiversity [108]. Potential development near wetlands could lead to the loss of crucial habitat for migratory species. Several waterfowl species are shown to exhibit high breeding and nesting site fidelity; the loss of specific ponds or wetlands could lead to alterations in migratory routes or breeding patterns [109,110]. In addition, many areas are economically dependent on revenue from waterfowl hunting, and the loss of certain species from wetlands could lead to impacts on the local economy [111]. More research is necessary to understand the full extent of the construction of this infrastructure in and around wetlands. While there have been documented accounts of fatal solar waterfowl interactions, the majority of studies have been conducted in arid landscapes, which do not represent a 1:1 comparison with these environments.

5. Conclusions

Data and impacts of solar farms and photovoltaic installations show varied effects on local ecosystems. In terms of benefits, solar farms have been shown to enhance biodiversity in arid and monocultural agricultural regions, as well as reduce carbon output. While there may be an apparent increase in biodiversity, the overall functional biodiversity of this kind of development can decrease. Studies have shown that upon review, while there may be an increase in the number of generalist species, there tends to be a decrease in specialists [95,112]. Furthermore, when looking at the overall biodiversity of a region, focusing on patches is not reflective of the greater trends on a landscape scale [113]. However, negative impacts have been noted as well. Arid regions have an increased risk of bird collisions with solar farms, changes in habitat usage, and the risk of environmental contamination through both the construction processes and the components of solar panels. Furthermore, as noted in our literature review, this type of installation has yet to be evaluated near a coastal wetland ecosystem, so there is the possibility of adverse effects that may not be known.

The potential negative impacts of solar farms on waterbird behavior, including altered flight patterns and feeding, should be carefully considered in planning, with further research required to elucidate mechanisms for mitigating these effects [80]. Strategic planning during the initial construction phase can enhance land productivity, optimize land connectivity, and promote the harmonious coexistence of renewable energy production and wildlife conservation [114]. With careful consideration, solar farms can be designed to minimally impact or potentially support endangered, threatened, or rare species by providing habitat, refuge, and foraging opportunities while also enhancing varying ecological functions, introducing beneficial microclimate variations, and mitigating adverse ecosystem impacts [82,115,116].

6. Future Directions

Ecologists need to understand better how solar farms will impact forested systems and wetlands with high biodiversity. The growing need for and spread of green infrastructure will necessitate future construction, but care must be taken to maintain natural habitats for their creation. Therefore, we make the following recommendations for mitigations to be considered prior to installation, as well as future research areas that must be addressed before construction in sensitive areas.

Wetland systems have received little attention for the implications of solar installations due to the predominance of these facilities in arid environments [64]. Impacts on local flora and fauna can be mitigated using a strategic environmental assessment to ensure the protection of wildlife, landscape, and fundamental ecological factors [14]. However, a strategic environmental assessment will not give real-time site-specific information that genuinely informs scientific knowledge and planning strategies to mitigate impacts on local flora and fauna. Spatial developments have been widely studied, and many international institutions use these methods to ensure ecological compliance, with site-dependent analysis yielding better outcomes for decision support [117–120]. A strong focus should be placed on impacts on waterbird species near solar farm installations, including estimates of waterbird site fidelity and usage, as well as potential alterations to migration patterns.

Many wetlands are used as overwintering habitats for migratory birds due to their co-occurrence with the major flyways used by migratory species. Solar engineering should implement measures that reduce the potential risks of collisions due to the "lake effect." UV-treated glass, along with different patterning techniques, has shown promise in providing the visual cues needed for birds to distinguish between clear glass and open flight space [121]. The application of white borders around the edges of solar panels also helps to break up the uniformity of solar farms, decreasing the potential impacts of the "lake effect" [122]. However, it should be noted that studies have also found that the "lake effect" may not be a universal signal or sighting for all waterfowl species [107]. Studies should examine the site distribution and fidelity for critical species of concern and should installations be placed near wetlands, selecting those that will have the most negligible impact on their migration and habitat usage.

Should areas associated with wetlands be selected as potential sites following previous mitigations, the infrastructure and design should incorporate design to increase habitat stability and reduce accidental mortality. Collisions with reflective surfaces represent a substantial risk to avian populations; however, the application of mitigation strategies, including acoustic, visual, tactile, and chemosensory interventions, may help reduce collision risks [87]. Nonetheless, these mitigation measures must be carefully evaluated, as they have the potential to disrupt migration patterns and other vital behavioral processes. Transmission lines and other tall structures should incorporate visibility enhancement measures to reduce the risk of collisions for waterfowl and other avian species. Additionally, all exposed connections on these lines should be insulated to prevent contact and minimize harm to wildlife, especially waterbirds. The installation of a conservoltaic system with a multi-purpose design that incorporates patches of natural habitat can lower the heat island effect, help maintain habitat connectivity for wildlife populations, and potentially offset avian mortality [49,81,123,124]. Incorporating beneficial native vegetation can enhance wildlife forage, shelter, and habitat while reducing ambient heat and enhancing solar farm cooling [125]. In addition, the inclusion of artificial habitat structures can assist in providing necessary habitat for wildlife species [126–129]. The use of single-axis tracking systems in site design can reduce impacts to moisture and vegetation, allowing more species to grow underneath. In contrast, fixed-tilt systems can lead to dryer soil conditions and limited vegetation diversity. Single-axis tracking systems reduce greenhouse gas emissions, land use, and water consumption compared to fixed-tilt systems and increase solar production by 10–24%, depending on latitude and climate [130–133]. The solar installation design should model system impacts with a community structure approach, as habitat fragmentation does not create a single-species impact [72]. Fencing should be used as minimally as possible and in a way that allows for corridors of passage for wildlife species [134].

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Appendix A. Search Query Terms and Date of Access

Database	Date	Query	Search String	Results
Web of Science	19 August 2024	Abstract OR Title OR Topic	("solar farm *" OR "photovoltaic power station *" OR "solar power plant *" OR "solar energy farm *" OR "solar array *" OR "solar field *") AND (habitat *) AND (impact * OR "change *")	50
Scopus	20 August 2024	Title, Abstract, Keywords	("solar farm *" OR "photovoltaic power station *" OR "solar power plant *" OR "solar energy farm *" OR "solar array *" OR "solar field *") AND (habitat *) AND (impact * OR "change *")	42
Web of Science	20 August 2024	Abstract OR Title OR Topic	("solar farm" OR "solar energy" OR "solar power") AND (construction OR development) AND ("soil health" OR "soil quality" OR "soil fertility") AND ("soil erosion" OR "land degradation" OR "soil conservation")	5
Scopus	21 August 2024	Abstract, title, keywords	("climate change" OR "global warming") AND ("wildlife" OR "animals" OR "species") AND ("migration" OR "migratory patterns" OR "seasonal movement") AND ("mating" OR "reproduction" OR "breeding") AND ("access to food" OR "food availability" OR "foraging") AND ("extinction" OR "species decline" OR "population decline") AND (impact OR effects OR consequences)	17
Scopus	21 August 2024	Abstract, title, keywords	("climate change" OR "global warming") AND ("wildlife" OR "animals") AND ("extinction" OR "species extinction" OR "biodiversity loss" OR "species decline") AND (impact OR effects OR consequences) AND ("terrestrial")	200
Scopus	23 August 2024	Abstract, title, keywords	("solar farms" OR "solar power") AND ("migrating waterfowl" OR "migratory birds" OR "ducks") AND ("impact" OR "effects" OR "influence" OR "displacement" OR "habitat disruption")	36
Scopus	26 August 2024	Abstract, title, keywords	("solar farm" OR "solar energy installation" OR "photovoltaic farm") AND ("hydrology" OR "water cycle" OR "water systems" OR "water resources") AND ("impact" OR "effect" OR "alteration" OR "change" OR "influence")	14
Web of Science	26 August 2024	Topic	("solar farm" OR "solar energy installation" OR "photovoltaic farm") AND ("hydrology" OR "water cycle" OR "water resources" OR "watershed") AND ("impact" OR "effect" OR "alteration" OR "change")	13

Database	Date	Query	Search String	Results
Scopus	26 August 2024	Abstract, title, keywords	(“solar farm *” OR “solar park *” OR “photovoltaic power station *” OR “solar power plant *” OR “solar energy farm *” OR “solar array *” OR “solar garden *” OR “solar field *”) AND (waterfowl * OR bird *)	58
Scopus	3 September 2024	Abstract, title, keywords	(“soil quality” AND (“native plants” OR “indigenous plants”) AND (growth OR health OR development))	38
Web of Science	9 September 2024	Topic	(“waterfowl”) AND (“ecosystem service *”)	169

Google Scholar was used when Boolean queries failed to produce literature. The first 20 journal papers were reviewed for keywords within the title, and the abstract was examined if the title identified it as a possible resource for this literature review.

Date	Search Term
14 August 2024	(“benefit *”) AND (“solar farm *” OR “solar energy farm *” OR “solar array *” OR “solar garden *” OR “solar field *”) AND (“waterfowl” OR “duck”) AND (“habitat”)
14 August 2024	(“benefit *”) AND (“solar farm *” OR “photovoltaic power station *” OR “solar power plant *” OR “solar array *” OR “solar garden *” OR “solar field *”) AND (birds OR waterfowl) AND (breeding OR nesting OR hatch survival)
14 August 2024	“green energy South Carolina” & “single axis solar versus fixed tilt solar energy production” & “solar farm wildlife disturbance” & “habitat alterations solar farm”
15 August 2024	“wildlife habitat structure loss from human activities” & “artificial habitat structures wildlife conservation solar farms” & “solar farm food webs”
16 August 2024	“habitat alterations solar farm” & “solar farm vegetative loss”
17 August 2024	“wildlife disturbance solar farm”
19 August 2024	fixed tilt versus tracking solar panels vegetation impacts
21 August 2024	(“solar farms” OR “solar energy” OR “solar power”) AND (“gene flow” OR “genetic diversity” OR “genetic connectivity”) AND (“wildlife” OR “animals” OR “species”) AND (impact OR effects OR influence)
22 August 2024	“wildlife habitat structure loss from solar farms” & “wildlife habitat improvement from solar farms”
4 September 2024	“solar panel component toxicity” & “waterfowl and solar farms” & “bird window collisions”

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