CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Investigating the “Lake Effect” Influence on Avian Behavior From California’s Utility-Scale Photovoltaic Solar Facilities

June 2024 | CEC-500-2024-055

PREPARED BY:

Robert Diehl
US Geological Survey

Bruce Robertson
Bard College

Karl Kosciuch
Western EcoSystems Technology, Inc

Primary Authors

David Stoms, Ph.D.
Project Manager
California Energy Commission

Agreement Number: EPC-16-064

Kevin Uy
Branch Manager
ENERGY GENERATION RESEARCH OFFICE

Jonah Steinbuck, Ph.D.
Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

ACKNOWLEDGEMENTS

The primary authors thank the following contributors:

Co-authors

Devin Fraleigh, Jackson Barratt Heitmann, and Olivia Rothberg of Bard College contributed to the design and data collection of research into avian perception of polarized light and the polarization properties of solar panels (Chapter 2). Todd Preston contributed to equipment preparation and data analysis toward understanding flight behavior in relation to utility-scale solar facilities (Chapter 3). Daniel Riser-Espinoza, Cyrus Moqtaderi, and Wally Erickson contributed to conception, data collection, and analysis of fatality data associated with utility-scale solar facilities (Chapter 4)

Funding and Site Access

- California Energy Commission
- First Solar
- NextEra Energy
- 8minuteenergy
- Duke Energy
- nrg
- Recurrent Energy
- US Geological Survey
- Burrtec, Inc

Administrative Support

- David Stoms and the staff at CEC
- Kelvin Miller, USGS
- Judy O'Dwyer, USGS
- Paula Thomsen, USGS

Data Collection

- Stephanie Herrera, WEST Inc
- Christina Van Oosten, WEST Inc
- Brandon Miller, WEST Inc
- Jen Wilcox, WEST Inc

Technical Support

- Parikhit Sinha, First Solar (TAC member)
- Jeff Buler, University of Delaware (TAC member)
- Tom Dietsch, USFWS (TAC member)
- Garry George, National Audubon Society (TAC member)
- Naresh Kumar, Electric Power Research Institute (TAC member)
- Magdalena Rodriguez, CA Department of Fish and Wildlife (TAC member)
- Amy Fesnock, US Bureau of Land Management
- Dave Brischke, Burrtec, Inc
- Jose Barajas, Burrtec, Inc
- Avian Solar Work Group

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

This project examined the so-called *lake effect* hypothesis that utility-scale solar facilities attract birds by simulating the visual cues birds use to locate water bodies. The study followed three interrelated themes matching the process by which birds could be attracted to solar facilities from: 1) detection by birds of an attractive cue such as polarized light that results in, 2) a corresponding adjustment in flight behavior toward a solar facility that, 3) leads to arrival and interaction of birds at solar facilities, potentially resulting in bird fatalities. Results of field experiments demonstrate that birds can see polarized light in the visible range and use it to make foraging decisions and locate water bodies. Results of solar-panel imaging studies show that both thin-film and polycrystalline panel types polarize reflected sunlight consistent with reflections from water bodies. Animals in flight show strong evidence of descent but not reorientation toward solar facilities, consistent with attraction from a solar cue. Bird fatalities were detected at photovoltaic solar facilities in Southern California more frequently than in surrounding areas. Attraction of aquatic habitat birds to photovoltaic solar facilities is likely a nuanced process; however, such facilities are unlikely to provide the cues of a lake to all aquatic habitat birds at all times. Results from this research are largely consistent with a lake effect hypothesis and could be influential in identifying approaches for reducing impacts on birds (for example, panel technologies that disrupt polarized light transmission). Demonstrating that such solutions can be effective at decreasing avian mortality could lower the regulatory costs of solar energy build-out and production, to the benefit of both California's ambitious clean-energy mandates and the state's ratepayers.

Keywords: solar energy, photovoltaic, bird, avian, behavior, attraction, fatality, polarized light, movement

Please use the following citation for this report:

Diehl, Robert, Bruce Robertson, Karl Kosciuch. 2021. *Investigating the "Lake Effect" Influence on Avian Behavior From California's Utility-Scale Photovoltaic Solar Facilities*. California Energy Commission. Publication Number: CEC-500-2024-055.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

Background

California is blessed with abundant sunshine, which the state increasingly harnesses to generate electricity. Experts expect that use of photovoltaic solar panels will rapidly expand throughout the state to advance California's 100 percent clean energy mandates, especially as electricity demand grows from transportation and buildings switching from gas to electricity for their energy.

Many stakeholders became concerned when dead birds were unexpectedly discovered at some solar photovoltaic facilities in the California desert. This was surprising because there seemed to be no obvious threat to the birds from the panels. Unlike concentrating solar power technology, photovoltaic panels generate no solar flux that could kill or injure birds. The panels are relatively low to the ground and do not have vertical structures like buildings or wind turbines where birds could collide. Especially surprising was the fact that at some facilities, birds associated with water habitats, like loons and grebes, were among the casualties; these birds would not normally be expected in desert landscapes. Scientists then speculated a "lake effect" hypothesis, which proposes that birds may mistake a large field of solar panels as a water body, and that birds attracted to them are consequently killed or injured when they attempt to land on them. The presence of these birds strongly suggested a lake effect. However, there was little evidence to determine what it is about these facilities that may cause them to appear as lakes: what the actual cause of death might be, how many birds were being killed, and how widespread that impact may be. Testing the lake effect hypothesis quickly became a leading research priority in the area of solar-wildlife interactions.

Around the time this hypothesis was put forward, concentrated solar power towers also faced tremendous pushback from stakeholders because of the disturbing number of birds killed by that solar technology. The concern was that photovoltaics might face similar resistance if birds were also at great risk from a lake effect. That would make it much more difficult to build out solar photovoltaic facilities rapidly enough to meet state renewable energy timelines and would no doubt increase the cost of permitting, monitoring, and mitigation. Determining the magnitude of the risk and testing the lake effect hypothesis was considered beyond the capacity of individual solar developers, so public interest energy research was deemed appropriate to tackle the problem.

Project Purpose

This study was the first to determine whether there was evidence to support the lake effect hypothesis, or if an alternative hypothesis better explained the bird deaths. The lake effect hypothesis implies a chain of events leading to bird fatalities, namely that birds in flight perceive large solar photovoltaic facilities as water bodies, reorient and descend toward those facilities, and in some cases either collide with the panels or are unable to take off from the ground. Like the surface of a water body, a solar panel is known to polarize light reflected from its surface. One possible explanation for the perception portion of this hypothesis relates to this shared polarization property between solar panels and water.

Project researchers assessed all three of the essential pieces of this hypothesis, with the following objectives:

- Measure the light polarization properties of photovoltaic panels under varying conditions and test whether these characteristics may be attracting birds to solar facilities.
- Establish whether birds change flight paths toward photovoltaic solar facilities and, if so, how that response varies with direction of travel, time-of-day, and altitude.
- Determine which birds interact with solar generation facilities and how many of each species die relative to nearby reference areas, with an emphasis on birds typically associated with water habitats.

The findings of this study can add to the knowledge of wildlife and energy regulators, permitting agencies, environmental groups, solar panel manufacturers, and solar energy operators. Understanding the physical and behavioral basis for a lake effect attraction, if there is one, would be necessary before identifying deterrents or mitigation techniques to reduce avian mortality.

Project Approach

A team with expertise in bird ecology and biology and remote sensing technologies designed a research approach to address the three objectives. First, the team used feeding- and bathing-station field experiments to determine whether birds are able to see terrestrial sources of polarized light and use the degree of polarized light as a cue in locating water bodies. They also conducted the first detailed investigation of the polarization properties of photovoltaic panels and whether panels polarize light in ways that mimic light from natural water bodies.

The researchers used radar to track bird movements at photovoltaic facilities and nearby reference areas during fall migration to see if birds change their flight paths (directions or altitudes) toward fields of utility-scale photovoltaic panels. Such a finding would establish a behavioral link between the perception of solar facilities as water bodies and observed bird fatalities at those facilities. Change in direction and descent of a bird's flight path toward solar facilities more frequently than occurs in the absence of a facility would represent behavior consistent with attraction to those facilities and would support a lake effect hypothesis.

The third part required investigating bird use and deaths at six photovoltaic facilities in southern and central California in desert scrub, grassland, and agricultural habitats. These surveys were matched to comparable surveys of nearby habitats without photovoltaic panels, including a small lake. Due to specific concerns about water-associated birds, this analysis concentrated on this group as the most likely to be attracted to water bodies in desert landscapes.

The team organized a technical advisory committee to ensure that the scientific approach was sound and that the results were presented in the most effective forms for diverse stakeholders. Members of this committee were from state and federal wildlife agencies, academia, an environmental group, a solar developer and operator, and an industry group. The research team responded to the many technical questions raised by the committee, which also reviewed some of the documents produced during the course of the project. The team also had an active outreach program, which made frequent presentations to avian-solar working groups and at scientific and professional conferences. Solar industry partners provided considerable match funding to expand the research and ensure access to solar photovoltaic facilities, without which the project could not have been successfully conducted.

Project Results

The study provided experimental evidence that many different birds can detect horizontally polarized light and that they can use that information to help locate water bodies. Researchers placed bird feeders, ground panels, and bird baths in the field with a range of color and polarization properties in both visible and ultraviolet wavelengths. Birds preferred feeding and bathing in proximity to black colored surfaces reflecting highly polarized visible light. Polarized ultraviolet light was less important to bird preference in bathing experiments.

Polarized imagery of the two types of solar panels commonly used in large solar installations showed that they polarize both visible and ultraviolet light that mimics natural water bodies from a range of angles, elevations, and distances that local and migrating birds would realistically experience. Taken together, the experimental results and the analysis of polarization from solar panels provide evidence that supports a new behavioral mechanism by which many species of birds could be attracted to solar panels.

The first task of this project demonstrated that solar panels mimic water surfaces in terms of polarization, although they cannot mimic other properties such as waves or the feel of water. The experiments showed that birds prefer to approach features such as feeding stations that polarized the most. But to rigorously test the second part of the hypothesis, it was necessary to show that flying birds would change their flight paths and approach an actual solar facility. This was tested by using portable radar units to track birds in flight at two solar photovoltaic facilities in Southern California and nearby reference sites without panels during the fall bird migration season.[1] Evidence was inconclusive that birds changed flight direction toward solar facilities. Relief in terrain may have had an outsized influence on directions of travel, overwhelming any measurable responses to solar facilities. Descent was notably more common at both solar facilities for south-bound birds (possibly migrating) and peaked near midday, indicting they were seeking water or refuge in the extremely arid landscape. This suggests that landscape context matters, and that solar panels in moister landscapes might be less attractive to flying birds and cause fewer deaths.

Radar tracking showed some tendency of birds to move toward solar facilities but did not, in and of itself, show either that birds collide with panels or are otherwise incapacitated. To explore this aspect of the lake effect hypothesis, the team surveyed bird use and deaths within solar facilities and comparable landscapes outside of the facilities. If aquatic habitat birds are attracted to photovoltaic facilities, scientists would expect to find both carcasses and live birds approaching or perched on panels at the facility. However, aquatic habitat birds were only infrequently observed at the desert/scrub and grassland study sites, with similar combinations of species observed at facilities and their reference areas. The researchers did not observe any behavior suggestive of a lake effect such as attempts by these birds to land on panels. There were no aquatic habitat bird carcasses found in the desert/scrub and grassland reference

[1] For purposes of discussing radar results, “birds” include both birds and insects, since it is difficult to distinguish between the two on radar.

areas outside of the solar facilities; whereas, a small number were found in the corresponding facilities. Thus, the team did not find support for the alternative hypothesis that bird fatalities are just random occurrences of similar frequency inside and outside solar facilities in desert/ scrub landscapes or grasslands. In contrast, aquatic habitat birds were more common at the solar facility located in an irrigated agricultural landscape than in desert or grassland. Bird use and the number of fatalities was similar at this facility and its reference area. From these bird use and fatality surveys, a lake effect hypothesis cannot be readily generalized to all aquatic habitat birds in all landscape contexts, but it seems to hold for some species in some landscapes.

In relation to the project objectives, the study found that solar panels polarize light in a manner similar to water, and that birds are more attracted to more highly polarized sources of visible light. Many birds approaching solar facilities from the north during daylight hours in the fall migration season were shown to descend toward solar facilities. Aquatic habitat birds, particularly birds that live on the water, were among the fatalities found at some of the solar facilities surveyed. The survey data on bird use and deaths at solar facilities and reference areas failed to support the alternative hypothesis that birds die at random locations across the landscape, independent of the presence of solar panels. Taken together, these results are consistent with a lake effect hypothesis of avian mortality at solar facilities.

Some of the results of this study are consistent with key predictions and assumptions of the lake effect hypothesis, so the evidence fails to reject the hypothesis. The results, however, do not confirm it conclusively. The radar study struggled to tell birds from insects, let alone identify which bird species changed flight paths around solar facilities to confirm if these were the species that suffered fatalities; nor did researchers observe any bird collisions or strandings that could be directly linked to attraction to solar panels.

Much remains unknown about how birds respond to polarized light and the importance of landscape context in determining behavior in relation to solar facilities. Such knowledge would be useful to finding ways to reduce the impacts of solar energy facilities on bird populations. It is still unknown how much polarization is required to attract birds. Although this knowledge is not essential to confirm the lake effect hypothesis, it would inform how much change in polarization is needed to inhibit attraction, and thereby, reduce avian mortality and sustain bird populations. Bird fatalities discovered in this study cannot be attributed to a particular time of day. Many birds are known to migrate at night when polarization is minimal and could not explain collisions that might occur at night, except perhaps during full moons. The project was limited to facilities in southern and central California, in arid desert and grassland landscapes and one surrounded by irrigated agriculture. It seems likely that the lake effect may be most impactful in this region where water bodies sought by aquatic habitat birds are scarce. However, it would be premature to extend the lake effect hypothesis to other landscape types, or to refute it, until comparable studies are conducted there.

Knowledge Transfer

Because of the widespread interest and high priority of this topic, the project and its findings were widely shared. One scientific article has been published on the bird use and death portion of the study (see Chapter 5), another is in scientific review, and still other articles are forthcoming. The research team gave 14 presentations at scientific and professional meetings, with more presentations on the horizon. Over the course of the project, the team also presented results four times to the Avian Solar Work Group, consisting of a number of stakeholders from the solar energy industry and environmental non-governmental organizations. The Avian Solar Work Group has shown interest in continuing research relating to how birds perceive solar facilities.

The technical advisory committee represented a broad spectrum of stakeholder interests including government, academia, industry, and the environment. In addition to advising the research team, committee members reviewed work plans and interim reports.

Benefits to California

Large-scale solar photovoltaic technology is one of the most cost-effective and commercially viable components of the state's greenhouse gas emission reduction mandates and is expected to play a major role in achieving California's clean energy targets. Wildlife concerns, however, can increase costs by lengthening the permitting process or requiring monitoring or mitigation. Studies such as this one benefit Californians by measuring the previously unknown level of risks to birds from solar panels, which should in turn allow more focused and cost-effective future monitoring requirements. This could potentially reduce the cost of permitting and operations of large-scale solar development, economic benefits that would be passed along to utility customers.

This study advances the environmental benefits of solar energy by suggesting methods to mitigate the light polarization of panels to reduce the attraction of birds. For instance, anti-reflective coating on the panels may limit the degree of polarization. This project lays the groundwork for future studies on mitigation options for species at greatest risk. It also establishes a research framework for replicating studies in other landscapes to determine if the lake effect is operational in less arid landscapes.

CHAPTER 1: Introduction

Background and Justification

California has established ambitious mandates requiring that renewable and zero-carbon resources supply 100 percent of retail electricity sales by 2045 (Senate Bill 100, De León, Chapter 312, Statutes of 2018). Utility-scale solar energy production is expected to provide a substantial share of the electricity now generated by fossil fuels and advance the decarbonization of the state's transportation and building sectors (CEC, 2021). Any substantial environmental challenges to solar energy production could create barriers to its deployment and hinder achievement of the state's energy and climate goals.

Recent reports of dead birds found at utility-scale photovoltaic (PV) solar facilities identified one such potential environmental challenge. Some of the deaths were of species associated with water habitats in a desert ecosystem that lacks many permanent large water bodies (Kagan et al., 2014). The detection of water-obligate and water-associate bird carcasses at PV facilities raised questions about the causes of the mysterious deaths since PV solar panels are typically placed within four meters of the ground and do not represent a vertical hazard in the airspace like buildings (Loss et al., 2014), communication towers (Gehring et al., 2011), or wind turbines (Erickson et al., 2014; Loss et al., 2013). In their report, Kagan et al. (2014) stated that solar panels might be "reminiscent" of bodies of water because some species of aquatic habitat birds (a broad group of birds including both water associates and water obligates; these groups differ in that water obligate birds rely on water for takeoff and landing) should not occur on the ground in a desert environment. An article formalized this as a lake effect hypothesis, inferring that birds may mistake a reflective PV utility-scale solar energy (USSE) facility for a water body (Upton, 2014). Specifically, PV panels may reflect polarized light in a manner similar to that of water. If birds associate polarized light reflection with water bodies and move toward those water bodies based on that cue, they may be similarly guided to PV USSE facilities in cases of mistaken identity. The outcome of a lake effect at PV facilities could be problematic for aquatic habitat birds if the causal mechanism occurs broadly across PV USSE facilities and bird species.

Before this project, how and why (or even if) USSEs attract birds and potentially kill or injure them was largely unknown. The issue was significant enough to identify the lake effect hypothesis as a high research priority by government agencies (Multiagency, 2016) and a consortium of the solar industry and environmental groups. This project posed novel questions and employed innovative methods to address this environmental concern. Understanding the behavioral basis for this attraction is an essential precursor to identifying what deterrents or mitigation techniques might reduce or otherwise address avian mortality. Each of the three primary objectives of this project reflects one stage in the process of attraction from identifying the causal attractive cue, measuring the behavioral response during flight, and, finally, documenting arrival at a solar facility.

The lake effect hypothesis (LEH), which posits that aquatic habitat birds are attracted to PV solar facilities, has been used to explain the occurrence of aquatic habitat bird carcasses at PV

USSE facilities; however, no data existed to understand how birds perceive PV USSE facilities, and no alternative hypotheses were proposed. Furthermore, as the LEH was developed based on one PV USSE facility, it was unknown if the occurrence of aquatic habitat birds was unique to the Desert Sunlight facility, or the pattern was widespread among PV USSE facilities in Southern California. In a summary of 13 studies at 10 PV USSE facilities in the Southwestern United States, Kosciuch et al. (2020) determined that carcasses of water-obligate birds were documented in 90 percent (9/10) of studies in the Sonoran and Mojave Desert (SMD) Bird Conservation Region (BCR), the region where Desert Sunlight is located. However, Kosciuch et al. (2020) found that water obligates were detected in only one of three studies outside the SMD BCR. Uncertainty, therefore, persists in how broadly the LEH can be applied, and if the LEH applies to all aquatic habitat birds, or is instead, limited to specific species.

Hypotheses

The lake effect hypothesis posits a chain of events leading to mortality, namely that birds in flight perceive USSEs as water bodies, reorient or descend toward those facilities, and in some cases die from collisions with panels or being unable to take off from dry land. To avoid accepting the lake effect hypothesis by default, alternative hypotheses were considered to explain this bird mortality. The only reasonable alternative hypothesis identified that could explain avian mortality observations suggests that avian fatalities are equally likely to occur both inside and outside PV solar facilities; that is, that the presence of solar panels has no effect on bird deaths. It is, therefore, only possible to attribute avian fatalities to the lake effect hypothesis over this random landing hypothesis by searching for fatalities outside of USSEs.

Objectives and Integrated Analyses

To address these hypotheses in the context of attraction by birds to PV solar facilities, the project developed the following objectives:

- Measure the light polarization properties of PV surfaces under various conditions and test how these characteristics may attract birds.
- Establish whether birds in flight respond behaviorally to PV solar facilities, and if that response varies with direction of travel, time-of-day, and altitude.
- Determine how birds interact with solar facilities relative to nearby reference areas.

Because photovoltaic facilities are known sources of polarized light pollution (Horváth et al., 2010; Száz et al., 2016; Kagan et al., 2014) it was speculated that avian mortality at California solar energy facilities was associated with light polarization. It was unknown, however, whether birds are capable of detecting horizontally polarized light or if they can locate water bodies via this or some other visual cue. This research identifies the light-polarizing properties of solar panels and examines whether birds are attracted to the polarization characteristics of light. However, detection of a light cue in the absence of a behavioral response will not lead to solar facility-related mortality; birds must actually respond to the cue in a manner consistent with attraction to a facility. A second element of this project explores the behavior of birds in the vicinity of solar facilities and attempts to determine whether those behaviors are consistent with attraction to solar facilities. Birds exhibiting movement toward solar facilities do not necessarily lead to injury or fatality. Given the modest level of documented mortality associated with solar energy facilities in the region (relative to some other anthropogenic sources), either the behavioral response by birds, if present, is itself modest (to such a degree that it would be difficult to detect) or it occurs vastly out of proportion to observed mortality. That is, many birds may be drawn to solar facilities, but few are actually harmed there. The final component of the project examines patterns of avian use and mortality at both PV solar and reference areas. The focus on water-associated, and especially water-obligate birds, offers perhaps the most compelling opportunity to link attraction specifically to water-seeking avian behavior.

CHAPTER 2: An Investigation of the Water-Mimicking Polarization Properties of Solar Panels and the Ability of Birds to Locate Water Using Horizontally Polarized Light

Background and Approach

Sunlight consists of electromagnetic rays vibrating at all possible planes relative to the direction of its travel, but it can become polarized when its waves start to oscillate partially or entirely in a single plane. There are two primary sources of polarized light in nature: sky and water. Unpolarized sunlight is scattered when it interacts with particles (e.g., gases and water droplets) in the atmosphere, but is polarized when its angle of reflection is perpendicular relative to an observer (Coulson, 1988). The result is a characteristic celestial polarization pattern of a stripe of polarized light across the sky 90 degrees (90°) from the sun (Können, 1985). Sunlight can also undergo a high degree of linear polarization (DoLP) via reflection from a water body. Rivers and lakes with darker substrates (e.g., mud) or higher turbidity (dissolved solids) absorb more transmitted light, and since surface-reflected light is 100 percent polarized, darker waters that absorb more of the light transmitted into the water can polarize up to 80 percent of light they collectively reflect from its surface and interior (Horváth and Varjú, 2004).

Birds have long been known to reorient in response to experimental manipulations of the sky-polarization pattern (Able, 1982; Helbig and Wiltschko, 1989; Moore, 1986; Moore et al., 1988), and it has recently been discovered that they can see the sky polarization pattern and use it to calibrate their magnetic compasses (Muheim et al., 2016). Birds could be pre-adapted to use this same sensory modality to locate water bodies via their ability to perceive polarized terrestrially reflected light, but this hypothesis remains untested. Solar panels (Horváth et al., 2010) are able to polarize light more strongly than most natural water bodies (between 35 percent and 80 percent), raising the possibility that birds could be mistaking solar panels for natural water bodies.

The goal of this study was twofold. First, to understand if birds are able to see terrestrial sources of polarized light and use the degree of polarized light as a cue in locating water bodies; and second, to conduct a detailed investigation of the polarization properties of solar panels and determine whether they mimic natural water bodies.

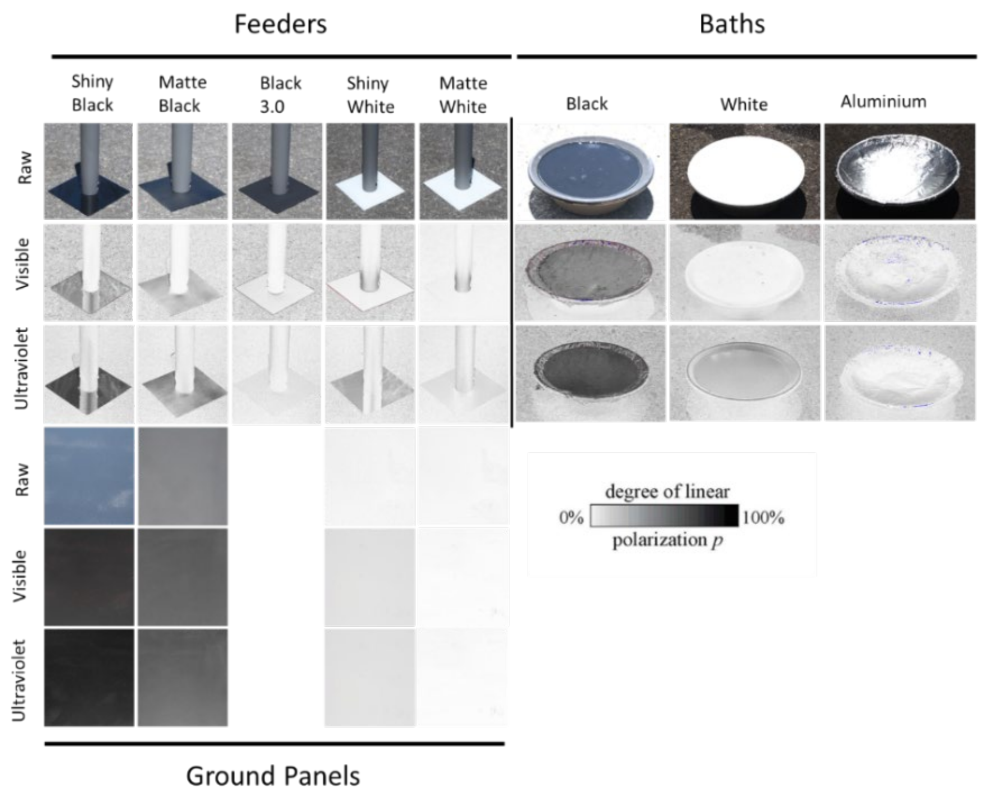
Methods

Experimental Exposure of Wild Birds to Polarized Light Cues

To address the first question, researchers designed a series of multiple-choice field experiments. First, researchers used modified bird feeders to determine if horizontally polarized light could make focal food sources more conspicuous to wild birds and guide their feeding behavior. The acrylic panel base was painted in one of five treatments designed to manipulate the color and horizontal polarization of reflected light: 1) White-shiny, 2) black shiny, 3) white-matte, 4) black-matte, and 5) Black 3.0 (a matte, non-polarizing paint, Figure 1). These treatments corresponded to degrees of polarized light in the visible range that were: 1) very high, 2) high, 3) low, 4) very low, and 5) very low, respectively. In the ultraviolet spectrum, this pattern of relative DoLP was similar but the white-shiny treatment polarized a moderate degree of light.

This study was conducted from November through April in the years 2018 to 2019 in Dutchess, Columbia, and Ulster counties in New York. The experiments were placed in flat, grassy areas in >1-acre grasslands, or cultivated lawns within a predominantly forested landscape. The experiments were placed two meters from linear lines of trees that were >25 meters long and placed at the centroid of their length. Sites were >200 meters apart. Observations were conducted from 6:00 a.m. to 1100 a.m. In the first year of the study, birds were exposed to treatments 1, 2, 4 and 5 at 15 locations (n=15), and treatments 1, 3, 4 and 5 at the same locations in Year 2.

Figure 1: Reflection-Polarization Characteristics of Experimental Treatments



Photographs and reflection-polarization characteristics (degree (d, percent) of linear polarization of reflected light) of: a) feeder bases, b) ground panels, and c) bird baths exposed to wild birds. The top rows of each portion represent a color image as it appears to human eyes (raw). The middle and lower rows represent the relative degree of horizontal polarization of test surfaces taken in human visual range (400 to 700 nanometers [nm], middle) and the ultraviolet (300 to 400 nm, lower) taken at the Brewster angle of maximal polarization. Imagery confirms that blacker and shinier test surfaces polarize a higher percentage of visible-range and ultraviolet light, than white-colored. Shinier surfaces can also polarize light in the ultraviolet, and researchers found a black material (Black 3.0) that was highly effective at reducing its polarization signature.

Source: Bruce Robertson, Bard College

Researchers secondly exposed wild birds to a collection of ground-based test surfaces that simulated the visual properties of natural water bodies, and outside of the context of feeding. These surfaces mimicked the orientation and color and/or DoLP of natural water bodies, but they lacked the tactile and olfactory cues of real water. Researchers used one meter by one meter square pieces of polyvinylchloride painted to create black-shiny, black-matte, white-shiny and white matte treatments with similar DoLPs to bird feeders 1, 2, 4 and 5 (Figure 1). These were placed at n = 15 field edges with a bird feeder to attract birds to the study area. Researchers used motion-activated remote cameras to determine the relative visits to each treatment of a 4-day exposure time.

In a third experiment, researchers allowed wild birds to choose, to drink from, and bathe in, three water sources whose polarization properties varied in their degree and wavelength. Researchers covered heated bird baths (diameter 35 centimeters [cm]) with one of three materials: black plastic sheeting, white plastic sheeting or aluminum foil creating three treatments: 1) low brightness, high DoLP, 2) high brightness, low DoLP, and 3) high brightness low DoLP (Figure 1). Remote cameras were, again, used to calculate the relative visitation rates to treatments. In all three experiments, researchers made inferences about the ability of birds to detect the DoLP and their relative attraction to it in different behavioral contexts from the relative number of visits birds made to different treatments over the course of an observation period.

Polarization Properties of Solar Panels

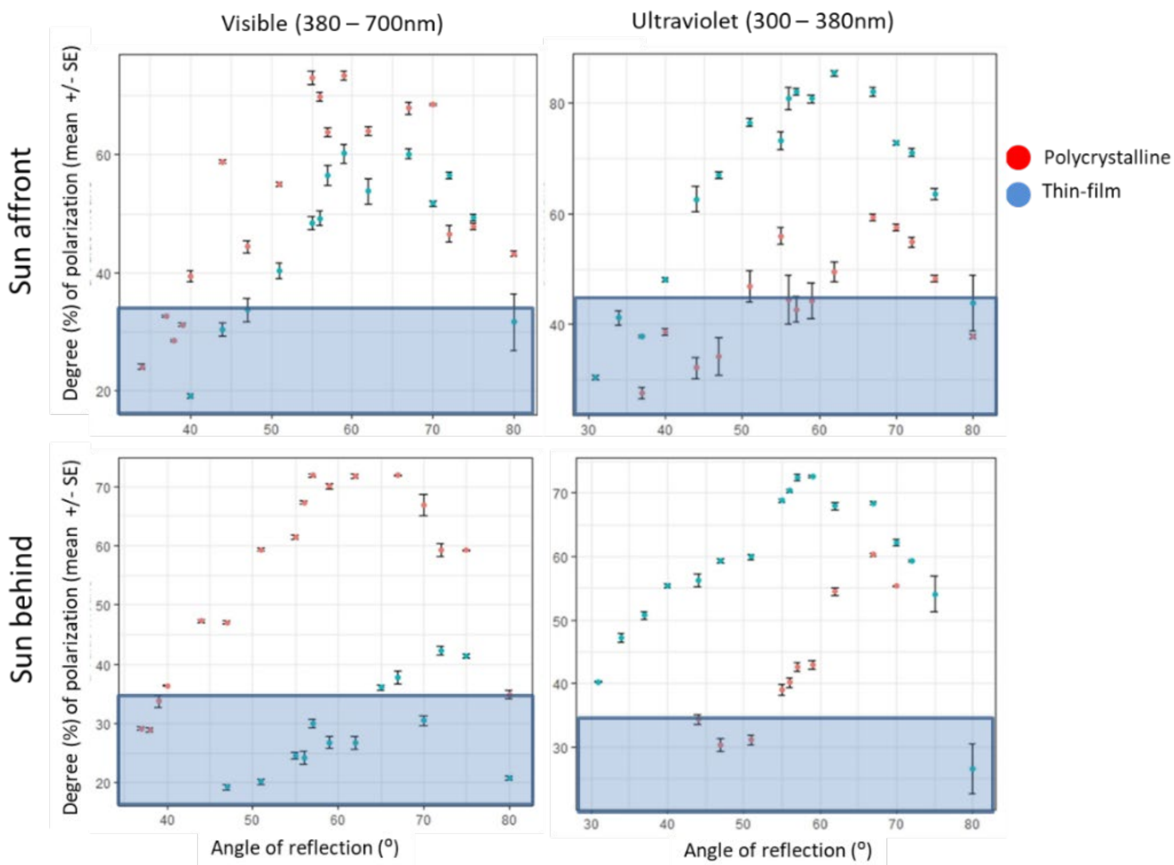
Researchers used imaging polarimetry to understand the conditions under which two types of solar panels used in USSE installations might appear to water-seeking birds. Researchers analyzed the DoLP of crystalline silicon (c-Si) and thin-film type solar panels to determine the range of angles at which solar panels mimic the polarization properties of natural water bodies in both the visible and ultraviolet spectrums. Researchers also examined the relationship between the degree of polarization at the Brewster's angle, *B* (defined more fully in the Methods section), and position of the sun to determine relative attractiveness or likeness of solar panel fields to natural water bodies, depending on the orientation of approach birds have when migrating. Detailed methods for all experiments are available in Appendix A.

Results

Polarization Properties of Solar Panels

Both thin-film and c-Si solar panels are capable of polarizing sunlight to a high-degree (visible maximum: 83 percent; ultraviolet maximum 84 percent), albeit under different lighting conditions, angles, and reflections from different types of solar panels. Reflection-polarization of visible light from thin-film solar panels exceeded 35 percent over a narrower range of vertical angles compared with c-Si solar panels (Figure 2), regardless of weather conditions, in the visible light spectrum. However, reflection polarization of ultraviolet light exceeded 35 percent from a broader range of angles from thin-film solar panels when compared with c-Si solar panels (Figure 2).

Figure 2: Thin-Film and c-Si Solar Panels Polarize Light Differently



The degree (percent) of visible and ultraviolet light polarized by thin-film and c-Si solar panels at various vertical angles of incidence from the observer to the light source. The blue-shaded portion of the figure represents DoLP values <35 percent, which is the minimum published DoLP value for natural water bodies and so angles at which the solar panel would not have water-like polarization properties. The figure shows that the degree of polarization is maximized at some intermediate angle or range of angles known as the Brewster angle. Polycrystalline type solar panels are more efficient at polarizing visible-range light while thin-film panels are better polarizers of ultraviolet light.

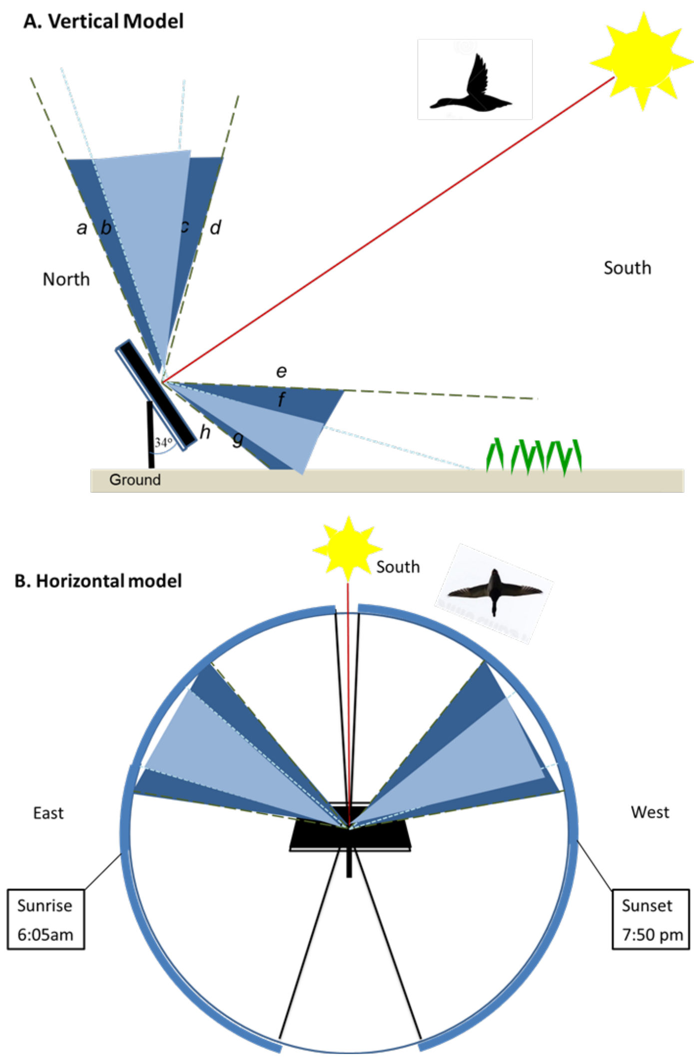
Source: Bruce Robertson, Bard College

Polarization patterns were qualitatively similar when viewing solar panels toward the sun versus away from it, but angle of viewing affected the degree of polarization and the Brewster angle. The Brewster angle for visible light reflecting from c-Si solar panels was somewhere between 55° to 68°, as this is the range of reflection angles over which the degree of polarization was maximized (Figure 2, left). For thin-film solar panels, the Brewster angle of visible light occurred over approximately the same range when facing the sun (58° to 67°), but that angle increased when facing away from the sun to approximately 72°. In the ultraviolet range, thin-film solar panels had a Brewster angle of 62° when facing the sun and 56 to 58 percent when facing away from it. Ultraviolet light reflecting from c-Si panels had a Brewster angle of 66° when facing toward or away from the sun.

The DoLP was also affected by the direction of view. Visible light was less polarized via reflection with solar panels of both kinds when facing away from the sun than toward it. Ultraviolet light, too, was less polarized by reflection from thin-film panels at the Brewster angle when facing away from the direction of the sun, though its maximum degree of polarization when reflecting from c-Si panels was unaffected by the direction of view.

Assuming a 34° angle of inclination from the vertical of ground-mounted solar panels, which is typical of ground-mounted panels at USSE installations in Southern California, the project team simulated the range of angles of view to an approaching bird over which visible light would be polarized more than 35 percent (minimum value of natural water bodies) by reflection with a solar panel. Figure 3 shows that c-Si panels would have higher degrees of polarization than natural water bodies for birds approaching at ground level (between e and h), and for birds approaching the panels and about to pass over the top of them (between a and d), but the degree of polarization drops below 35 percent at intermediate angles of approach (between angles d and e). A similar pattern exists for thin-film solar panels, but over a slightly narrower range of values (Figure 2).

Figure 3: How Approaching Birds See Panel-Polarized Light



The range of: a) vertical and b) horizontal angles over which birds approaching a solar panel would see visible light polarized more than 35 percent, the minimum value known for natural water bodies. The vertical diagram A. assumes an angle of tilt of a ground-mounted solar panel of 34 degrees. Letters represent angles of view relative to the solar panel that might be experienced by a bird for whom the reflection of the sky from the panel would be polarized at least 35 percent

and so angles at which the solar panel would have water-like polarization properties. For each type of panel there are two 'cones' in which solar panels would have water-like properties (c-Si: a to d (66º to 106º) and e to h (186º to 226º); thin-film: b to c (72º to 95º) and f to g (197º to 220º)). A bird flying and approaching the panel moving right to left would pass through the upper high-polarization cone primarily as it passed more directly over the solar panels, though a northward migrating bird would encounter this cone 70m before passing over the panel if migrating very low and at 100m in elevation. Animals migrating at an elevation of 2000m would encounter this visual cue 388.7 meters before passing over it. This horizontal model (b) assumes east-to-west single-axis tracking at the latitude of southern California on April 21st during early bird migration and illustrates high-polarization cones in relation to a northward migrating bird. It indicates that cones of high DoLP light extend forward from the solar panel at ground level and should mimic the polarization properties of water to animals viewing panels from side-long angles during mid-day. At this time, a bird or insect flying north past the panel at ground level at a distance of 100m would intersect the cone of high DoLP light 70 meters in front of the panel. At dawn, when solar panels are tracking the sunrise to the east, cones of polarization will extend at ground level toward both the SSE and to the NE, and these cones of high DoLP light will rotate around to face SSW and NW around sunset. Combining these two models together into a three-dimensional representation, illustrates that these polarization cones extend diagonally upward across a range of angles that would intersect birds at a diversity of elevations and side-ward angles at different times depending on the time of day.

Source: Bruce Robertson, Bard College

Polarization Characteristics of Test Surfaces

Researchers created bird feeders, ground panels, and bird baths with a range of color and polarization properties (Figure 1). In the feeder experiment, the matte-grey paint of the feeder tubes was a consistently weak polarizer of visible light, while the acrylic bases varied widely in their color and degrees of polarization (Figure 1, top left). As predicted, the average degree of polarization was highest in the shiny-black treatment, next highest in the matte-black treatment, very low in the shiny-white treatment and nearly zero in the matte-white treatment. The Black 3.0 treatment had a dark, black pigment (Figure 1, top row), but a very low degree of visual-range polarization similar to the shiny-white treatment. The shiny-black, matte-black and shiny-white treatments were all strong polarizers of ultraviolet light, while the Black 3.0 and matte-white treatments polarized very low percentages of ultraviolet light. The DoLP of the polyvinylacrylic ground panels were similar to those of the feeder bases (Figure 1, bottom left). Only the black-painted bird bath was a significant linear polarizer of visible light and a very strong polarizer of ultraviolet light (Figure 1, right). The white-painted bird bath polarized a small fraction of the ultraviolet light only, while the aluminum coated bath was not a significant source of polarized light of any wavelength.

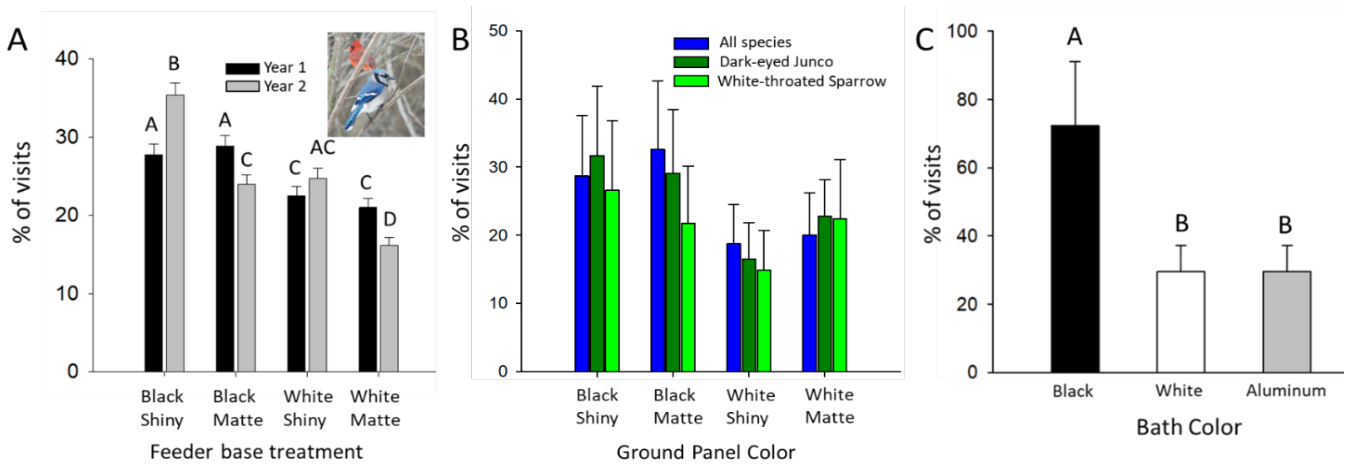
Avian Responses to Visual Treatments

Twenty species of woodpecker (*Piciformes*), dove (*Columbiformes*) and songbirds (*Passeriformes*) (Appendix A, Table A-1) common during the fall and winter in southern New York were detected. The visitation data were a good fit to models with values close to 1.0 and <4.0, and researchers fit feeder data to a Poisson distribution ($\hat{c} = 0.98$), ground panel data to negative binomial distributions ($1.5 < \hat{c} < 3.8$) and bird bath data to a Poisson distribution ($\hat{c} = 0.98$).

Birds preferentially visited feeders with black shiny and matte test surfaces over those with white-colored bases during the first year of the study, but preferences shifted to strongly favor feeders with black-shiny test surfaces during the second year of the study when researchers introduced a new reduced-polarization black-matte test surface (all species combined: $\chi^2_{treatment} = 102.7$, $P < 0.001$; $\chi^2_{year} = 0.55$, $P = 0.46$; $\chi^2_{interaction} = 32.0$ $P < 0.001$, Figure 4A).

Increased preference for black-shiny surfaces in the second year of the study corresponded with a reduction in attraction for white-matte surfaces that polarized the lowest percentage of polarized light. Birds visiting the ground panels showed no preference for visual treatment (all species: $\chi^2_{treatment} = 2.332$, $P < 0.51$; Dark-eyed Junco: $\chi^2_{treatment} = 2.4$, $P = 0.48$; White-throated Sparrow: $\chi^2_{treatment} = 1.14$, $P = 0.75$, Figure 4B). Birds visited black-based bird baths twice as often as those coated with white plastic or aluminum foil (all species: $\chi^2_{treatment} = 7.87$, $P < 0.02$, Figure 4C).

Figure 4: Effect of Reflection-Polarization on Songbird Visits to Test Surfaces



The effect of reflection-polarization patterns on songbird visits (± standard error) to test surfaces in the A) feeder-based, B) ground panel-based, and C) bird bath-based experiments. In the first year of the feeder study, visitation rates for the two black-colored surfaces were higher than for the white ones. In the second year of the study when the black-matte treatment was replaced with a very low polarization treatment, bird visitations were highest only in the black-shiny treatment. Visitation rates of birds to bird baths were more than twice as high in the black treatment than in the white or aluminum foil treatments. Letters denote the differences between treatments as a result of post-hoc pairwise comparisons; mean values are shown with standard errors.

Source: Bruce Robertson, Bard College

Discussion

This study provides experimental evidence that birds can detect terrestrial sources of horizontally polarized light, and that they can further apply that information to locate water bodies and inform their foraging decisions. Researchers also demonstrated that two types of solar panels commonly installed in utility-scale solar installations can polarize visible light to a degree that mimics the DoLP of natural water bodies from the range of angles, elevations, and distances that local and migrating birds realistically experience at desert-solar installations. Because these experimental results suggest that water-seeking ability via polarization vision is taxonomically widespread in passerine birds and exists in two other orders (*Columbidae*, *Picidae*), this research provides evidence supporting a new behavioral mechanism that explains global and taxonomically broad bird collisions with solar panels (Walston et al., 2016; Smith and Dwyer, 2016; Visser et al., 2019; Kosciuch et al., 2020) from polarized light pollution (Horváth et al., 2009).

Experimental Studies on Wild Birds

Feeder-based experiments manipulated the color and DoLP of the feeders-bases, not to simulate the appearance of water bodies to birds, but to see if manipulating their horizontal polarization would make them more visually conspicuous to birds in ways that could affect their food-source selections. In the first year of this study, birds were more likely to visit the feeders associated with the two black-colored treatments (visible range: black-shiny DoLP ~87 percent, black matte DoLP ~77 percent) at similar and higher rates than the two white-colored treatments (visible range: white-shiny DoLP ~36 percent, white matte DoLP ~12 percent). From this result alone, researchers would be unable to distinguish between attraction to the color black and attraction to high DoLP in the visible range. These results are much less consistent with avian attraction to ultraviolet polarized light because the white-shiny treatment had a relatively high degree of polarization (DoLP ~67 percent), but birds visited it no more frequently than the nearly unpolarizing white-matte treatment.

In the second year of the study, researchers used a replacement black-matte treatment created by using an extremely matte paint called Black 3.0 that reduced the polarization of that treatment to a level (visible range: DoLP ~13 percent) approximating the two white treatments. This resulted in a simultaneous drop in the visits by birds to the white-matte treatment, an increase in the visits to the remaining white-shiny that is now the only highly polarizing visible range treatment, and a drop in visits to the white-shiny treatment with the lowest visible-range DoLP.

Visitation rates to feeders in this experiment also suggest that birds appear to discriminate between visible range polarized light sources that are below ~37 percent and above 77 percent. The reported range of DoLP for natural water bodies is between approximately 35 to 80 percent (Horváth and Varjú, 2004), roughly this same range of values. The ability to accurately locate water sources and discriminate them from terrestrial vegetation, which also polarizes lower degrees of light through reflection (<30 percent, Peltoniemi et al., 2015) may be the primary selective force in avian attraction to terrestrial sources of horizontally polarized light. The ability of birds to see ultraviolet polarized light was less clear. In the first year of the study, visitation rates to the more highly polarizing white-shiny treatment did not differ from visitations to the white-matte treatment. In the second year of the study, when the second strongest source of polarized light (black matte) was all but eliminated by replacing it with the very weakly polarizing Black 3.0 treatment, the white-shiny treatment became more attractive than the white-matte treatment. This could indicate the birds are able to see and use UV polarized light to locate water and food sources, but only do so when visible-range polarization is less common. An unpublished follow-up experiment by one of the authors (Robertson, 2021) supports the ability of Black-capped Chickadees to see ultraviolet polarized light and so supports this hypothesis.

Researchers designed a second study to effectively simulate a ground-based polarization signature that created simulated water bodies but did so without the cues that actual water bodies typically exhibit (e.g., waves, tactile properties). Birds visited the ground panels frequently though it was found, on average, that they did not show any preference for a higher DoLP. Given that Experiment 1 definitively demonstrated that many species of songbirds are able to see at some wavelengths of polarized light, the absence of systematic variation in visitation rates amongst treatments in this experiment requires explanation. It is possible that these test surfaces became soiled by dirt and dust and periodically covered by leaves in ways that altered the visual properties of the panels or temporarily occluded them from sight, even though technicians cleared panels of snow, debris, and dirt every day. Alternatively, the bird species visiting these ground-based panels were different than those associated with other experiments (Appendix A, Table A-1) and were dominated by ground-based foragers such as Dark-eyed Junco and Mourning Dove, which may have different sensory-cognitive abilities or behaviors than species visiting the feeder study. Given the taxonomic breadth of birds exploiting polarized light to guide feeding decisions in Experiment 1, this explanation seems less likely. Finally, birds may identify water bodies first by approaching terrestrial sources of polarized light they spot at a distance but later confirm the presence of water at closer range through other cues such as waves and the way it feels.

In contrast to the bird feeder experiment, Experiment 2 spatially separated the food source from the test surfaces in ways that prevented birds from associating color and DoLP with a food source and made it more likely that approaching simulated water bodies was for the purpose of drinking or bathing. However, unlike the feeder study in which birds could view the color and DoLP of test surfaces only during the narrow window of time in which their behavior was monitored by field observers, ground panels were constantly visible to birds over the course of four days, allowing them time to learn that even highly polarizing panels were not actual water bodies. In this way, while birds were placed in a more focally water-seeking context in this experiment, they also had the ability to learn to discriminate water from PV panels.

The third bird bath experiment provided polarization cues with degrees typical of natural water bodies (black: visible (DoLP ~76 percent) and ultraviolet (DoLP ~84 percent); white: ultraviolet only (DoLP ~35 percent) and non-water objects (white: visible (DoLP ~10 percent); aluminum: visible (DoLP ~17 percent) and ultraviolet (DoLP ~17 percent), with substrates of various colors along with an unpolarizing (aluminum) control. This provided other tactile cues that characterize natural water bodies. The study indicated that birds visited ground-based sources of polarized light for bathing and drinking, and that they preferentially approached the treatment with the highest degree of polarized light in both the visible and ultraviolet ranges (black). Birds visited the white and aluminum baths fewer than half as many times. In light of the birds' ability to use polarization to select feeders in the first experiments, this result supports the idea that the failure of birds to show preference for artificial water bodies in the ground panel experiment could be due to the absence of ancillary water-based cues (e.g., tactile cues). This experiment offers fewer clues about the wavelength of polarization that birds may be using to locate water bodies. Birds strongly preferred black-lined baths that highly and horizontally polarized light in both visual and ultraviolet ranges, but the experiment was unable to determine which wavelength could be more important for avian water seeking.

Each of the three experiments was designed to complement each other in the types of evidence they gathered and were limited in ways that required careful attention. For example, by itself the bath experiment could not determine whether birds are attracted to black-colored baths because of their color or their degree of polarization. It was designed in this way because the researchers were unable to conceptualize physical materials that could simultaneously provide the tactile and olfactory cues of water while manipulating polarization in ways that provided black (yet non-polarizing) treatments, and white (yet highly polarizing) treatments. This may be physically impossible. When examined within the context of the ground-panel-based study that provided the same color-polarization treatments, the study suggests that these ancillary cues of water are important, though researchers made anecdotal observations of birds attempting to bathe on black-shiny feeder-bases and ground-panels. The feeder-based study clearly showed that the birds were not systematically attracted to the color black, but rather to the highly-polarized light that is commonly associated with darker-colored water bodies and other man-made objects (e.g., asphalt: Malik et al., 2018; glass buildings: Malik et al., 2008, Kriska et al., 2008a; automobiles: Kriska et al., 2006; and solar panels: Horváth et al., 2010, Száz et al., 2016). In this context, the authors could more reasonably conclude that the birds visiting the bird baths exhibited a preference for black baths due to their ability to highly polarize reflected light and the presence of tactile, olfactory, or other cues associated with actual water. This study was more limited in its ability to identify which specific wavelengths of polarized light that birds both see and use to guide their feeding and water-seeking behaviors; in this context, the feeder experiment was more consistent with the greater importance of visible-range light.

Finally, the study has some taxonomic breadth in its inferences. While the authors examined the response to experimental treatments by bird communities (Appendix A, Table A-1) as a whole in the feeder experiment, very similar results were found by one of the authors when examining the responses of: 1) Black-capped Chickadees (*Poecile atricapillus*), 2) Tufted Titmouse (*Baeolophus bicolor*), and 3) all other bird species combined as separate groups (Robertson, 2021 unpublished data). Black-capped Chickadees and Tufted Titmouse were the two most common species observed in the feeder and bath experiments, making the results of these studies more comparable. Given that similar results were observed in both individual species and broader communities of birds, study results indicate that this characteristic may be taxonomically widespread in birds.

Evidence of birds being attracted to man-made artificial sources of polarized light suggests the ability of birds to use the DoLP to locate water. Water-associated (e.g., ducks) and more terrestrial birds are attracted to open-air ponds of crude oil waste (Bernáth et al., 2001) where they become engulfed and die, and historical evidence of bird skeletons in tar pits suggests that this association has been an enduring one. Obligate water birds such a pelicans, grebes and loons are occasionally found dead, injured, or stranded upon and unable to take off from roads and asphalt parking lots (McIntyre and Barr, 1997; Montevecchi and Stenhouse, 2002; Kriska et al., 2008b). Photovoltaic solar panels have been noted as strong sources of polarized light pollution (Horváth et al., 2009, 2010; Száz et al., 2016; Black and Robertson, 2019), and increasing evidence of avian collisions with solar panels resulting in mortality at USSEs suggests that birds could be mistaking solar fields for desert lakes (Kosiuch et al., 2021).

Imaging Studies on Solar Panels

Solar panels differ from natural water bodies in that they are typically mounted at an angle facing the sun. They commonly contain thin, non-polarizing metal dividers and lack other cues typically associated with water bodies (e.g., ripples, vegetation, tactile wetness, scent) that birds could use to distinguish these objects from actual water bodies. Tactile cues can only be used at close proximity, and because water can be perfectly smooth on windless days, ripples can only be used by birds to confirm the presence of actual water when they interact with it. Finally, birds may approach solar panel arrays from various directions, depending on whether they are migrating over and past them, if they are exhibiting more local movements, or if they are resident birds living in close proximity to solar panels (utility-scale, residential, or part of newer technologies like canal- or lake-covering solar panels). The angle of view of a solar panel or other polarizer relative to the sun and the presence or absence of clouds may also play an important role in the ability of solar panels to polarize light (Száz et al., 2016), but a more detailed analysis is needed to understand how these factors might relate to conditions that birds actually experience in the field.

The authors found that both thin-film and c-Si solar panels are capable of polarizing light to a high degree (visible maximum: 83 percent; ultraviolet maximum: 84 percent), albeit under different lighting conditions, angles, and as a result of reflection from different types of solar panels. These maximum values of polarization were observed at Brewster angles identified for these panel types. Both panels had similar Brewster angles for visible range light and respective angles at higher angles for ultraviolet light, but the Brewster angle was different when facing away from the sun as opposed to facing toward it. The range of degree of polarization values for both the thin-film and c-Si panels imaged fell within the normal range of visible range values expected for a natural water body (35 percent ≤ DoLP ≤ 80 percent), and this was true under both clear and overcast skies. Thin-film panels were more efficient polarizers of ultraviolet light when compared with c-Si panels. This difference likely reflects the heavier reliance upon c-Si technology to capture ultraviolet light and convert it to energy, which in turn led to higher surface reflection-polarization by thin-film. Both types of panels imaged also polarized light within the ultraviolet range across a similar range of values, which supported previous research findings that the polarization of solar panels was generally lower when facing away from the sun (Szaz et al., 2016).

The authors incorporated this information about the degree of polarization across a range of angles of observation into a visual model for how a migrating bird might view the visual-range polarization of an angle-mounted solar panel when approaching it from the south while migrating north and directly away from the sun (Figure 3). Researchers avoided imaging panels from orthogonal directions (e.g., west and east) because it is known that the degree of polarization, at least of c-Si panels, is much lower at those angles (Szaz et al., 2016). The visual model showed that migrating birds should pass through two different cones of high polarization (DoLP >35 percent) at a high enough percentage of reflected sunlight that they either meet or exceed the minimum degree of polarization associated with water. The results suggest that birds migrating low to the ground, given the height of the solar panel, should generally always perceive both thin-film and c-Si solar panels as water-mimicking (Figure 3). Furthermore, this study indicates that birds migrating at higher altitudes and distances will pass through two separate bands of polarization that will be wider in the visual range for c-Si panels than for thin-film panels. In this way, if birds are relying more heavily on visual-range polarized light to locate water bodies in which to drink, bathe, and rest, c-Si panels will mimic the degree of polarization of natural water bodies for longer periods of time during their flight than will thin-film type panels. This difference could make c-Si panels more attractive and increases the likelihood that birds would attempt to approach and land on them, especially if they are approaching at an elevation and angle away from the Brewster angle (such that the degree of polarization of panels only just exceeds that of typical water bodies). However, the exact reverse could be true if avian vision is either more sensitive to ultraviolet polarized light or if birds weigh it more heavily in their water-seeking behaviors, or both.

Project researchers calculated the various combinations of distance and elevation that the edges of one of these *cones of polarization* should represent in order to better understand how realistic it would be for migrating birds to mistake solar panels for water bodies at realistic migration elevations. Average surface visibility in the Mojave Desert, for example, site of a number of utility-scale photovoltaic facilities, is 11 miles (Climate, 2024). Migrating birds maintain an average altitude ranging from 200 to 1,400 meters (Mateos-Rodríguez and Liechti, 2012), and will view solar panels through a cone of vision that expands as a function of distance from the solar panel. Based upon these numbers, the authors find that migrating birds should be flying through the lower-angle polarization cones of these panels beginning at a relatively short distance (c-Si: 445 m; thin-film: 344 m) and before that up to about 5,000 meters for c-Si panels. This would give birds plenty of time to identify panels as potential water sources and decide to either land on or otherwise approach them. A high degree of polarization would be maintained as birds descended within the cone (Figure 3). Birds migrating through and out of the lower cone would pass through the second high-angle cone, albeit more quickly, and would again view panels as water-mimicking.

Birds not flying directly north toward and over a solar facility would view the panels at angles lower than at the Brewster angle, so should see less polarization. Solar panels at some USSE facilities horizontally track the sun left and right. As solar panels track the sun horizontally, the panels will increase or decrease the perceived polarization depending on a bird's angle of approach and altitude, though the primary effect of panel orientation on DoLP would be the angle of the sun and sky to both the panel and the bird. This tracking effect could create higher DoLP from panels when viewed by birds passing between panels and the sun at an angle, making them more attractive, but would also reduce the DoLP (and possibly their attractiveness), for birds flying by panels on the side away from the sun. Results, therefore, suggest that under sunny skies, regardless of the broad direction of approach, birds migrating north-south could potentially view c-Si and solar panels as natural water bodies. The degree to which panels tilt (by time of day), would create similar effects. In summary, the DoLP of solar panels viewed by birds as they fly above them is a function of both the angle and direction of a bird's approach, the time of day, the orientation of the sun, and the orientation of the solar panels and their polarization properties (e.g., thin film, polycrystalline). Researchers calculated the max DoLP of a small subset of these scenarios that represent both extreme high and extreme low values.

What can realistically be concluded from this analysis about the susceptibility of birds to mistake solar panels for water bodies, and how those effects can be minimized? Results suggest that the two solar panel types should be equally attractive flying south, most likely during fall migration, but that thin-film panels are not as attractive to birds flying north, most likely to occur during spring migration. If birds are more reliant upon visible range polarization in locating water bodies, this would suggest an increased role for thin film panels in reducing exposure to water-mimicking degrees of polarization light in ways that could reduce avian collisions during spring migration. Previous research shows that anti-reflective coatings (ARCs) can both increase panel energy efficiency and reduce the degree to which they polarize light by up to 12 percent (Szaz et al., 2016; Fritz et al., 2020). In this way, if ARCs reduce the polarization not just at the Brewster angle, but across all angles, this technology could play an important role in limiting the exposure of birds to polarized light pollution (Horváth et al., 2009). ARCs are typically integrated into the design of most utility-scale solar panels but could play an increased role in residential panels.

This imagery-based study is limited in many ways. It can be extrapolated from close-range imagery of solar panels placed flat on the ground that dust in the air that collects on solar panels may dramatically reduce their ability to polarize reflected sunlight. Visual simulations of how passing birds might see solar panels focus on the visual range and some specific and direct angles of approach relative to both the panels and the position of the sun. These represent the circumstances in which the degree of polarization should be maximized, so should also represent the circumstances of greatest concern. Researchers estimate an error of ±2º in the ability to estimate angles throughout this study, which limits its resolution in several ways. Finally, error bars in the degree of polarization seen in the c-Si panel measurements between 52º and 59º, and the thin-film panel at 80º in the ultraviolet range, are due to physical properties of the panel itself that create unevenness in polarization across a particular range of angles (Figure 2). This doesn't appear to be a limitation of the study, but rather a reflection of the visual properties of the technology itself.

Conclusion

This project supports the hypothesis that broad-scale collisions of birds with solar panels may be explained by their attraction to photovoltaic solar panels that they mistake for desert water bodies. This study focused only on a subset of bird species and was conducted primarily on songbirds in a part of the world outside where most bird-solar collision studies have been conducted (Kosciuch et al., 2020; Visser et al., 2019). Follow-up studies should monitor bird movements and behaviors near solar panels and other man-made sources of polarized light to explore bird movements and collisions. In this regard, a tunnel study where birds are allowed to fly toward simulated solar panels (with various elevations, angles, and visual properties) could help determine what cues birds employ to avoid collisions and to see polarized light in close proximity to solar panels. This study represents the first evidence that birds can visualize terrestrial sources of polarized light and use it to guide their behaviors. The study suggests that in the absence of tactile, olfactory, or other cues of water bodies, some species can learn to avoid them. However, water is an essential resource for all birds, whether or not they forage in or near water bodies. Fast-flying water-associated birds are less maneuverable in flight and typically land on water bodies at high speeds, making them particularly susceptible to collision with panels. New sources of polarized light pollution are being created all the time by a wide range of man-made objects, including windows (reviewed by Horváth et al., 2014). Solar energy is the most rapidly growing component of the energy sector, and has been for a decade, so there is an urgent need to better understand the environmental impacts of this abundant renewable resource.

CHAPTER 3: Response of Flying Animals to Industrial-Scale Photovoltaic Solar Facilities

Introduction

As will be described in Chapter 4 of this report, birds succumb to solar facilities at above background rates (Kosciuch et al., 2021). Unlike other human infrastructure that serves as a source of mortality to birds, utility-scale photovoltaic solar panels do not protrude appreciably into the airspace.[2] Avian mortality associated with these facilities, therefore, is less likely to result in incidental impact with structure as is the case with wind turbines (Smallwood and Ball 2020; Erickson et al., 2014; Erickson et al., 2001), communications towers (Gehring et al., 2009, 2011), power lines (Loss et al., 2014a), and some buildings (Loss et al., 2014b). This implies that birds actively seek to occupy USSE PV facilities and in the process are injured or killed when colliding with solar panels, the ground, or some other structure associated with these facilities. For water-obligate species (e.g., grebes, loons), the consequences may be fatal even if landing is successful since these birds are unable to take flight from the ground so are therefore vulnerable to predators or desiccation.

It is hypothesized in this report that this mortality results from birds being attracted to, and impacted by, solar PV arrays and nearby surfaces after perceiving them as a lake or some sort of oasis. As explored in Chapter 2, birds may perceive polarized light reflected off solar panel surfaces as open water. Birds in flight are well known to alter their flight paths in response to anthropogenic light while aloft (Horton et al., 2019; Van Doren et al., 2017; Gauthreaux and Belser, 2005) when those light sources originate from the ground (Cabrera-Cruz et al., 2020; McLaren et al., 2018). Although birds are known to perceive polarized light (Muheim et al., 2016; Muheim et al., 2006), the range of circumstances to which birds respond is less well understood.

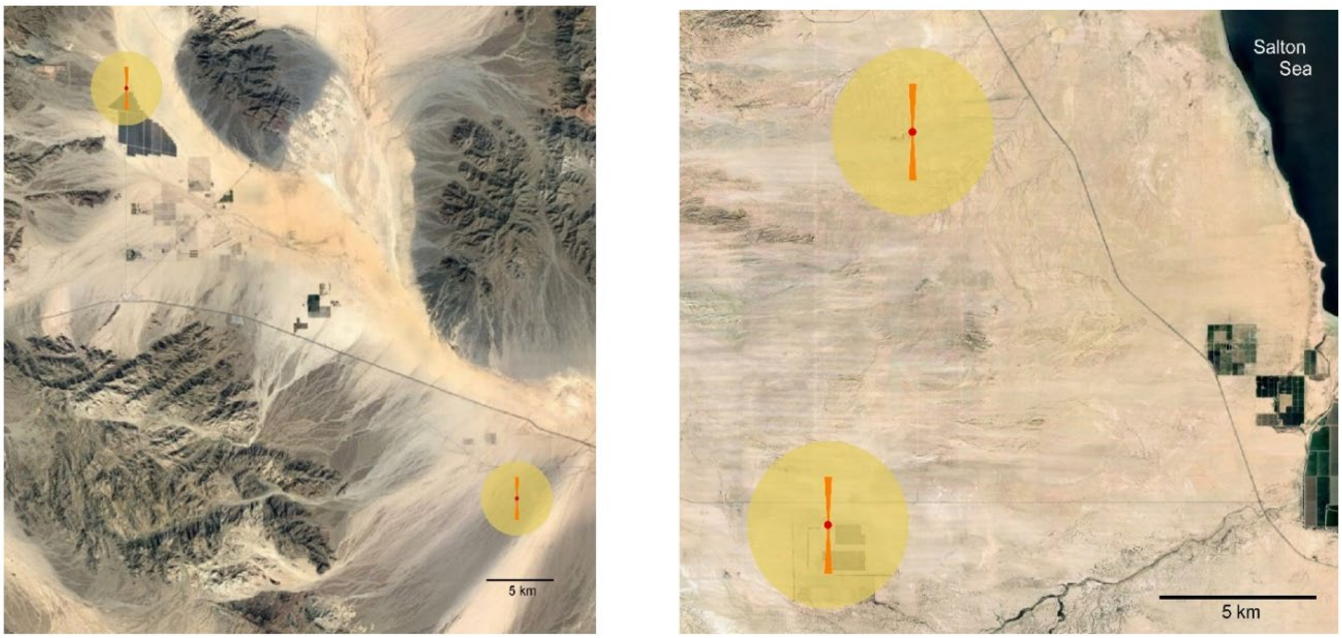
This chapter establishes the behavioral link between avian perceptions of solar facilities as water bodies and observed bird fatalities at those facilities. The lake effect hypothesis was tested by identifying evidence of behavioral attraction by birds while in flight and determining whether those behaviors are consistent with attraction by a polarized light cue. Flying animal behavior consistent with the lake effect hypothesis includes lateral reorientation and descent of an animal's flight path toward solar facilities more frequently than that expected to occur without a facility. Specifically, this report examines the lateral reorientation and vertical descent of flying animals toward two photovoltaic solar facilities in Southern California by time of day, direction of travel, and altitude.

[2] Although some forms of concentrated solar energy such as the Ivanpah Solar Electric Generating System are exceptions by projecting hazardous flux fields into the airspace (Diehl, 2021; Diehl et al., 2016).

Methods

To obtain data on lateral and altitudinal responses of birds to PV USSE facilities, portable X band radars were deployed at two solar facilities in Southern California and their corresponding control sites: Desert Sunlight Solar Farm (33.844880°N, -115.40179°W, hereafter, Desert Sunlight), the Seville Solar Farm (33.119431°N, -116.008486°W, hereafter Seville) and their respective control sites located 40.6 kilometers (km) to the southeast (33.585855°N, -115.092211°W) and 12.8 km to the north-northeast (33.232191°N, -115.979166°W, Figure 5).

Figure 5: Radar Study Areas



Portable radar deployment locations (red dots) at utility-scale solar facilities in Southern California. Yellow shaded regions show radar coverage in the horizontal domain and a narrow orange stripe shows the location of the north-south orientation of data gathered in the vertical domain. The left panel shows radar locations near the Desert Sunlight Solar Farm (upper left) and a corresponding control to the southeast. The right panel shows radar locations near Seville (lower left) and a corresponding control to the north-northeast.

Source: US Geological Survey, Landsat

The Desert Sunlight facility and its corresponding control location are located within the Sonoran Basin ecoregion of California (Griffith et al., 2016). The facility itself sits south of the Colorado River Aqueduct in an alluvial valley that slopes gradually downward toward the south-southeast and is surrounded, at various distances, by mountainous terrain. The control site, also within the Sonoran Basin, is in more open country on alluvium that gradually slopes downward toward the northeast. Vegetation is sparce in both locations and oases are limited to some holding ponds and a small retirement community 8.5 km south of the facility. Seville and its associated control site are also within the Sonoran Basin and are located 18 km and 11 km west-southwest of the Salton Sea, respectively. The Imperial Valley lies east-southeast of the Seville facility and is characterized by abundant irrigated agriculture. A few hedge rows occur near the facility, but otherwise vegetation in the region is sparse and much of the area lies at or below sea level. The control area is located near a local landfill. Unattended radar operated continuously and was checked every two to seven days, depending on circumstances.

Data in the horizontal and vertical domains were gathered continuously during October in 2018 and 2019 at Desert Sunlight and Seville, respectively. Two radars were outfitted with different antennas to gather data in these domains, and their locations between treatment and control areas was alternated every three to four days at Desert Sunlight and weekly at Seville. Some analyses subset the data based on time of day, wherein diurnal is defined as the time between local sunrise plus one hour and local sunset minus one hour and nocturnal is defined as the time between the end of evening civil twilight (i.e., sun position is 6˚ below the horizon after sunset) and before the beginning of morning civil twilight (i.e., sun position is 6˚ below the horizon before sunrise).

Discriminating Animal Types

Radars operating at X-band detect birds and insects in such a way that they cannot be discriminated by the strength of their radar echo (Vaughn, 1985). The longer wavelengths of S-band radar systems considerably reduce insect contamination, but at the cost of also rejecting small birds during data collection. For this reason, X-band was viewed as the more conservative approach; however, the challenge of rejecting insect clutter during post-processing proved move vexing than expected. Alternate methods of discrimination considered included those based on airspeed (Larkin, 1991) and identified times dominated by bird movement according to regional classified Next Generation Weather Radar (NEXRAD) data. After evaluation, these methods were judged insufficient for reliably discriminating birds from insects. Given the inability to apply established approaches for discrimination, results are usually presented without respect to specific taxonomic groups. Otherwise, relatively high and low ground-speed thresholds of flying animals were used, with the understanding that particularly high speeds are more likely associated with birds and low speeds with insects. Note that some analyses were based on data gathered in the vertical domain and were not well suited to discrimination based on airspeed.

Reorientation

The radar-gathering data in the horizontal domain were transmitted with horizontal polarization and outfitted with a 1.2-meter diameter parabolic antenna inclined 30°, relative to the horizon. Maximum range was three km, the pulse length was 0.3 microsecond (μs), and animal tracks linked ≥4 successive detections during antenna rotation using the program radR (Taylor et al., 2010). Other operational and data capture properties of this radar are described in Cryan et al. (2014). When operating in this configuration, the radar is well suited to gathering data on the ground speed and direction of flying animals. Changes in altitude may be detectable but are imprecise.

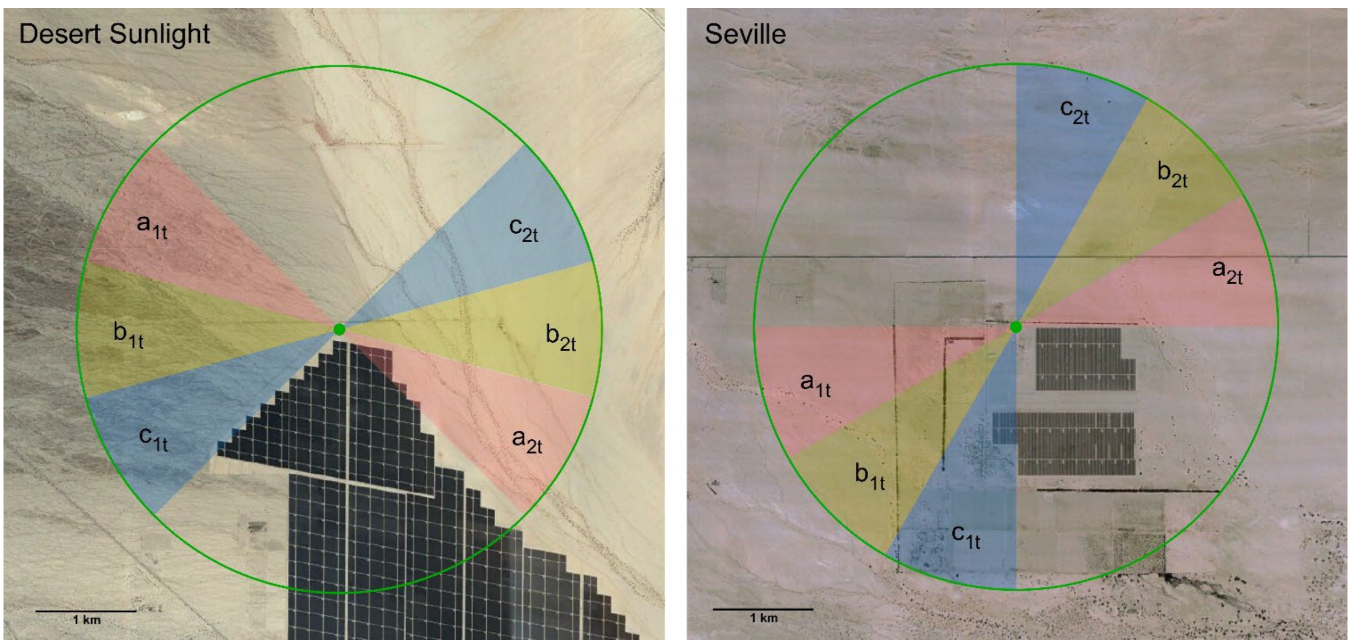
Reorientation toward solar facilities was quantified as the difference across the season between treatment and control areas in the propensity for flying animals to exhibit movement toward the region of radar coverage consistent with that of the solar facility, all while attempting to account for aspect bias. The approach is premised on the expectation that animals near the facility exhibit a greater propensity to reorient their flight toward the facility than animals further away. Since the direction of flight captured by radar is strongly influenced by aspect, the mean direction of movement for regions near the PV facility (Figure 6, a2t, c2t) are compared with directions for regions corresponding to areas opposite and more distant (Figure 6, a1t, c1t); b1t and b2t in Figure 6 are opposing and equidistant from the solar facility and may each show some response by flying animals. This layout of sampling areas shown for treatment areas (Figure 6) is replicated for control areas and incorporated into a simple difference model (see Appendix B, "Reorientation Methodology").

Only diurnal and nocturnal southbound animals were examined using this model since it is less certain how northbound animals behave with respect to solar facilities. Movement is considered diurnal if it occurs one hour after sunrise and one hour before sunset. Movement is considered nocturnal if it occurs one hour after sunset and one hour before sunrise. It is also unclear whether nocturnal flying animals might respond since visual cues in the form of polarized light or background contrast would be nonexistent or compromised. For this reason, positive or negative model results are possible. A positive diurnal response supports the hypothesis suggesting animals reorienting toward solar facilities rely on visual cues.

Descent

Radars were outfitted with open-array antennas (Furuno XN20AF, 1.23° beam width by 20° beam height) and adjusted to rotate in a vertical plane, oriented north-south to detect animal ascent, descent, and direction of travel relative to radar along the plane of rotation. Radar operating in this orientation cannot reliably measure specific ground speed and direction.

Figure 6: Reorientation Sampling Areas



Distribution of sampling areas for quantifying animal direction of movement in relation to the Desert Sunlight and Seville solar facilities. Results for each colored and labeled pair equal one inch. See Appendix B.

Source: US Geological Survey, Landsat

Maximum range was 1,500 meters and pulse length was 0.3 μs. The orientation of polarization was parallel to the plane of rotation. Other operational properties are similar to those of the radar outfitted for gathering data in the horizontal domain.

Ground clutter (that is, unwanted radar echoes caused by vegetation, anthropogenic structure, or relief in terrain) interferes with most terrestrial biological radar operations. Data gathered in the vertical domain were cropped within the 700 meter range and at 20 degrees above each horizon to eliminate any ground clutter that survived earlier processing.

A ratio-based model was developed to quantify the proportion of animals descending over a solar facility while accounting for aspect bias and adjusting for background levels of ascent using data from control locations. This model is applied to all analyses of descent based on flight direction, time of day, and height. A second model examines change in descent over solar facilities throughout a 24-hour day. These methods are described in detail in Appendix B, "Descent Methodology."

Results

From October 2 to November 1, 2018, and from October 1 to November 4, 2019, radars operating in the horizontal and vertical domains detected 6,754,118 and 4,391,364 flying animals, respectively. Southbound animals exceeded northbound animals by 2.06 times, diurnal animals exceeded nocturnal animals by 1.49 times, and the number of animals passing through the Seville sites exceeded those passing through Desert Sunlight sites by 1.57 times (Table 1). Note that, throughout this section, results for Desert Sunlight are shown in blue and Seville in red.

Table 1: Flying Animal Abundances on Radar

Desert Sunlight				
	vertical North bound	**vertical South bound**	**horizontal North bound**	**horizontal South bound**
Diurnal	448,077	679,572	435,420	976,244
Nocturnal	247,189	397,739	225,815	464,059
Seville				
	vertical North bound	**vertical South bound**	**horizontal North bound**	**horizontal South bound**
Diurnal	414,011	818,544	838,047	1,349,801
Nocturnal	255,716	617,719	390,670	1,406,498

Flying animal abundance metrics associated with Desert Sunlight and Seville treatment and control areas

Source: US Geological Survey

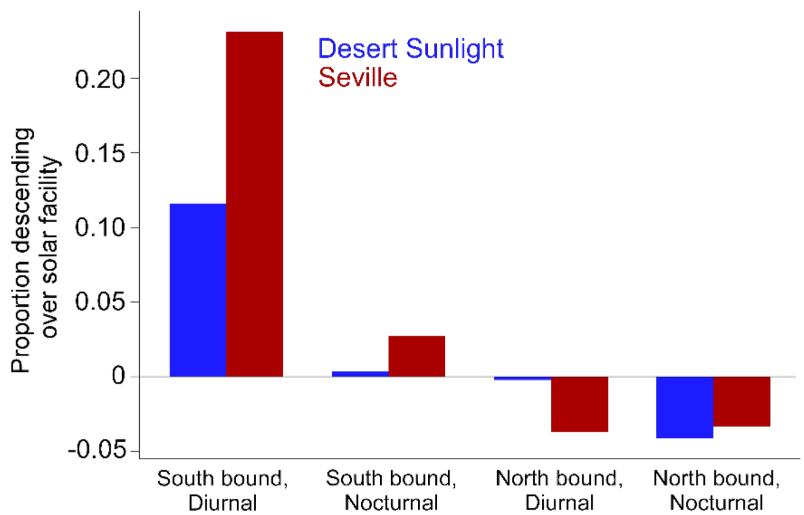
Reorientation

Diurnal, southbound animals with ground speeds ≤5 meters per second (m/s) were likely dominated by insects, conforming to predictions associated with reorientation toward both Desert Sunlight and Seville solar facilities (Table 2). By contrast, animals with ground speeds ≥14 m/s were more likely dominated by birds showing mixed conformity to predictions associated with reorientation. Conformity was also mixed for nocturnal, southbound, fast- and slow-moving groups. Not surprisingly, confining the analysis to a narrower range of directions (i.e., toward 180°±45° versus 180°±85°), yielded a lower magnitude reorientation response, most evident among slow-moving animals (Table 2).

Descent

The propensity for descent attributed to both facilities considerably favored animals traveling toward the south during the day (Figure 7), although the response was strongest at the Seville facility. The proportion descending (or ascending) at both facilities among nocturnal southbound animals and all northbound animals was negligible.

Figure 7: Direction and Time-of-Day Influence Descent



Proportion of north- or southbound animals descending over solar facilities during different times of day.

Source: US Geological Survey

Among the diurnal southbound animals, the proportion descending was highest among those flying between 400 to 700 meters above ground level at both sites (Figure 8). However, the nature of vertical radar sampling, together with conservative clutter filtering, could introduce bias in height estimates of the descending animals.

Table 2: Horizontal Attraction by Flying Animals

Ground Speed	≤5 m/s				≥14 m/s			
Site	**Desert Sunlight**	**Desert Sunlight**	**Seville**	**Seville**	**Desert Sunlight**	**Desert Sunlight**	**Seville**	**Seville**
180°±	**85°**	**45°**	**85°**	**45°**	**85°**	**45°**	**85°**	**45°**
θa'	11.09°	5.96°	5.75°	4.36°	7.96°	8.14°	3.88°	2.17°
θc'	9.57°	2.58°	10.15°	4.68°	10.48°	9.75°	-1.06°	0.50°
θb'	8.92°	4.09°	10.23°	5.74°	12.25°	14.32°	1.41°	0.21°
θa	7.06°	5.68°	6.72°	2.66°	-0.03°	4.15°	-17.40°	-3.22°

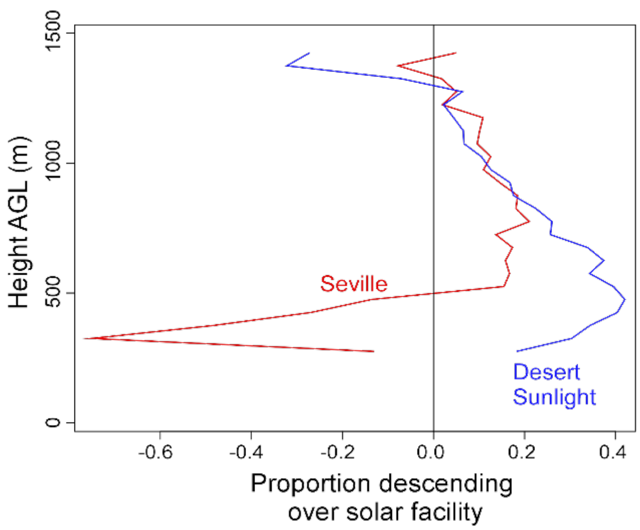
Ground Speed	≤5 m/s				≥14 m/s			
Site	Desert Sunlight	Desert Sunlight	Seville	Seville	Desert Sunlight	Desert Sunlight	Seville	Seville
θc	6.99°	2.41°	4.63°	4.86°	1.68°	2.40°	10.67°	0.29°
θb	3.52°	2.26°	4.67°	3.22°	2.43°	5.29°	-5.60°	-0.90°

For Desert Sunlight and Seville, the degree difference in lateral movement toward PV facilities between treatment and control areas for animals flying toward 180°±85° and 45° degrees at ground speeds ≤5m/s and ≥14 m/s. Values in normal font satisfy criteria consistent with movement toward facilities at Desert Sunlight and Seville respectively (see text), and values in italics fail to satisfy those criteria. The top three rows of results (θx') are the differences between x2t – x1t, and the bottom three rows (θx) are the results of Equation 1 (see Appendix B for complete description of methods).

Source: US Geological Survey

The proportion descending toward both solar facilities was inversely related to animal speed (Figure 9). All things being equal, high and low extremes in speed may function as a proxy for vertebrates and invertebrates, respectively, but the notions of animal speed and direction are ambiguous and interacting for radars operating in the vertical domain.

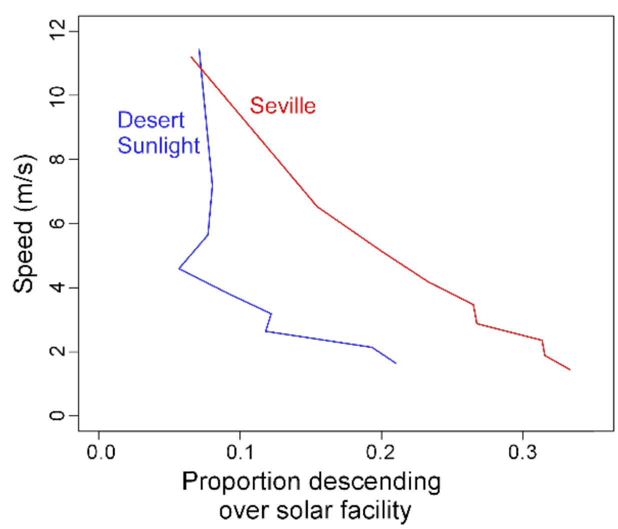
Figure 8: Descent and Height



Proportion of southbound, diurnal animals descending toward solar facilities at different heights above ground level.

Source: US Geological Survey

Figure 9: Descent and Speed



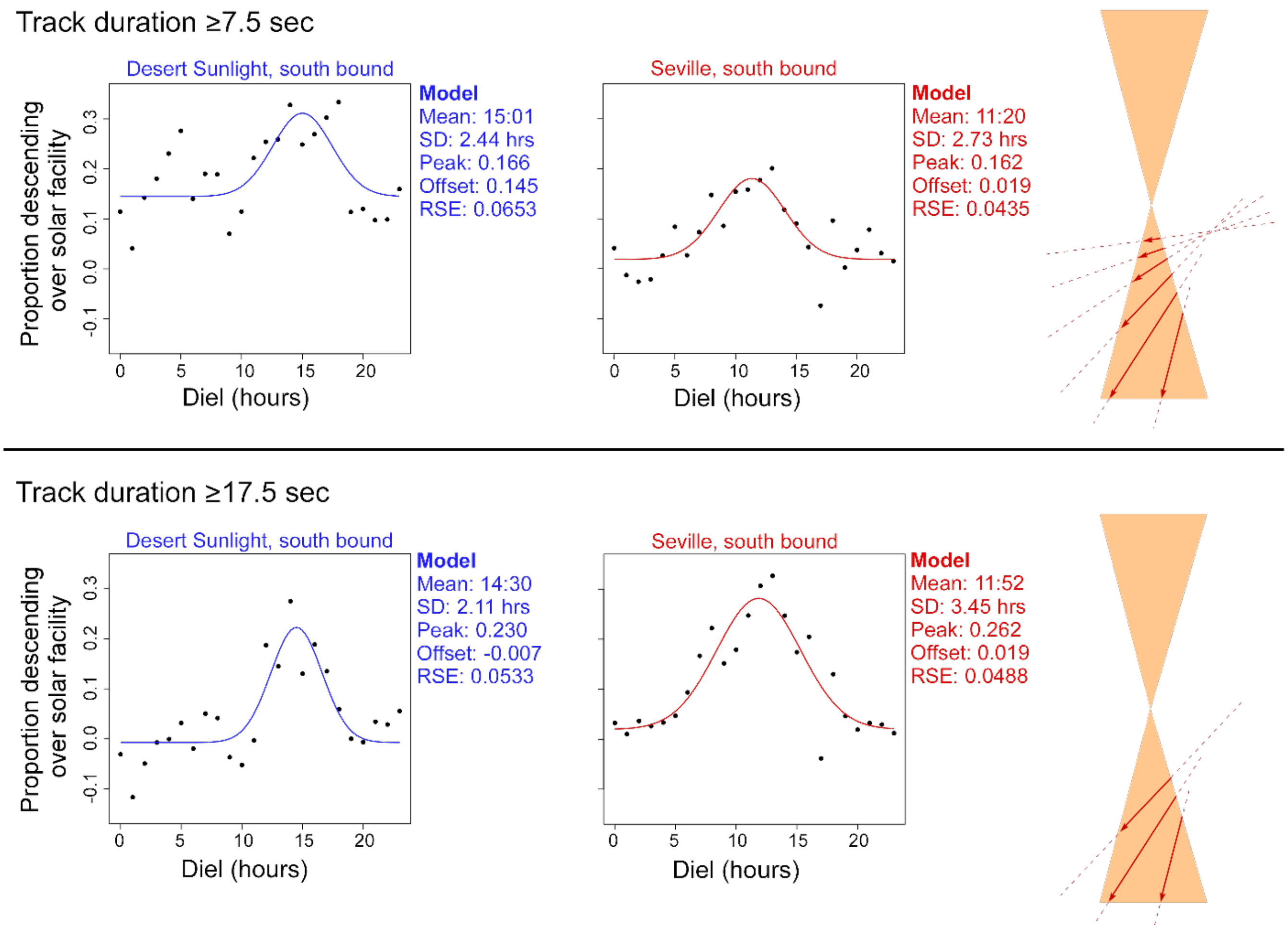
Proportion of southbound, diurnal animals descending toward solar facilities at different minimum speeds.

Source: US Geological Survey

Analysis of change in proportion descending throughout the diel included datasets using both the minimum available track duration threshold (≥7.5 seconds) and the higher threshold (≥17.5 seconds) used in most analyses (Figure 10). These shorter and longer thresholds were used as a proxy for the lower and higher propensity, respectively, for animal tracks to be oriented toward true south (conceptually diagrammed in the far right of Figure 10). Among all four models in Figure 10, the offset term, which is the base of the Gaussian function and essentially represents minimum levels of descent, significantly differed from zero only for analyses including short tracks at Desert Sunlight (see Appendix B, "Gaussian Model Results").

In other words, in most cases the proportion descending was near-zero for non-diurnal times of day, consistent with Figure 7. Shorter track durations were generally associated with a lower proportion of animals descending toward the facilities.

Figure 10: Descent Throughout the Diel



Changes in the proportion of southbound animals descending toward solar facilities throughout the diel for short (top) and longer (bottom) minimum radar track durations. The conceptual effect of shorter and longer minimum track duration thresholds is depicted to the right. The arrowed segments of hypothetical animal tracks through a simplified top-down view of radar coverage in the vertical domain vary in length and direction depending on track duration. The results of Gaussian function parameters are given for each track duration-facility combination.

Source: US Geological Survey

The peak proportion descending above baseline increased considerably when only the longer duration tracks were included. Among these longer tracks, the peak proportion descending differed between sites by about 2.6 hours, occurring at Seville at 11:52 local time (LT) and at Desert Sunlight at 14:30 LT. At Seville, positive proportion descents began and ended near local sunrise and sunset. By contrast, positive proportion descents began much later at Desert Sunlight, around 11:00 LT, and also ended around sunset. This difference in the duration of positive levels of proportion descending was captured by the model's standard deviation, specifically 2.11 hours for Desert Sunlight and 3.45 hours for Seville.

Discussion

Approach

The approach to radar data collection and analyses was based in part on the following assumptions, which were addressed during study design, data collection, and data processing. The assumption that similar species exist at both the facility treatment area and its associated control was addressed by limiting the distance between these areas and selecting similar landscape contexts. This was not entirely possible at Desert Sunlight, however. The assumption that animal distributions and non-effect behavior (i.e., behaviors not associated with solar facilities) across a given radar's coverage area are relatively uniform was addressed by not locating radars near relief in terrain. It was assumed that the 3- to 7-day interval between alternating horizontal and vertical data collection between treatment and control areas did not bias the samples. While there were occasional pulses of animals passing through radar coverage (Appendix B, "Dense Animal Movement"), the general phenology of animal movement behavior occurs in much longer time frames than in the location-alternating intervals. Phenology across avian and invertebrate species differs, and it is likely that the sampling window captured species in various stages of their autumn-movement phenologies. For example, during October, populations of eared grebes at the Salton Sea increase just as those of the red-necked phalarope decrease (Sullivan et al., 2009). Finally, although seldom used, it was assumed that relatively extreme ground speed thresholds function as a reasonable proxy for discriminating birds from insects. Greater detail follows on how some of these assumptions were addressed.

Security was a limiting factor in the selection of exact locations at Desert Sunlight and both control areas, though a suitable radar location at Seville was found within the secure area of the facility. Budget constraints precluded continuous radar monitoring at all hours. Avoiding human populations resulted in a Desert Sunlight control location that was about 40 km southeast of the Desert Sunlight treatment location, a distance that may partially violate assumptions of species similarity and explain some discrepancy in descent response between the two sites. For security purposes, the Seville control site was located near a local landfill, which may attract both birds and insects. The project approach to addressing a possible bias follows.

A routine constraint of biological applications of radar concerns limited ability to know the precise taxonomic identities of flying animals. Two approaches based on three external data sources were considered. The airspeed-based approach relies on the availability of accurate data on wind conditions. Archived data from the nearest available surface winds from Blythe, California, were too distant (78 km from the Desert Sunlight radar location) to be reliable in airspeed calculations. Moreover, surface winds are often not a reliable indication of winds aloft. Wind estimates at the surface and aloft from the North American Regional Reanalysis model (Mesinger et al., 2006) were extracted, using National Center for Atmospheric Research Command Language (NCL) version 6.6.2 (NCL, 2019), but these produced unreasonable results likely stemming from their coarse spatial resolution (~32 km 2 grid). An alternative approach would rely on classified data from NEXRAD to identify periods of high regional bird activity. Relatively recent progress in the biological classification of weather radar data (Gauthreaux and Diehl, 2020; Lin et al., 2019) was considered, briefly explored, but ultimately rejected. Insects are so-called Rayleigh scatterers at the wavelengths of NEXRAD (S-band) and produce extremely weak radar echoes. As a result, even during times when machine learning algorithms classify NEXRAD observations as dominated by birds, insects may still be abundant in the atmosphere and prominent on X-band radar. Other reliable methods of discerning birds from insects on X-band radar (e.g., wingbeat-based approaches, Schmaljohann et al., 2008) were not available at the time data were collected. However, these methods are now available and could be implemented in future studies (see Appendix B, "Example Wingbeat Patterns").

Despite challenges with discrimination, a widespread pattern or phenomenon detected by radar may indicate that the behavior is shared among a wide range of species, which is likely the case here. Otherwise, for one or a few species to be responsible for observed patterns requires that those species occur in relatively large numbers over many days and are widely distributed enough to yield similar diel patterns between two areas separated by ~90 km.

Bias introduced by the pitch angle adopted by animals in flight was also considered (see Appendix B, "Pitch Angle Bias").

Reorientation

Considerably more animals passed through the Seville area than through the Desert Sunlight area. Assuming that observed differences in animal abundance generally reflect variability across the region, those observations suggest that meaningful abundance differences and probably species composition influence the exposure levels of flying animals to solar facilities. Future solar facility developments could be sited in ways that reduce exposure to birds based on regional surveys of avian abundance, especially if they reflect existing fatality data and characterizations of solar facility properties and their landscape contexts.

Orientation is more properly defined as the direction an animal's head is pointing. A clearer indication of directional motivation may be better associated with head orientation than track orientation that does not take wind direction into account. If adequate data on winds aloft had been available, it may have been possible to examine the response of true head orientation to the location of solar facilities.

The results for slow-flying animals more associated with insects suggest reorientation toward solar facilities at above background levels given that the response exceeds the criteria for reorientation at both sites. The result is more ambiguous for fast-flying animals typically associated with birds. That said, ground speed is an unreliable indicator of animal type even though the thresholds chosen were conservative compared with those identified in the literature for airspeed (e.g., Horton et al., 2015; Larkin, 1991). Birds and insects likely contribute to both slow- and fast-animal categories.

At Desert Sunlight, the periphery of radar coverage is within two kilometers of relief in terrain that may influence animal movement in ways that bias background directions of travel within the radar coverage area. Therefore, differences between treatment and control directions of travel may vary in ways unrelated to the solar facility. The impacts of such directional bias may be stronger in the horizontal domain than in the vertical domain because of its considerably larger coverage area. Narrowing the range of directions of travel in analyses of reorientation (e.g., direction toward 180°±45° versus 180°±85°) helps reduce the impact of this bias, if present, but would probably not eliminate it altogether.

The spatial scale of response to avian reorientation and descent was unknown at the project's outset. The original study design called for measuring responses at intermediate distances from solar facilities, but budgetary constraints and the practical limits of identifying such locations prevented this from happening. Some results for reorientation, mostly for descent, suggest that the spatial scale of response is on the order of hundreds to the low thousands of meters for at least some flying animals. It is also possible that the spatial scale of response for some species is much larger than that captured by the radar coverage area. The spatial scale of response is not necessarily the same as the spatial scale of perception, though it seems likely that animals motivated to respond to polarized light would respond quickly to its detection. Response distances by birds to ground features are not well understood. Diehl (2003) found the range of response by migrating birds to forest fragments of stopover habitat in an agricultural matrix was four kilometers or less. The scale of perception and response may play a role in species conservation if, for example, the source of the cue can be sited beyond the range of perception and response of high-traffic corridors.

Descent

Desert Sunlight and Seville differ in size, manner of solar panel deployment (rotating at Seville versus stationary at Desert Sunlight), location, geography, and landscape context. Nonetheless, among animals with long tracks (≥17.5 seconds), both sites are characterized by a descent response among diurnal, southbound animals and nearly no descent response among contemporaneous diurnal, northbound animals or nocturnal animals from any direction. The lack of response among northbound, diurnal animals suggests refuge seeking from daytime heat did not drive descent behavior. Alternatively, species composition among northbound and southbound animals may differ in ways that result in differences in response. The same might be said of possible behavioral differences between these groups, such as motivation or specific directions of travel. There is no way to measure differences between northbound and southbound animals in true directions of travel in the vertical domain; only relative differences in direction either toward or away from the radar are knowable.

Limiting analyses to longer tracks increases the likelihood that tracks assume directions that are closer to parallel with the north-south orientation of the plane of rotation; this tends to homogenize some differences that may emerge between treatment and control locations. For example, the landfill near the Seville control site was located west of the radar, so some movements to and from the landfill through vertical radar coverage would have a greater tendency to be perpendicular to the plane of rotation and therefore have short duration tracks. Reducing the prevalence of such tracks is a benefit of setting a longer track duration threshold (≥17.5 seconds) than the minimum available from first stage processing (≥7.5 seconds). Similarly, data gathered at the Desert Sunlight treatment location benefits from analyses of longer tracks since the precise data collection location was unavoidably close to considerable relief in terrain compared with the control (Figure 5). This relief may cause animal movement through the radar coverage area to be concentrated in certain directions not characteristic of the control area. Finally, use of longer tracks also decreases the likelihood of spurious tracks resulting from the inadvertent linking of radar locations between adjacent animals during periods of exceptionally dense movement (see Appendix B). Few long tracks survive this filter under these circumstances, which reduces the likelihood that extreme events, dominated by insects, would bias the overall sample.

The most notable similarities between Desert Sunlight and Seville are extreme aridity and local isolation from other perceived substantial natural or anthropogenic oases, though the Salton Sea and the Imperial Valley are within 20 to 30 km of the Seville facility. Diurnal descent at both facilities may be explained as water-seeking or, more broadly, as resource-seeking behavior among flying animals. This suggests that landscape context matters, and that PV USSE facilities in more mesic landscapes might elicit less resource-seeking and experience lower mortality.

Animals flying between approximately 400 to 700 meters above ground level exhibited the highest propensity for descent, although this may be an artifact of biology and the nature of radar data collection in the vertical domain. Ground clutter filtering at short radar ranges and at the angular extremes of coverage (i.e., those capturing animal movements closest to the ground north and south of the radar) eliminated the ability to assess animal behavior at the lowest heights above ground level. Relatively few samples survive this filtering at low heights, and this could result in sampling errors, leading to spurious estimates of P, particularly for Seville (Figure 8). Radar coverage in the vertical domain approximates a half circle, oriented vertically with widest lateral coverage closest to the ground and narrowing at higher altitudes, which limits the number of samples at high altitude. High altitude measures also occur at long radar ranges, approaching the maximum of 1,500 meters, and typically fewer animals fly at high altitudes. Also, the open-array antennas used in this vertical mode of operation have considerably lower gain than their parabolic counterparts (used for data collection in the horizontal domain). Taken together, these factors – narrow coverage, spreading loss, fewer animals, and reduced sensitivity – resulted in fewer animal detections at high altitudes and increased likelihood of sampling error and spurious estimates of proportion.

Lower proportions of higher-speed animals descended toward facilities, suggesting bird-like animals may be less inclined to descend than their insect-like counterparts. However, the speeds of animals passing through radar coverage in the vertical plane are relative to the radar, and thus underestimate true speed in all instances except when the animal is moving exactly parallel with the plane of rotation; specifically, true speed equals the relative speed divided by the cosine of the angular difference between the animal's track through the coverage plane and the orientation of the coverage plane. For this reason, relative speed estimates of animals passing through the plane of rotation are extremely conservative, and bird-like animals are likely well represented at lower relative speeds and may be counted among those animals with a higher likelihood of descent (Figure 9).

Diel change in the proportion of animals descending toward both solar facilities was accurately modeled by a Gaussian function and, at both sites showed the strongest response at midday, albeit at times that differed by >2.5 hours between the two sites. The close agreement between the data and the model suggests a mechanistic diel process at work, among long duration tracks at Seville, but the nature of such a process remains unclear. Several potentially relevant extrinsic factors change throughout the day, including the weather (heat, humidity, prevailing winds) and sun position, light conditions, panel orientation, and their aggregate effect on the angle of reflection of polarized light. Some intrinsic factors (to the animal) may also have diel periodicity, including thirst and energetic/caloric state and associated foraging behavior.

Refuge-seeking associated with daytime heat might be expected to follow the observed Gaussian trend. The hottest part of the day for this region occurs around 15:00 LT, which matches observations of peak descent at Seville but not at Desert Sunlight. Mismatch in peak descent and duration of the diurnal descent period does not comport directly with a response to heat. Perhaps most important, diurnal, northbound animals did not show a strong descent response. This rules out extrinsic and intrinsic factors that depend on both daily periodicity and the animals' general directions of travel.

A multi-way interaction between the sun's position in the sky, the angle of solar panels, and general direction of flight may optimally expose animals to a polarization cue (or similarly mediated solar cue) in a way that elicits a descent response with the observed diel pattern, accounting for the discrepancy in time of peak response between the two facilities. The effect is more pronounced among animals with long duration tracks that should be oriented more toward true south. Specifically, the proportion of descending animals with long-duration tracks increased by 38.5 percent over to their short-duration counterparts at Desert Sunlight, and by 61.7 percent at Seville.

Overall, evidence for attraction to PV facilities by descent linked to a polarization cue includes: 1) similar descent response at both facilities despite their differences, 2) response primarily during daytime hours, 3) response largely limited to southbound animals, 4) Gaussian response pattern suggesting a cue consistent with that of the sun's presence and movement, and 5) stronger response among animals adopting tracks oriented more directly than tangentially south. Because the proportion of animals descending over solar facilities considerably exceeds that measured at control sites, the lake effect hypothesis is broadly supported.

CHAPTER 4: Aquatic Habitat Bird Community Responses to Photovoltaic Energy Development in Southern California

Introduction

Background in Avian Mortality Associated with Industrial-Scale PV

The detection of water-obligate and water-associate bird carcasses at PV solar facilities (Kagan et al., 2014) raised questions about the causes of the avian deaths since PV solar panels are typically within four meters of the ground and do not represent vertical hazards in the airspace like other forms of anthropogenic development such as buildings (Loss et al., 2014), communication towers (Gehring et al., 2011), and wind turbines (Erickson et al., 2014, Loss et al., 2013) do. Desert Sunlight is also located in a desert ecosystem that lacks many permanent large water bodies. In their report, Kagan et al. (2014) stated that the solar panels might be somehow "reminiscent" of bodies of water because some species of aquatic habitat birds (a broad group of birds including water associates and water obligates) should not naturally occur on the ground in a desert environment. A Scientific American article hypothesized that this "lake effect" may cause birds to mistake a reflective PV USSE facility for a water body (Upton, 2014). The outcome of this lake effect could be negative effects on aquatic habitat birds if the causal mechanism occurs broadly across many PV USSE facilities and bird species.

The lake effect hypothesis (LEH), which posits that aquatic habitat birds are attracted to PV solar USSE facilities, was used to explain the occurrence of aquatic habitat bird carcasses at PV USSE facilities; however, no data existed at the time to understand how birds perceive PV USSE facilities, and no alternative hypotheses were proposed by Kagan et al. (2014). Further, as the LEH was developed based on one PV USSE facility, it was unknown if the occurrence of aquatic habitat birds was unique to Desert Sunlight or if this pattern was widespread among PV USSE facilities in Southern California. In a summary of 13 studies at 10 PV USSE facilities in the Southwestern United States, Kosciuch et al. (2020) determined that carcasses of water obligate birds were documented in 90 percent (9/10) of studies in the SMD BCR, where Desert Sunlight is located. However, Kosciuch et al. (2020) found that water obligates were detected in only one of three studies outside the SMD BCR. Thus, uncertainty remains in how broadly the LEH can be applied, and if the LEH applies to all aquatic habitat birds or just to specific species.

Study Objectives

Because the LEH was only recently defined and inference beyond bird mortality is limited, the research objective was to examine the species composition, abundance, and distribution of live and dead aquatic habitat birds at five PV solar facilities and nearby reference areas in Southern California. Researchers also collected data from a small regional lake as an indicator of the potential aquatic habitat bird community that would occur at the study sites. Including live bird surveys in the study was an important advancement in investigating the LEH because the risk profile for all aquatic habitat birds is diverse. For example, species that forage over water (e.g., tree swallow [*Tachycineta bicolor*]) are at lower collision risk than species that land on water (e.g., western grebe [*Aechmophorus occidentalis*]) and are less likely to be represented in fatality data even if attracted to the facility. It is unknown how the aquatic habitat bird diversity and abundance at PV solar facilities compares with those at regional water bodies; the objective was to understand if a local lake could provide a context for the findings at the PV solar sites. The final objective was to determine if there was support for these novel questions by employing innovative methods. Searching for aquatic habitat bird carcasses in reference areas outside the PV solar sites would allow the team to determine if there was support for an alternative hypothesis that avian mortality was not predicated on attraction to PV solar facilities.

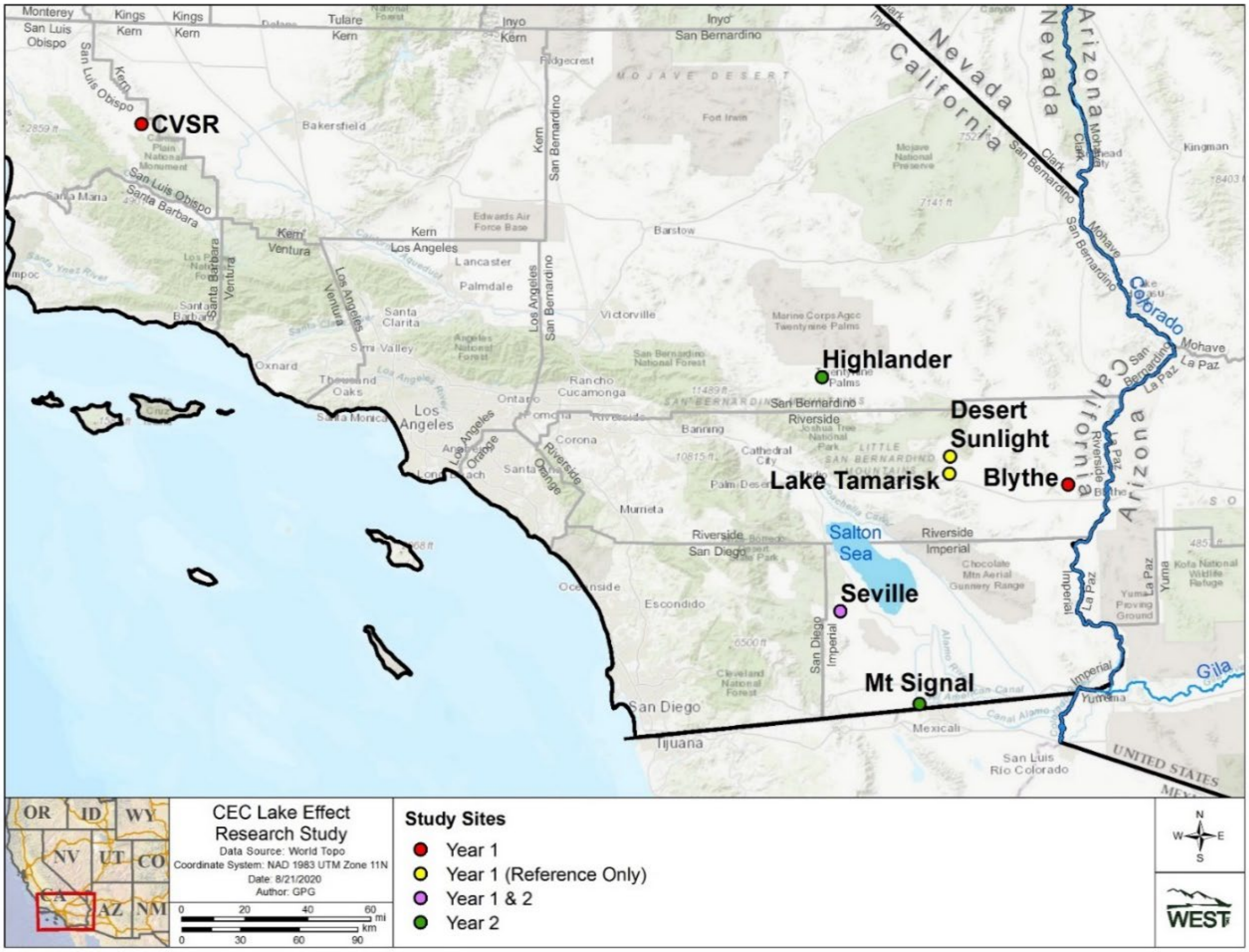
Methods

Study Sites and Reference Areas

In 2018, PV USSE study sites included the Blythe Solar Energy Center (Blythe; 235 megawatts [MW]) located in Riverside County, California Valley Solar Ranch (CVSR; 250 MW) located in San Luis Obispo County, California, and Seville 1 and Seville 2 Solar (treated as one site called Seville; 50 MW) located in Imperial County, California. A paired reference area was selected at least 1 km from a facility with similar vegetation community as the facility prior to construction for a matched pairs design (Conkling et al., 2020). Reference areas were selected that contained neither a solar facility nor anthropogenic features that could cause aquatic habitat bird deaths.

In addition, two reference areas were monitored in 2018 that were not paired with a PV USSE facility: desert habitat outside of Desert Sunlight (Reference A) in Riverside County, and Lake Tamarisk in Riverside County. Reference A was selected because it is within 1.25 km from Desert Sunlight, where 96 water-associated and water-obligate bird carcasses and bird injuries had been detected during the first two years of fatality monitoring (Kagan et al., 2014). Researchers selected Lake Tamarisk, an approximately 5.5-hectare (ha) artificial lake located approximately 6.4 km from the nearest PV USSE facility (Desert Sunlight), as an indicator of avian species' composition and abundance at a water body local to the study sites. In 2019, PV USSE study sites included one studied in 2018 (Seville) and two new sites: Highlander II (10 MW) in San Bernardino County, and Mt. Signal 3 (328 MW) in Imperial County. The same criteria were used to select reference areas in 2019. Given the agricultural landscape in the Imperial Valley, it was challenging to locate reference areas without anthropogenic features so the reference area for Mt. Signal contained anthropogenic features; however, these features were present at the solar site prior to development. Data were not collected at either Reference A or at Lake Tamarisk in 2019. One of three general habitat classes was assigned to each site based on dominant vegetation on the surrounding landscape: grassland, desert/scrub, and agriculture. Blythe, Seville, Desert Sunlight, and Highlander were desert/scrub, Mt. Signal was agriculture, and CVSR was grassland. Lake Tamarisk is an artificial lake that was not included in one of the three habitat categories but is located in desert/scrub habitat. Study sites are shown in Figure 11.

Figure 11: Study Sites



Study site locations in California during Fall 2018 and 2019.

Source: Western EcoSystems Technology, Inc.

Point Count Surveys

The objective of fixed-point count surveys was to collect data to evaluate patterns of live aquatic habitat bird use at PV USSE study sites and reference areas. Ten-minute fixed-point count locations (with a survey defined as one complete 10-minute observation period at an individual 10-minute point location) were established and surveyed both within each solar facility and at the reference areas (Ralph et al., 1995). Point count locations were determined by randomly sampling coordinates within facility boundaries and polygons defining accessible public or private land for reference areas. At Mt. Signal, point count locations were selected along roads adjacent to reference areas due to access limitations. The number of point count locations was based on PV solar facility size, and varied among study sites (Appendix C, Table C-1). In 2019, one 60-minute fixed "long-sit" point count was added at each study site to increase the likelihood of observing aquatic habitat bird behavior (with a survey defined as a complete 60-minute observation period at an individual 60-minute long-sit point location). The long-sit, named to distinguish it from a standard 10-minute point count, was situated so that a surveyor was able to observe birds flying over the solar facility or the surrounding habitat. In

2018 and 2019, 10-minute point count locations were surveyed four times each (a total of 40 observation minutes per location) during the study period. Long-sit point count sites were surveyed only in 2019 and were surveyed two times each (a total of 120 observation minutes per location) during the study period. During both 10- and 60-minute counts, observations for small birds were limited to within a 100-meter radius from an observer; no limit was imposed on observations of large birds (e.g., Family *Podicipedidae*). The number of 10-minute points surveyed per day varied depending upon study site, but typically ranged between 10 and 15 points surveyed per day. Surveys for all 10-minute point count locations typically began 30 minutes before dawn and were conducted no later than four hours after dawn. Long-sit point counts were conducted once during the dawn period and once during the mid-day or evening period (within six hours of sunset) to capture temporal differences in flight.

Fatality Monitoring Surveys

The objective of fatality surveys was to understand the distribution of aquatic habitat bird carcasses both inside and outside PV USSE facilities in Southern California. Distance sampling was used (Buckland et al., 2001; Buckland et al., 2004; Huso et al., 2014) to search for carcasses and feather spots (a group of 10 or more body feathers, or three or more flight feathers; hereafter referred to as "detections") of birds in both facility and reference areas. Distance sampling is well suited to PV USSE facilities, especially when vegetation is low or nonexistent and other visual barriers are absent, because it allows for efficient sampling of large areas. The design of PV USSE facilities is also amenable to distance sampling; a surveyor can walk perpendicular to PV panel rows and look down each row for detections. For each facility study site, a viewshed (maximum distance to search during distance sampling surveys) was established based on the length of the facility's typical panel row. For reference areas, the viewshed was always 100 meters, with the exception of CVSR, where the viewshed was 50 meters due to visibility limitations from vegetation density. Cumulatively, approximately 546 ha of the PV USSE facilities were sampled using distance sampling and 1,038 ha of the reference areas; the area sampled varied by facility and was based on the field schedule and facility size. Each study site was monitored for a two-week focal period within the fall migration period, alternating between live-bird surveys and fatality surveys. During each week, three fatality surveys and two point count surveys were conducted for a total of six fatality surveys and four point count surveys per study site. Slight variations in survey frequency were due to weather and scheduling logistics.

During fatality monitoring, not all carcasses are detected by searchers; observers can fail to see a carcass, or a carcass may have been removed by scavengers between searches. Thus, searcher efficiency and carcass persistence are measured to adjust for detection bias in fatality studies. Given that carcass persistence times were typically at least one to two days for even the smallest trial birds at other solar projects, carcass persistence was not measured because researchers assumed that most fatalities would persist through the average search interval of 48 hours.

Searcher Efficiency Trials

Searcher efficiency trials were conducted to calculate the probability of carcass detection. Searcher efficiency trials are typically conducted with actual bird carcasses; however, given logistical constraints associated with travel between study sites, a variety of surrogates were used to mimic likely species at each study site, including Dokken waterfowl trainers (Dokken Dog Supply Inc., Northfield, Minnesota) and characteristically appropriate birds obtained from craft stores similar to passerines typically detected at PV USSE facilities. Surrogates represented small (average weight ≤100 grams [g]) and large (average weight >100 g) bird species typically found at the sites. Whenever possible, surrogates were modified by hand to more closely resemble actual detections. Modifications included color modifications to better represent local bird species and the attachment of feathers to the bodies of surrogates to mimic fatality postures. Trials were administered prior to surveys by a biologist not otherwise involved with the daily fatality surveys. The biologist conducting fatality surveys was unaware of the time or location of surrogate deployments, or of the number of surrogates being dropped (USFWS, 2012). All biologists participating in fatality surveys were tested multiple times throughout each study period to estimate their search efficiency.

Statistical Analysis

A metric of use was calculated for each aquatic habitat species, by site and facility or by reference area. Density estimates were not calculated because the dataset included flying animals and rarely encountered perched animals. Researchers acknowledge that detection could have differed among species, but similar detection was assumed for an aquatic habitat species between the PV solar sites and reference areas because field crews focused on birds in flight above the solar panels and vegetation. For each species, the count of birds by point and visit (including flyovers) was totaled, averaging overall points within a survey, and then averaged across all surveys (four surveys at each site in each year of study). Researchers then averaged over sites within a habitat category (desert, grassland, or agriculture) and calculated relative frequencies of point count observations of aquatic habitat species in both facility and reference areas within each ecoregion. Relative frequencies were calculated as the averaged use value for each aquatic habitat species, divided by the sum of use values for facility and reference areas, respectively. Furthermore, species richness and Chao's estimator of richness (Choa, 1987; Chiu et al., 2014, using the "vegan" package in R) were calculated to assess bird communities across the sampled sites. Species richness was calculated as the number of unique identifiable aquatic habitat species by site and facility, or by reference area. Counts of aquatic habitat species were used to test the null hypothesis that aquatic habitat birds would occur as frequently at the PV solar site as the paired reference area by performing a Cochran–Mantel–Haenszel test (significance level $\alpha = 0.10$) on the aquatic habitat bird count data. The counts of aquatic and nonaquatic habitat birds were tabulated into bins by facility or reference and habitat category (desert, agriculture, or grassland). The live aquatic habitat bird community was visualized using unconstrained ordination based on latent variable models with the boral (Bayesian ordination and regression analysis) package in R to determine whether any of the PV facility sites would be grouped with the lake (Hui, 2016).

Results

Relative Frequency of Occurrence of Live Aquatic Habitat Birds at PV Solar and Reference Areas

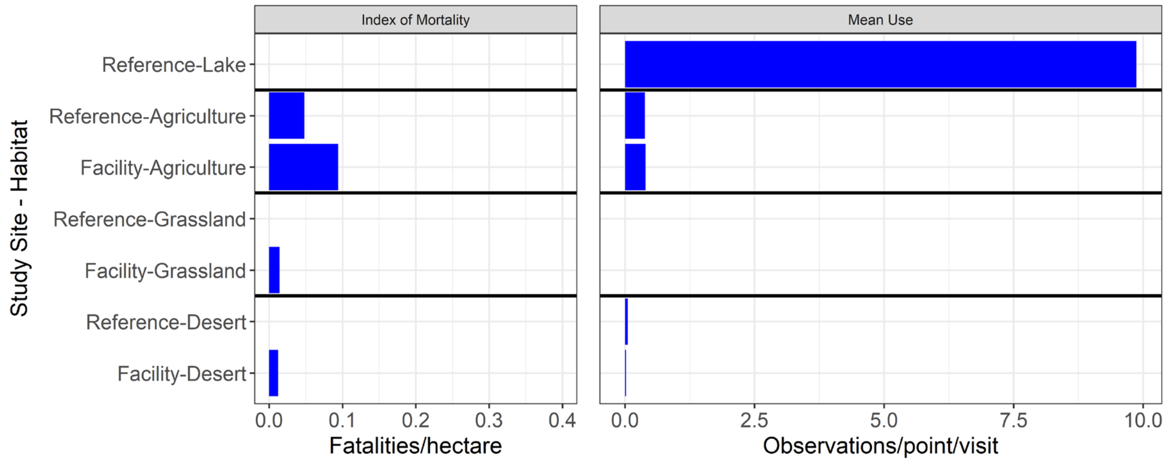
In 2018, 234-point count surveys were completed at three PV USSE facilities, 229-point count surveys at three paired reference areas, 88 at Reference A, and 18 at Lake Tamarisk. In 2019, 172-point count surveys were completed at three solar facilities and 216-point count surveys at three paired reference areas; 12 long-sit point counts were also completed (four surveys per long-sit point count location at each study site in 2019). Over the two study periods at all study sites, 4,128 aquatic habitat birds of 26 species were observed during point counts (Appendix C, Table C-1). During long-sit point counts, 299 aquatic habitat birds representing seven species were observed.

Patterns in the relative frequency of occurrence were examined to determine whether aquatic habitat birds occurred more frequently at the PV solar site than at the paired reference area. For the sites in the desert/scrub habitat, it was found that of the eight aquatic habitat species observed during point counts, four species (50 percent) occurred more frequently in the reference areas than in the solar facilities. For the site in the agricultural habitat, it was found that of the 11 aquatic habitat species observed during point counts, 6 species (55 percent) occurred more frequently in the reference areas than in the solar facility. Aquatic habitat birds were not observed during point counts at the solar facility area in the grassland ecoregion, and only a single species was observed in the reference area (tree swallow (*Tachycineta bicolor*)). No statistically significant difference ($\chi 2 = 0.0297$, $p = 0.8633$) was found in the distribution of aquatic habitat birds between facility and reference areas, accounting for habitat. The test result is consistent with the qualitative analysis of relative frequencies of aquatic habitat birds by habitat in that they did not appear in higher relative frequency in facility areas compared with reference areas.

Patterns in species diversity and use were examined to determine how the aquatic habitat bird community at PV solar facilities compared with a regional lake. Using Chao's estimator, richness was estimated for live aquatic habitat birds to be highest at the lake (14.5, standard deviation [SD] = 1.28; Table 3), which was 20.8 percent higher than the strata with the next highest richness estimate (agriculture reference, 12, standard deviation of error = 4.48; Table 3). The remaining strata where aquatic habitat birds were observed during point counts (agriculture facility, desert facility, desert reference, and grassland reference) had richness estimates between one and seven for aquatic habitat species. However, 90 percent confidence intervals generally overlapped between all strata, and it was not clear whether there were any statistically significant differences in Chao's estimate between any two strata (Table 3). Among the strata with bird fatality detections, there was a high degree of variability (Table 4). The agriculture reference area had the highest Chao's estimate (21, SD = 13.46; Table 4), followed in rank by agriculture facility, desert facility, and grassland facility (no aquatic habitat birds were found during fatality monitoring in the grassland or desert reference areas). However, due to the small number of aquatic habitat birds detected during fatality monitoring, the standard deviation was large relative to richness estimates. The percent coefficient of variation (100 × estimate/SD) was between 64 percent and 71 percent for the strata with more than one aquatic habitat bird fatality, and 90 percent confidence intervals were wide compared with the live bird data and largely overlapping for all strata (Table 4).

Researchers also qualitatively compared the mean avian use and fatality index of aquatic habitat birds within each stratum to account for differences in use, fatality rate, and effort associated with each site (Figure 12). The results were consistent, if not more pronounced than the comparison of species richness, with the lake showing an order of magnitude higher use by aquatic habitat species (10 observations/point/visit) compared with the next highest site, agriculture facility (0.75 observation/point/visit, Figure 13).

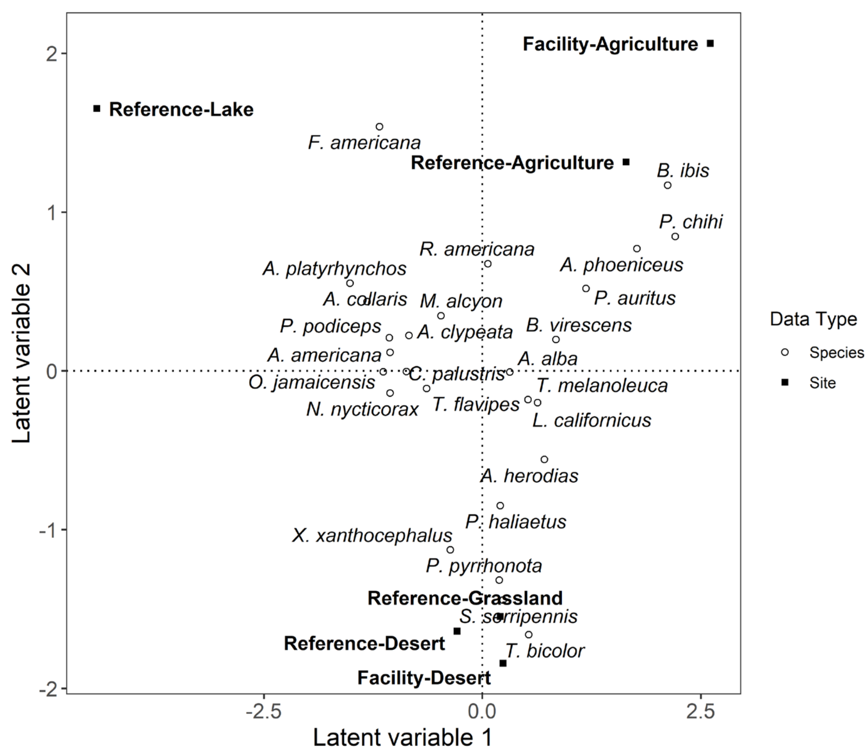
Figure 12: Index of Mortality



Index of mortality (found fatalities per hectare of area searched, adjusted for searcher efficiency) and mean use (live birds counted per point per survey visit) of aquatic habitat birds found at the facility and reference survey areas in three habitat regions and a lake (no fatality surveys occurred at the lake).

Source: Western EcoSystems Technology, Inc.

Figure 13: Ordination of Aquatic Habitat Bird Species



Ordination of aquatic habitat species observed during point count surveys and facility or reference areas in three habitat regions based on two latent variables in a Bayesian ordination and regression analysis. No aquatic habitat birds were observed in the facility-grassland stratum.

Source: Western EcoSystems Technology, Inc.

Mortality of Aquatic Habitat Birds at PV Solar and Reference Areas

During the 2018 field season, 201 searcher efficiency trials were deployed across the sites (90 large bird trials and 111 small bird trials), including 87 trials in facility areas and 114 trials in reference areas. In 2019, 144 trials were deployed (78 large bird trials and 66 small bird trials), including 70 trials in facility areas and 74 trials in reference areas. No trials were placed at Blythe facility areas, which had an existing bias trial dataset resulting from over two years of standardized fatality monitoring (95-meter row lengths), and Reference A (given the proximity and similarity to Blythe reference areas). Furthermore, no trials could be placed in any area at the Mt. Signal site due to access restrictions. The ground conditions (e.g., amount of visible bare ground, presence of rubble or vegetation, typical vegetation height, and density) at Mt. Signal were similar to Seville's facility and reference areas than to any other site monitored during the study. It was assumed that the probability of detection in the facility and reference areas of Mt. Signal would be comparable with Seville, using the 2019 Seville data.

Table 3: Species Richness for Live Aquatic Habitat Birds

Metric	Reference-Lake	Facility-Desert	Reference-Desert	Facility-Agriculture	Reference-Agriculture	Facility-Grassland	Reference-Grassland
Species richness	14	6	7	6	9	0	1
Chao's estimator	14.5	7.5	8	6	12	NA	1
Standard deviation	1.28	2.54	2.24	0.46	4.48	NA	0
90 percent Confidence interval	14.05–19.20	6.22–16.16	7.11–16.04	6–NA	9.51–26.81	NA	NA

Species richness and Chao's estimator of richness for aquatic habitat birds observed during live bird counts in three habitat regions and a lake. Birds unidentifiable to species were excluded from species richness calculations.

Source: Western EcoSystems Technology, Inc.

Table 4: Species Richness for Bird Carcasses

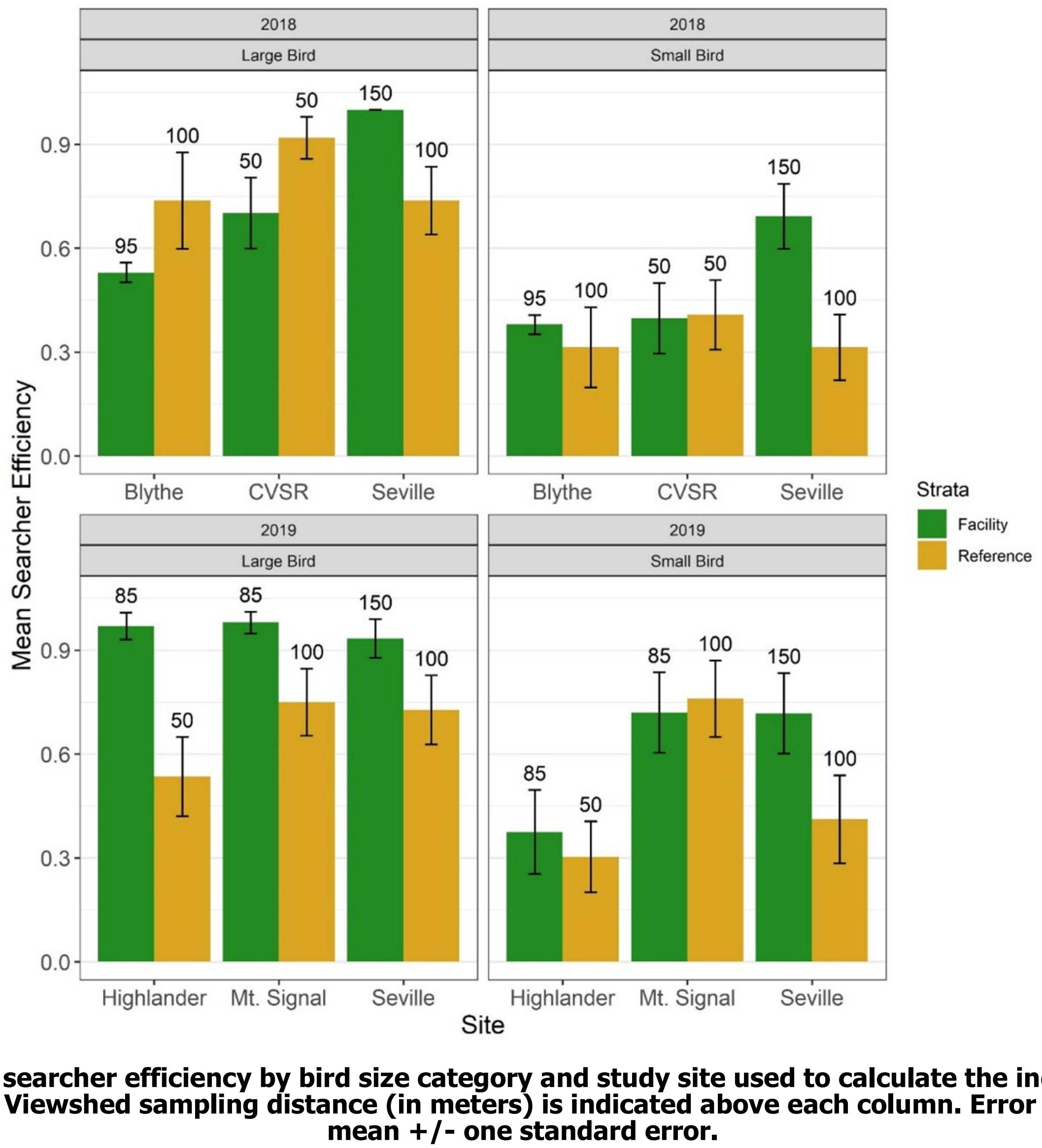
Metric	Facility-Desert	Reference-Desert	Facility-Agriculture	Reference-Agriculture	Facility-Grassland	Reference-Grassland
Species richness	3	0	5	6	1	0
Chao's estimator	6	NA	15	21	1	NA
Standard deviation	4.29	NA	10.04	13.46	0	NA
90 percent Confidence interval	3.53–20.00	NA	7.53–44.49	10.24–59.09	NA	NA

Species richness and Chao's estimator of richness for aquatic habitat birds detected as fatalities at facility and reference survey areas in three habitat regions. Birds unidentifiable to species were excluded from species richness calculations.

Source: Western EcoSystems Technology, Inc.

Searcher efficiency varied by study site and whether trials were in facility or reference areas (Figure 14). The best-fit model for 2018 facility areas was a half-normal detection function, including a covariate for the study site (i.e., systematic differences in search efficiency, by facility) for both small and large birds. The top model for reference areas in 2018 did not include any covariates (i.e., no systematic differences in search efficiency by facility) and was a half-normal detection function for large birds and a hazard detection function for small birds. In 2019, the best-fit model for facility areas included the study site and was also a uniform detection function for small birds, while the large bird model for facilities did not include any covariates and used a half-normal detection function. In the reference areas, models for both small birds and large birds used an exponential detection function and included the study site as a covariate.

Figure 14: Searcher Efficiency



Mean searcher efficiency by bird size category and study site used to calculate the index of mortality. Viewshed sampling distance (in meters) is indicated above each column. Error bars show mean +/- one standard error.

Source: Western EcoSystems Technology, Inc.

Within the facility and reference areas of each study site, respectively, searcher efficiency was generally lower for small birds compared with large birds in each year (Figure 14).

There were 15 detections of aquatic habitat species across all study sites and years of study, ranging from 0 (6 of the 11 combinations of site and facility or reference) to 6 (Mt. Signal reference area). Given the small number of detections relative to total hectares surveyed, the fatality index for aquatic habitat species showed little variability within the two-week study periods at each study site, ranging from 0 (grassland reference) to 0.09 fatalities/ha/study period (agriculture facility; Figure 12). Thus, when accounting for differences in searcher efficiency and different amounts of total area searched, the fatalities were not distinctly higher in the reference or facility areas at any site.

Discussion

Based on mortality patterns at PV USSE facilities, biologists hypothesized a lake effect, that is, that a PV facility provided a signal of water to aquatic habitat birds (Kagan et al., 2014). Data gaps existed in understanding the LEH; however, since live-bird behavior at PV solar facilities had not been examined, nor had an alternative to the LEH been considered. Further, context for the number of carcasses detected was lacking as aquatic habitat bird mortality had never been evaluated against the bird community at a regional water body. Live aquatic habitat birds appeared at PV solar facilities, but researchers did not observe flocks approaching the solar sites exhibiting landing behaviors. Aquatic habitat bird diversity was lower at PV USSE facilities when compared with Lake Tamarisk, and standardized use was more than an order of magnitude higher at Lake Tamarisk than at the PV USSE facilities. Aquatic habitat bird detections were not made in the desert/scrub and grassland reference areas; researchers therefore did not find support for the alternative hypothesis that mortality is independent of the PV facility. Taken together, the LEH cannot be readily generalized to all aquatic habitat birds, and avian fatality risk could be species specific and context dependent.

If aquatic habitat birds are attracted to PV solar facilities across taxa, one would expect to find, in addition to fatality detections, live aquatic habitat birds approaching or perched at the facility. Results show that aquatic habitat birds were infrequently observed at the desert/scrub and grassland study sites, and no evidence was found of the expression of maladaptive behaviors, such as landing attempts or flocks repeatedly circling a facility. Rather, the observations were of aquatic habitat birds flying past the facility, though the same species were often observed in the paired reference area. Some species of aquatic habitat birds found as detections in this study (and in Kosciuch et al., 2020), migrate nocturnally (Laporte et al., 2020), and it is possible that aquatic habitat bird exposure at the PV facilities nocturnally was higher than was measured diurnally. However, species resolution is limited with radar, and interpreting patterns in the context of the LEH is challenging. Thus, point count results demonstrate limitations in understanding the extent of a potential lake effect when interpreting diurnal patterns of live aquatic habitat birds at PV solar facilities. Overall, diurnal point count surveys for aquatic habitat birds may not provide sufficient data to predict the number of fatalities for these species.

Mt. Signal, the PV solar facility and paired reference area in the agriculture habitat, differed from other study sites having higher aquatic habitat bird diversity, use, and detections. Mt. Signal was developed in a landscape that was altered by irrigation from the Salton Sea, where irrigation and farming have converted the agricultural habitat into a novel ecosystem with a high level of human disturbance and changes to the biota reflected in the bird community (Hobbs et al., 2009). It follows that aquatic habitat bird use was higher in an irrigated landscape compared with a grassland and desert/scrub habitat; however, the mortality patterns at PV solar facilities in agricultural landscapes are poorly studied (Kosciuch et al., 2020). The adjusted fatalities/ha were similar between the facility and reference site for Mt. Signal, suggesting that mortality risk is not isolated to the solar facility. Thus, in the agricultural landscape context, for some species it is difficult to untangle a lake effect from other sources of mortality (e.g., predation). Arid landscapes without water in close proximity to PV USSE facilities, like the desert/scrub study sites, provide more inference into the LEH because possible attraction is obscured in agricultural landscapes, which can be hybrid or novel ecosystems inhabited by aquatic habitat birds.

The premise of the LEH is that PV USSE facilities attract aquatic habitat birds, but the magnitude of attraction has not been suggested, leaving a gap in understanding about how aquatic habitat bird abundance and diversity at a PV USSE facility compare with a natural water body. No aspect of the LEH limits the number of live or dead aquatic habitat birds that could occur at a PV solar facility, and the expression of maladaptive behaviors could lead to exaggerated patterns (Robertson and Blumstein, 2019). The major water body in the vicinity of the study sites in the desert/scrub and agricultural habitat is the Salton Sea, an approximately 89,000 ha saline lake that is a known stopover location for hundreds of thousands of aquatic habitat birds (Shuford et al., 2002). Since none of the PV USSE sites approached the size of the Salton Sea, Lake Tamarisk, a 5.5 ha artificial lake in a desert community, was surveyed and thousands of birds were counted during the sampling period, underscoring the importance of water bodies in this arid environment. Lake Tamarisk was distinct from the solar facilities and paired reference areas in the multivariate analysis and had between 25 to 800 times the abundance of aquatic habitat birds compared with the PV USSE sites, including the site in the agricultural habitat where aquatic habitat birds were part of the local bird community. Surveys at Lake Tamarisk included birds that were foraging or resting on the lake, which is not possible at a PV USSE facility. It therefore follows that mean use was higher at Lake Tamarisk than at the PV USSE facilities. However, understanding the regional aquatic habitat bird community at a water body is important for research questions relating to the magnitude of the LEH and predicting aquatic habitat bird presence. Although water bodies are scarce in the desert/scrub habitat near the study sites, had researchers surveyed a different lake, the results would likely have been different as well. However, sampling one lake in a water-limited environment does not alter conclusions about a context for understanding the availability of birds that could be present at the PV solar facilities in this study.

Developing alternatives to a hypothesis established through abduction is important so that an original hypothesis is not accepted by default (Josephson and Josephson, 1996; Kosciuch et al., 2006). An alternative hypothesis to the LEH is that ill or exhausted birds land randomly on a landscape, including on PV USSE facilities. Thus, under a random landing hypothesis, aquatic habitat bird detection would be as likely to occur outside of a PV USSE facility as inside a facility. Given that there was no reference area monitoring associated with 9 of 10 PV USSE sites summarized by Kosciuch et al. (2020), it is possible that broader patterns of mortality were not detected earlier because of the survey methods used in those studies. The appearance of water-obligate species (such as loons and grebes) on dry land away from water bodies is maladaptive since those species become stranded and ultimately perish on dry land (Robertson and Chalfoun, 2016).Therefore, there is no evolutionary context for a common loon (*Gavia immer*, a species detected as a fatality at the Seville study site) to occur in the desert on dry land. The presence of aquatic habitat bird detections found at PV USSE facilities in a desert/scrub habitat provides the most compelling evidence that these birds were attracted to the facility because fatalities were not found in the paired reference areas. No aquatic habitat bird detections were found in Reference A, which was located outside of Desert Sunlight, the site in Kosciuch et al. (2020) that had the highest number (n = 94 detections over two full years of monitoring) and greatest proportion of aquatic bird detections at PV arrays among the 10 sites summarized. Thus, if a mechanism other than attraction were responsible for aquatic habitat bird detections at PV solar facilities (e.g., exhaustion, random landing), researchers would have expected to find aquatic habitat bird detections in Reference A.

Aquatic habitat bird detections were found at all PV facilities and in the agricultural site reference area, but not at reference areas in a desert/scrub or grassland habitat. Searcher efficiency was similar at the PV facilities and reference areas with three exceptions where the value at the reference area was approximately half that at the paired PV facility. Large differences in searcher efficiency between PV facility and reference areas could limit conclusions about mortality patterns. However, a larger area at the reference locations was searched and did account for these differences in the fatality index. Although carcass persistence trials were not performed (as is common for fatality-monitoring studies), the goal was not to produce robust estimates of fatalities as summarized in Kosciuch et al. (2020); it was rather to have a high likelihood of detecting aquatic habitat species as fatalities. Furthermore, it was assumed that carcass persistence was similar in facility and reference areas, and that the frequency of searches (<48 hours apart) would limit potential bias from different rates of carcass removal by scavengers in either area.

Conclusions and Broader Implications

The results from this study suggest that some species of aquatic habitat birds could be attracted to PV USSE facilities, and if attraction occurs, it is likely context-dependent. The most compelling evidence for attraction is the mortality of water-obligate species (e.g., loons) found at PV USSE facilities in desert environments without water; those species perish on dry land. Untangling mortality at PV solar facilities in landscapes with other anthropogenic features is challenging for many species because of the potential for facility-independent mortality, or background mortality. Data from Lake Tamarisk suggest that mortality at the PV USSE facilities was low compared with the regional abundance and diversity of birds. However, the sampling methods did not measure nocturnal exposure; thus, if aquatic habitat birds were moving nocturnally, the study would have underestimated site-specific exposure. Understanding the potential risk at future PV USSE facilities is currently best informed by the regional context of the facility, as suggested by Kosciuch et al. (2020). However, it is unknown how other landscape contexts outside of this study region and the availability of natural water bodies will influence aquatic habitat bird behavior at PV USSE facilities.

CHAPTER 5: Knowledge Transfer Activities

Six members made up the technical advisory committee (TAC), a group representing academia, industry, non-governmental organizations, and state and federal governments. The TAC provided input on the broad goals and activities of the project, methodology, results, and reporting during two formal TAC meetings and numerous ad hoc meetings. Formal TAC meetings were held as webinars on December 13, 2018, and July 12, 2019. The results of the formal meetings were recorded in a question-and-answer format and submitted to the CEC as summary reports. Ad hoc meetings typically included only a subset of the TAC and focused on specific areas such as publishing strategy or future research. Finally, TAC members provided valuable feedback on written products.

To date the project has generated one scientific publication, four reports to stakeholders, and, as of this writing, 14 professional presentations. Several more scientific publications and numerous presentations to largely professional audiences are anticipated.

Publications

- Kosciuch K., D. Riser-Espinoza, C. Moqtaderi, and W. Erickson. 2021. "Aquatic Habitat Bird Occurrences at Photovoltaic Solar Energy Development in Southern California, USA." *Diversity*, 13:524. https://doi.org/10.3390/d13110524
    - Robertson, B. A., D. C. Fraleigh, J. B. Heitmann, K. L. Kosciuch, R. H. Diehl, and O. Rothberg. "Birds use color polarization vision to find food and water." *PLOS ONE,* in review.

Presentations

- 2017 Technical Symposium on Avian-Solar Interactions (1x)
- 2018 American Ornithological Society Symposium on Avian-Solar Interactions (1x)
- 2020 Wildlife Society Panel Presentation on Avian-Solar Interactions (1x)
- 2020 Annual Meeting of the Animal Behavior Society (1x)
- 2021 Annual Meeting of the Wildlife Society (1x)
- 2021 International Congress for Conservation Biology (1x)
- 2021 AWWI Solar Power & Wildlife/Natural Resources Symposium (3x)
- 2021 Wildlife Society webinar on renewable energy (1x)
- 2022 USGS Friday Findings presentation series (1x)
- 2022 Wildlife Society Renewable Energy Working Group webinar (1x)
- 2022 Wildlife Society symposium on conservation issues with renewable energy (2x)

Reports to Stakeholders

Over the course of the project, the Principal Investigators presented results four times to the Avian Solar Work Group (May 2019, August 2019, October 2020, November 2021), which includes a number of stakeholders from industry and environmental non-governmental organizations.

CHAPTER 6: Conclusions/Recommendations

Review of Major Findings

The purpose of this project was to determine whether birds perceive PV solar facilities as water bodies (the lake effect) by studying the mechanisms, behavioral responses, and consequences of that perception. The results indicate that birds are more attracted to highly polarized sources of visible light, and that solar panels polarize light in a manner similar to water. A large percentage of flying animals (perhaps 10 percent or more) approaching solar facilities from the north during daylight hours in the fall migration season were shown to descend toward facilities. Finally, and perhaps most compelling, is the observed mortality of water-obligate species, which perish on dry land, found at PV solar facilities in desert environments without water. Taken together, these results are consistent with an operational lake effect hypothesis of avian mortality at arid solar facilities.

Knowledge Gaps

While some of the results of this study align with key predictions and assumptions of the lake effect hypothesis, they do not conclusively confirm it. It is not clear whether birds use polarized light above a threshold (e.g., 35 percent) to locate water, nor is it known whether reductions in the degree of polarization across the range of values for known water bodies (35 percent to 80 percent) reduce that attraction. More broadly, it is also unknown whether other non-polarization-related light properties, of light associated with PV facilities, contribute to the lake effect. For example, it is possible that reducing the polarization of a solar panel from 80 to 65 percent will have no effect in reducing avian attraction for one or all species of birds; whereas, reducing polarized light from 65 to 40 percent, also a reduction of 15 percent, could lead to a drastic reduction in attraction. Effects may not be linear or consistent across this range of values. Even so, the use of integrated or laminate versions of ARCs are known to reduce the percentage of light polarized by panels by 10 to 15 percent while simultaneously leading to increased panel efficiency; these reduce attraction by some species of polarotactic aquatic insects (Száz et al., 2016; Fritz et al., 2020). Aquatic insects also use polarized light to locate water, and these reductions do lead to reduced attraction in some of them.

The idea of lake effect in which birds perceive a PV USSE facility as a water body (or the facility creates a lake effect) and are attracted is likely a nuanced process at a given PV solar facility mediated by species type, intrinsic condition of the animal, behavioral motivation, extrinsic conditions, and the simple geometry of the animal's location in the airspace with respect to the sun and to the facility. The results from this study suggest that some species of aquatic habitat birds could be attracted to PV USSE facilities, but that the breadth of that attraction across species is not yet known. There were additional challenges with discriminating among animal types in radar data that limited the taxonomic breadth of observed behavioral responses, so it is also unknown whether the species responding were also those being killed at the PV facilities. Motivational states and other factors intrinsic to the birds that might drive water-seeking behavior are usually unknown and only operational during part of the day (and may be more or less frequently operational during certain parts of the avian annual cycle). These factors include thirst, hunger, the need for rest, and predator avoidance. Extrinsic factors including the weather, landscape context, and characteristics of solar facilities likely have a strong influence on water-seeking by birds. These vary considerably across the country and through time and their influence on bird behavior with respect to solar facilities is largely unknown. For example, a lake effect may also be operational at the heliostat fields of concentrating solar power tower facilities, though these facilities were not examined in this study. That said, light reflected off mirrors tends to retain the polarization properties of the incident light (i.e., mirrors tend not to polarize light). The tendency for surfaces to polarize incident light depends on the surface material. Finally, results of this study begin to explore the role played by geometry for polarization-cue availability. There are strong indications that the position of a bird relative to the sun and solar facility is critical to receiving polarized light cues. However, detailed knowledge on flight directions with respect to facilities requires further investigation, as do the presence and distribution of polarized "sweet spots" in the airspace near facilities.

Recommendations and Future Research Needs

Thin-film and c-Si solar panels have different light-polarizing properties, but it is unknown whether these properties attract birds. Further experimentation is required on birds' responses to different panel types and different surface treatments (e.g., ARCs) that reduce the degree of polarization so that solar facilities will not be perceived as water bodies. Such attempts at interference with the neuro-perceptual channel has an analog in preventing bats from approaching wind turbines. Bats are thought to be attracted to wind turbines, perhaps perceiving them as roost trees encountered during migration (Cryan et al., 2014). Strobing turbines with ultra-violet light are being studied as a method of interfering with this perception (Cryan, pers. comm.). Mitigation techniques that alter polarization by PV panels similarly need to be investigated to determine their effectiveness, ideally while not significantly reducing electricity generation.

Data from radar and fatality searches show a notable disconnect between the relatively large proportion of animals descending toward solar facilities and the relatively few birds that actually succumb. Signal-processing techniques that aid in discriminating animal types on radar that were unavailable during the study are now available. Follow-up studies could examine the geometry of bird attraction more precisely. Future research should also examine bird movements and behaviors near solar panels and other man-made sources of polarized light to more directly link movements to collisions (e.g., the Electric Power Research Institute has initiated a project to explore close proximity interactions between birds and solar panels).

The lake effect hypothesis is unexplored in contexts outside the desert southwest and should be examined in a wider geographic and temporal context. This would allow exploration of avian responses among more species in a broader spectrum of landscapes across different stages in the avian annual cycle, all of which may inform future solar energy siting decisions and mitigation strategies. For example, it is quite possible that landscape context matters, and that PV facilities in more mesic landscapes elicit less water-seeking behavior linked to solar facilities so would in turn experience lower avian mortality. These observations could populate facility siting models that integrate mortality data with information on landscape context and solar facility characteristics.

CHAPTER 7: Benefits to Ratepayers

Greenhouse gas emission reductions are subject to a variety of factors both inside and outside of the electricity sector; it is clear, however, that utility-scale solar is one of the most cost-effective and commercially viable pathways to achieving those reductions in California. Continued deployment of utility-scale solar will assist with achievement of the state's mandated 100 percent clean energy goals. Some utility-scale solar projects on federal land are already required to develop bird- and bat-conservation strategies that identify risk and avoidance, minimization, and mitigation of impacts. The solar industry estimates that the costs associated with just the development of, and compliance with, these strategies can range from between one million and four million dollars for a 1,000-acre project. Results of this project are consistent with a lake effect avian attraction to polarized light reflection similar to that of open water. The use of ARCs to disrupt the reflection of polarized light may reduce the avian perception of PV panels as water bodies; thereby, reducing the likelihood of attraction and subsequent mortality. This project should also help clarify the impacts of utility-scale solar on avian species, which should in turn allow for more focused and cost-effective monitoring and mitigation requirements in the future. This would have the effect of reducing permitting and operational costs of utility-scale solar development, leading ultimately to lower costs for utility-scale solar, which would directly benefit utility ratepayers.

Intangible benefits of the project include a better understanding of how to develop solar projects in an environmentally responsible manner, balancing development of utility-scale solar with conservation efforts. Based on projected median surface warming, geographic range shifts of bird populations responding to climate change may result in between 5 to 7 percent of species becoming extinct, and more than 30 percent of species becoming at risk by the year 2100 (Sekercioglu et al., 2008). It is critical that California, a leader in renewable energy, climate policy, and conservation, more fully understand and address the relationship between birds and solar facilities to allow continued commercial deployment of utility-scale solar projects without creating additional pressure on climate-constrained avian species.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
~	About, or approximate
±	plus or minus
°	degree
<, >	less than, more than
≤, ≥	less than or equal to; more than or equal to
ARC	anti-reflective coating
BCR	bird conservation region
Blyth	Blythe Solar Energy Center
c-Si	polycrystalline silicon, crystalline silicon
CEC	California Energy Commission's
cm	centimeter
CVSR	California Solar Valley Ranch
DoLP	degree of linear polarization
EPIC	Electric Program Investment Charge
g	grams
ha	hectare
km	kilometer
LEH	lake effect hypothesis
LT	local time
μ	micro
m/s	meters per second
mm	millimeter
MW	megawatt
n	number
NCL	National Center for Atmospheric Research Command Language
NEXRAD	Next Generation Weather Radar
nm	nanometer
PV	photovoltaic
SD	standard deviation
SMD	Sonoran and Mojave Desert
TAC	technical advisory committee
μs	microsecond
USSE	utility-scale solar energy

References

Able, Kenneth P. 1982. "Skylight polarization patterns at dusk influence migratory orientation in birds." *Nature,* 299:550-551.

Adler, Kraig. 1976. "Extraocular photoreception in amphibians." 1985. *Extraretinal Photoreception*, (1976):275-298.

Adler, Kraig, and John B. Phillips. 1985. "Orientation in a desert lizard (*Uma notata*): time-compensated compass movement and polarotaxis." *Journal of Comparative Physiology A,* 156:547-552.

Auburn, Jill Shore, and Douglas H. Taylor. 1979. "Polarized light perception and orientation in larval bullfrogs Rana catesbeiana." *Animal Behaviour,* 27:658-668.

Bernáth, B., G. Szedenics, G. Molnár, Gy Kriska, and G. Horváth. 2001. "Visual ecological impact of a peculiar waste oil lake on the avifauna: dual-choice field experiments with water-seeking birds using huge shiny black and white plastic sheets." *Archives of Nature Conservancy and Landscape Research,* 40:1-28.

Black, Theodore V., and Bruce A. Robertson. 2020. "How to disguise evolutionary traps created by solar panels." *Journal of Insect Conservation,* 24:241-247.

Buckland, Stephen, David Anderson, Kenneth Burnham, and Jeffrey Laake. 1993. "Distance Sampling: Estimating Abundance of Biological Populations." Chapman & Hall: London, UK.

Buckland, Stephen, David Anderson, Kenneth Burnham, Jeffrey Laake, David Borchers, and Len Thomas. 2001. *An Introduction to Distance Sampling: Estimating Abundance of Biological Populations*. Oxford University Press: Oxford, UK.

Buckland, Stephen, David Anderson, Kenneth Burnham, Jeffrey Laake, David Borchers, and Len Thomas. 2004. *Advanced Distance Sampling*. Oxford University Press: Oxford, UK.

Cabrera-Cruz, S., E. Cohen, J. Smolinsky, and J. Buler. 2020. "Artificial Light at Night is Related to Broad-Scale Stopover Distributions of Nocturnally Migrating Landbirds along the Yucatan Peninsula, Mexico." *Remote Sensing,* 12:395. Available at https://doi.org/10.3390/rs12030395.

CEC (California Energy Commission). 2021. *SB 100 Joint Agency Report: Creating a Path to a 100% Clean Energy Future.* California Energy Commission. Publication Number: CEC-200-2021-001.

Chao, Anne. 1987. "Estimating the Population Size For Capture-Recapture Data with Unequal Catchability." *Biometrics*, 43(1):783–791.

Chiu, Chun-Huo, Yi-Ting Wang, Bruno Walther, and Anne Chao. 2014. "An improved nonparametric lower bound of species richness via a modified good-turing frequency formula." *Biometrics*, 70(3):671–682.

Climate & Weather Averages in Mojave Desert, California, USA". 2024. Available at: https://www.timeanddate.com/weather/@5373972/climate

Conkling, Tara, Scott Loss, Jay Diffendorfer, Adam Duerr, and Todd Katzner. 2021. "Limitations, lack of standardization, and recommended best practices in studies of renewable energy effects on birds and bats." *Conservation Biology*, 35(1):64–76. doi:10.1111/cobi.13457.

Coulson, Kinsell L. 1988. *Polarization and Intensity of Light in the Atmosphere*. A Deepak Pub, University of Michigan. ISSN 2995-3529.

Cryan, P., M. Gorresen, C. Hein, M. Schirmacher, R. Diehl, M. Huso, D. Hayman, P. Fricker, F. Bonaccorso, D. Johnson, K. Heist, and D. Dalton. 2014. "Behavior of bats at wind turbines." *Proceedings of the National Academy of Sciences*, 111:15126–15131.

Danthanarayana, W., and S. Dashper. 1986. "Response of some night-flying insects to polarized light." *In Insect Flight*, 120-127. Springer, Berlin, Heidelberg.

Dacke, Marie, Dan-Eric Nilsson, Clarke H. Scholtz, Marcus Byrne, and Eric J. Warrant. 2003. "Insect orientation to polarized moonlight." *Nature*, 424:33-33.

Diehl, R. H., E. W. Valdez, T. M. Preston, M. J. Wellik, and P. M. Cryan. 2016. "Evaluating the Effectiveness of Wildlife Detection and Observation Technologies at a Solar Power Tower Facility." *PLOS ONE,* 11:e0158115. doi:0158110.0151371/journal.pone.0158115.

Diehl, R. 2021. "Response by flying animals to a concentrated solar tower and its heliostats field." Unpublished report submitted to the California Energy Commission.

Erickson, W., G. Johnson, D. Strickland, D. Young, Jr., K. Sernka, and R. Good. 2001. "Avian Collisions with Wind Turbines: A Summary of Existing Studies and Comparisons to Other Sources of Avian Collision Mortality in the United States." National Wind Coordinating Committee. Available at https://www.osti.gov/servlets/purl/822418.

Erickson, W., M. Wolfe, K. Bay, D. Johnson, and J. Gehring. 2014. "A Comprehensive Analysis of Small-Passerine Fatalities from Collision with Turbines at Wind Energy Facilities." *PLOS ONE,* 9:e107491. Available at https://doi.org/10.1371/journal.pone.0107491

Fraleigh, Devin C., Jackson Barratt Heitmann, and Bruce A. Robertson. 2021. "Ultraviolet polarized light pollution and evolutionary traps for aquatic insects." *Animal Behaviour,* 180:239-247.

Freake, M. J. 1999. "Evidence for orientation using the e-vector direction of polarised light in the sleepy lizard *Tiliqua rugosa*." *Journal of Experimental Biology,* 202:1159-1166.

Fritz, Benjamin, Gábor Horváth, Ruben Hünig, Ádám Pereszlényi, Ádám Egri, Markus Guttmann, Marc Schneider, Uli Lemmer, György Kriska, and Guillaume Gomard. 2020. "Bioreplicated coatings for photovoltaic solar panels nearly eliminate light pollution that harms polarotactic insects." *PLOS ONE,* 15:e0243296.

Gauthreaux, S., and C. Belser. 2005. "Effects of artificial night lighting on migrating birds." In: C. Rich and T. Longcore (Eds). *Ecological Consequences of Artificial Night Lighting*. Washington, DC: Island Press.

Gauthreaux, S., and R. Diehl. 2020. "Discrimination of Biological Scatterers in Polarimetric Weather Radar Data: Opportunities and Challenges." *Remote Sensing,* 12:545. Available at https://doi.org/10.3390/rs12030545.

Gehring, J., P. Kerlinger, and A. Manville. 2009. "Communication towers, lights, and birds: successful methods of reducing the frequency of avian collisions." *Ecological Applications*, 19:505-514.

Gehring, J. L., P. Kerlinger, and A. Manville. 2011. "The role of tower height and guy wires on avian collisions with communication towers." *Journal of Wildlife Management,* 75:848-855.

Griffith, G.E., J.M. Omernik, D.W. Smith, T.D. Cook, E. Tallyn, K. Moseley, and C.B. Johnson. 2016. Ecoregions of California (2-sided color poster with map, descriptive text, and photographs). U.S. Geological Survey Open-File Report 2016-1021, map scale 1:1,100,000. Available at http://dx.doi.org/10.3133/ofr20161021.

Hart, Nathan S., and Misha Vorobyev. 2005. "Modelling oil droplet absorption spectra and spectral sensitivities of bird cone photoreceptors." *Journal of Comparative Physiology A,* 191:381-392.

Helbig, A. J., and W. Wiltschko. 1989. "The skylight polarization patterns at dusk affect the orientation behavior of blackcaps, *Sylvia atricapilla*." *The Science of Nature,* 76:227-229.

Hobbs, Richard, Eric Higgs, and James Harris. 2009. "Novel ecosystems: Implications for conservation and restoration." *Trends in Ecology and Evolution,* 24(11): 599–605. Available at https://doi.org/10.1016/j.tree.2009.05.012.

Horton, K., W. Shriver, and J. Buler. 2015. "A comparison of traffic estimates of nocturnal flying animals using radar, thermal imaging, and acoustic recording." *Ecological Applications* 25:390-401.

Horton, K., C. Nilsson, B. Van Doren, F. La Sorte, A. Dokter, and A. Farnsworth. 2019. "Bright lights in the big cities: migratory birds' exposure to artificial light." *Frontiers in Ecology and the Environment,* 17:209– 214. Available at doi:10.1002/fee.2029.

Horváth, Gábor, and Dezsö Varjú. 1997. "Polarization pattern of freshwater habitats recorded by video polarimetry in red, green and blue spectral ranges and its relevance for water detection by aquatic insects." *The Journal of Experimental Biology,* 200:1155-1163.

Horváth, Gábor, and Dezsö Varju. 2004. *Polarized Light in Animal Vision: Polarization Patterns in Nature.* Springer Science & Business Media.

Horváth, G., G. Kriska, P. Malik, and B. Robertson. 2009. "Polarized light pollution: a new kind of ecological photopollution." *Frontiers in Ecology and the Environment*, 7:317-325.

Horváth, Gábor, Miklós Blahó, Ádám Egri, György Kriska, István Seres, and Bruce Robertson. 2010. "Reducing the maladaptive attractiveness of solar panels to polarotactic insects." *Conservation Biology,* 24:1644-1653.

Horváth Gabor, editor. 2014. *Polarized Light and Polarization Vision in Animal Sciences*. Berlin, Heidelberg Springer Berlin Heidelberg.

Horváth, Gábor, György Kriska, and Bruce Robertson. 2014. "Anthropogenic polarization and polarized light pollution inducing polarized ecological traps." In *Polarized Light and Polarization Vision in Animal Sciences*, 443-513. Springer, Berlin, Heidelberg.

Hui, Francis. 2016. "Boral: Bayesian ordination and regression analysis of multivariate abundance data in R." *Methods in Ecology and Evolution,* 7(6): 744–750.

Huso, Manuela, Thomas Dietsch, and Chris Nicolai. 2016. "Mortality Monitoring Design for Utility-Scale Solar Power Facilities." doi:10.3133/ofr20161087. U.S. Geological Survey, Reston, Virginia, USA. Available at https://pubs.er.usgs.gov/publication/ofr20161087.

Josephson, John, and Susan Josephson. 1994. *Abductive Inference: Computation, Philosophy, Technology.* Cambridge University Press, Cambridge, UK.

Kagan, Rebecca, Tabitha Viner, Pepper Trail, and Edgar Espinoza. 2014. "Avian Mortality at Solar Energy Facilities in Southern California: A Preliminary Analysis." National Fish and Wildlife Forensics Laboratory, U.S. Fish and Wildlife Service, Ashland, Oregon, USA.

Konnen, G. P., and G. P. Können. 1985. *Polarized Light in Nature*. Cambridge University Press Archive.

Kosciuch, Karl, Timothy Parker, and Brett Sandercock. 2006. "Nest desertion by a cowbird host: An antiparasite behavior or a response to egg loss?" *Behavioral Ecology,* 17(6): 917–924. doi:10.1093/beheco/arl025.

Kosciuch, Karl, Daniel Riser-Espinoza, Michael Gerringer, and Wallace Erickson. 2020. "A summary of bird mortality at photovoltaic utility scale solar facilities in the Southwestern US." *PLOS ONE,* 15:e0232034.

Kosciuch, K., D. Riser-Espinoza, C. Moqtaderi, and W. Erickson. 2021. "Aquatic Habitat Bird Occurrences at Photovoltaic Solar Energy Development in Southern California, USA." *Diversity,* 13:524. Available at https://doi.org/10.3390/d13110524.

Kriska, G., Z. Csabai, P. Boda, P. Malik, and G. Horváth. 2006. "Why do red and dark-coloured cars lure aquatic insects? The attraction of water insects to car paintwork explained by reflection–polarization signals." *Proceedings of the Royal Society B: Biological Sciences,* 273:1667-1671.

Kriska, György, Péter Malik, Ildikó Szivák, and Gábor Horváth. 2008. "Glass buildings on river banks as 'polarized light traps' for mass-swarming polarotactic caddis flies." *Naturwissenschaften,* 95:461-467.

Kriska, Gy, A. Barta, B. Suhai, B. Bernath, and G. Horváth. 2008. "Do brown pelicans mistake asphalt roads for water in deserts." *Acta Zoologica Academiae Scientiarum Hungaricae*, 54:157-165.

LaPorte, Nicholas, Robert Storer, and Gary Nuechterlein. 2020. "Western Grebe (*Aechmophorus occidentalis*)." version 1.0. In: *Birds of the World*; Paul Rodewald, Ed. Cornell Lab of Ornithology, Ithaca, New York. doi:10.2173/bow.wesgre.01.

Larkin, R. 1991. "Flight speeds observed with radar, a correction: slow "birds" are insects." *Behavioral Ecology and Sociobiology*, 29:221-224.

Lin, T., K. Winner, G. Bernstein, A. Mittal, A. Dokter, K. Horton, C. Nilsson, B. Van Doren, A. Farnsworth, F. La Sorte, S. Maji, and D. Sheldon. 2019. "MistNet: Measuring historical bird migration in the US using archived weather radar data and convolutional neural networks." *Methods in Ecology and Evolution,* 10:1908–1922.

Loss, Scott, Tom Will, and Peter Marra. 2013. "Estimates of bird collision mortality at wind facilities in the contiguous United States." *Biological Conservation* ,168: 201–209. Available at https://doi.org/10.1016/j.biocon.2013.10.007.

Loss, S., T. Will T, and P. Marra. 2014a. "Refining Estimates of Bird Collision and Electrocution Mortality at Power Lines in the United States." *PLOS ONE*, 9:e101565. Available at https://doi.org/10.1371/journal.pone.0101565.

Loss, S., T. Will, S. Loss, and P. Marra. 2014b. "Bird–building collisions in the United States: Estimates of annual mortality and species vulnerability." *The Condor*, 116:8-23, Available at https://doi.org/10.1650/condor-13-090.1.

Malik, Péter, Ramón Hegedüs, György Kriska, and Gábor Horváth. 2008. "Imaging polarimetry of glass buildings: why do vertical glass surfaces attract polarotactic insects?" *Applied Optics,* 47:4361-4374.

Malik, Péter, Ramón Hegedüs, and Gábor Horváth. 2010. "Asphalt Surfaces As Ecological Traps for Water-Seeking Polarotactic Insects." Nova Science Publishers, Incorporated.

Mateos-Rodríguez, María, and Felix Liechti. 2012. "How do diurnal long-distance migrants select flight altitude in relation to wind?" *Behavioral Ecology,* 23:403-409.

Mcintyre, Judith W., and Jack Francis Barr. 1997. "Common Loon(Gavia immer)." *The Birds of North America,* 313:32. Montevecchi WA and Stenhouse IJ. Dovekie.

McLaren, J., J. Buler, T. Schreckengost, J. Smolinsky, M. Boone, E. van Loon, D. Dawson, and E. Walters. 2018. "Artificial light at night confounds broad-scale habitat use by migrating birds." *Ecology Letters,* 21:356–64.

Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, and coauthors. 2006. "North American Regional Reanalysis." *Bulletin of the American Meteorological Society*, 87:343–360. Available at doi:10.1175/BAMS-87-3-343.

Melnikov, V., M. Istok, and J. Westbrook. 2015. "Asymmetric radar echo patterns from insects." *Journal of Atmospheric and Oceanic Technology*, 32:559-674.

Moore, Frank R. 1986. "Sunrise, skylight polarization, and the early morning orientation of night-migrating warblers." *The Condor,* 88:493-498.

Moore, Frank R., and John B. Phillips. 1988. "Sunset, skylight polarization and the migratory orientation of yellow-rumped warblers, *Dendroica coronata*." *Animal Behaviour* 36:1770-1778.

Muheim, R., F. Moore, and J. Phillips. 2006. "Calibration of magnetic and celestial compass cues in migratory birds - a review of cue-conflict experiments." *Journal of Experimental Biology,* 209:2–17. Available at doi: https://doi.org/10.1242/jeb.01960.

Muheim, R., S. Sjöberg, and A. Pinzon-Rodriguez. 2016. "Polarized light modulates light-dependent magnetic compass orientation in birds." *Proceedings of the National Academy of Sciences,* 113:1654-1659.

Multiagency Avian-Solar Collaborative Working Group. 2016. "Avian-Solar Science Coordination Plan." Available at https://www.energy.gov/sites/default/files/2019/03/f61/MASCWG%202016.pdf.

NCL (National Center for Atmospheric Research [NCAR] Command Language). 2019. "NCAR Command Language (Version 6.6.2)." National Science Foundation. Boulder, Colorado. Available at http://dx.doi.org/10.5065/D6WD3XH5.

Peltoniemi, Jouni I., Maria Gritsevich, and Eetu Puttonen. 2015. "Reflectance and polarization characteristics of various vegetation types." In: *Light Scattering Reviews,* 9:257-294. Springer, Berlin, Heidelberg.

Ramirez, Pedro. 2010. "Bird mortality in oil field wastewater disposal facilities." *Environmental Management,* 46:820-826.

Ralph, John, John Sauer, and Sam Droege. 1995. "Monitoring Bird Populations by Point Counts." Pacific Southwest Research Station. US Department of Agriculture, Forest Service, Albany, California, USA. Available at https://www.fs.usda.gov/research/treesearch/31461. Accessed July 27, 2021.

Robertson, Bruce, and Anna Chalfoun. 2016. "Evolutionary traps as keys to understanding behavioral maladaptation." *Current Opinion in Behavioral Sciences,* 12:12–17. Available at https://doi.org/10.1016/j.cobeha.2016.08.007.

Robertson, Bruce A., Isabel A. Keddy-Hector, Shailab D. Shrestha, Leah Y. Silverberg, Clara E. Woolner, Ian Hetterich, and Gábor Horváth. 2018. "Susceptibility to ecological traps is similar among closely related taxa but sensitive to spatial isolation." *Animal Behaviour,* 135:77-84.

Robertson, Bruce, and Daniel Blumstein. 2019. "How to disarm an evolutionary trap." *Conservation Science and Practice,* 1(11):e116. doi:10.1111/csp2.116.

Robertson, Bruce A., and Gábor Horváth. 2019. "Color polarization vision mediates the strength of an evolutionary trap." *Evolutionary Applications,* 12:175-186.

Schmaljohann, H., F. Liechti, E. Bachler, T. Steuri, and B. Bruderer. 2008. "Quantification of bird migration by radar - a detection probability problem." *Ibis,* 150:342-355.

Schwind, Rudolf. 1991. "Polarization vision in water insects and insects living on a moist substrate.: *Journal of Comparative Physiology A,* 169:531-540.

Schwind, R. 1995. "Spectral regions in which aquatic insects see reflected polarized light." *Journal of Comparative Physiology A,* 177:439-448.

Sekercioglu, C., S. Schneider, J. Fay, and S. Loarie. 2008, "Climate Change, Elevational Range Shifts, and Bird Extinctions." *Conservation Biology*, 22:140-150. Available at https://doi.org/10.1111/j.1523-1739.2007.00852.x.

Shashar, N., S. Sabbah, and N. Aharoni. 2005. "Migrating locusts can detect polarized reflections to avoid flying over the sea." *Biology Letters,* 1:472-475.

Shuford, W. David, Nils Warnock, Kathy Molina, and Kenneth Sturm. 2002. "The Salton Sea as critical habitat to migratory and resident waterbirds." *Hydrobiologia,* 473:255-274. Available at https://doi.org/10.1023/A:1016566709096.

Smallwood, K., and D. Bell. 2020. "Effects of Wind Turbine Curtailment on Bird and Bat Fatalities." *Journal of Wildlife Management*, 84:685- 696. Available at https://doi.org/10.1002/jwmg.21844.

Smith, Thomas B., Steven Beissinger, Wally Erickson, Vasilis Fthenakis, Trevon Fuller, Luke George, Kristen Ruegg, and Rodney Siegel. Undated. Avian Solar Working Group Research Questions Framework.

Smith, Jennifer A., and James F. Dwyer. 2016. "Avian interactions with renewable energy infrastructure: An update." *The Condor: Ornithological Applications,* 118:411-423.

Sullivan, B.L., C.L. Wood, M.J. Iliff, R.E. Bonney, D. Fink, and S. Kelling. 2009. "eBird: a citizen-based bird observation network in the biological sciences." *Biological Conservation,* 142:2282-2292.

Száz, Dénes, Dávid Mihályi, Alexandra Farkas, Ádám Egri, András Barta, György Kriska, Bruce Robertson, and Gábor Horváth. 2016. "Polarized light pollution of matte solar panels: anti-reflective photovoltaics reduce polarized light pollution but benefit only some aquatic insects." *Journal of Insect Conservation,* 20:663-675.

Taylor, P., J. Brzustowski, C. Matkovich, M. Peckford, and D. Wilson. 2010. "radR: an open-source platform for acquiring and analysing data on biological targets observed by surveillance radar." *BMC Ecol*,10:22. doi:10.1186/1472-6785-10-22. PMID: 20977735.

Upton, John. 2014. "Solar Farms Threaten Birds." *Scientific American*. Available at https://www.scientificamerican.com/article/solar-farms-threaten-birds/. Accessed July 27, 2021.

USFWS (United States Fish and Wildlife Service). 2012. "Land-Based Wind Energy Guidelines." U.S. Fish and Wildlife Service, Washington, D.C. Available at https://www.fws.gov/sites/

default/files/documents/land-based-wind-energy-guidelines.pdf. Accessed July 27, 2021.

Van Doren, B., K. Horton, A. Dokter, H. Klinck, S. Elbin, and A. Farnsworth. 2017. *Proceedings of the National Academy of Sciences,* 114:11175-1180. doi:10.1073/pnas.1708574114.

Vaughn, C. 1985. "Birds and insects as radar targets: a review." *Proceedings of the IEEE*, 73:205-227.

Visser, Elke, Vonica Perold, Samantha Ralston-Paton, Alvaro C. Cardenal, and Peter G. Ryan. 2019. "Assessing the impacts of a utility-scale photovoltaic solar energy facility on birds in the Northern Cape, South Africa." *Renewable Energy,* 133:1285-1294.

Von Frisch, Karl. 2013. *The Dance Language and Orientation of Bees*. Harvard University Press.

Walston Jr, Leroy J., Katherine E. Rollins, Kirk E. LaGory, Karen P. Smith, and Stephanie A. Meyers. 2016. "A preliminary assessment of avian mortality at utility-scale solar energy facilities in the United States." *Renewable Energy,* 92:405-414.

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix A: Detailed Methodology (re Chapter 2)

June 2024 | CEC-500-2024-055

APPENDIX A:
Detailed Methodology (re Chapter 2)

Imaging Polarimetry and Spectroscopy of Test Surfaces in the Behavioral Study

As a general rule, smooth, dark-colored man-made objects are stronger polarizers of reflected light (Horváth et al., 2009). Because color is typically intertwined with the ability of an object to polarize a particular wavelength of light via its absorption of transmitted light, and to make inferences about the ability of birds to see and behaviorally respond to polarized light versus color, test surfaces were designed that were able to manipulate color more independently of their degree of reflection-polarization. The degree to which test surfaces could polarize light was quantified (DoLP = percent of reflected photons polarized) along with spectral irradiance of test surfaces across the range of light that birds are known to detect (300 to 750nm, Hart et al., 2005).

Imagery was conducted on the campus of Bard College in Annandale-on-Hudson, New York. Two polarimetric imaging lenses attached to cameras were used to photograph solar panels under varying weather and sunlight conditions between January 13, 2020, and April 27th, 2020. Researchers focused on the visual properties of: 1) a flexible thin film CIGS SoloPower SP1 80-watt 12-volt solar panel, and 2) a Renogy polycrystalline silicon (c-Si) 270-watt, 24-volt solar panel. These two solar panel categories (thin film and c-Si) represent the most widely used solar panels at utility scale photovoltaic power installations in use in the U.S.

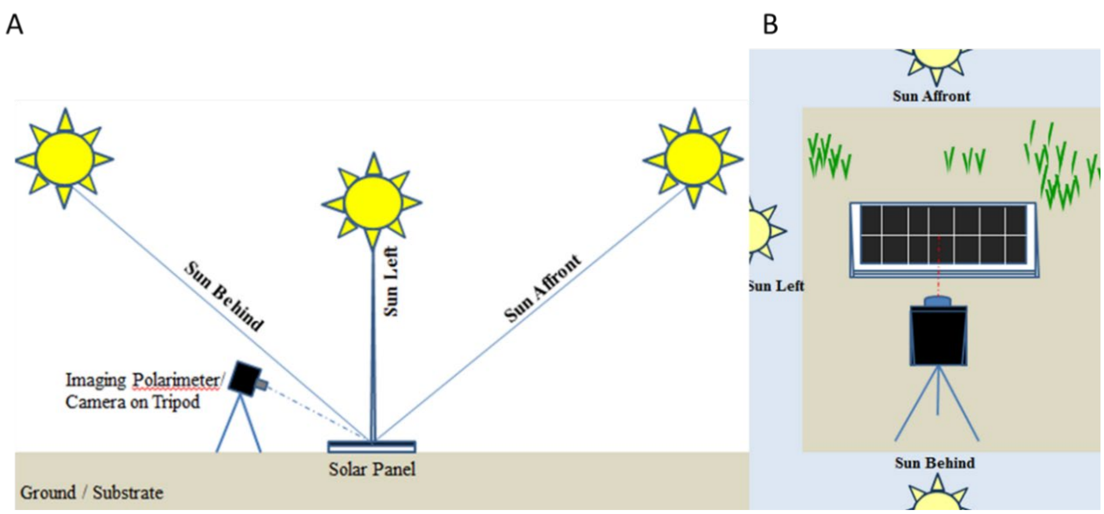
It isn't known if birds, like aquatic insects (Horváth and Varjú 2004), are more attracted to light sources that are more highly polarized horizontally (reviewed in Horváth et al 2014), but since birds still face the challenge of distinguishing water bodies from more weakly polarizing natural objects such as vegetation, soil and rock (Horváth and Varjú 1997), it is possible that they associate water with a high DoLP. The DoLP changes dramatically depending on the angle from the sun to a reflection-polarizer (i.e., solar panels, glass windows) to the polarimeter, this is known as the angle of incidence (Horváth et al., 2010). The maximum DoLP is achieved at the Brewster's Angle $^{\theta}B$ = arctan, when reflected light is perpendicular to refracted sunlight (Robertson and Horváth 2019). In addition to the angle of incidence, there are other factors known to affect the DoLP of natural and human-made objects, including: color (i.e., spectral absorbance), the brightness and directionality of lighting (direct or indirect), surface texture (smooth vs. matte), and its chemical composition that affects the angle of refraction of light that penetrates the substance (Horváth and Varjú 2004). Thus, to better understand the conditions under which solar panels have potentially different inherent polarization properties, two types of solar panels were imaged, at three times of day, at three different sun directions, and two types of weather conditions.

Imaging polarimetry in visible wavelengths was conducted using a Canon DSLR that had been converted into an imaging polarimeter following processes and technical specifications described previously (Horváth and Varjú 1997). Researchers also designed and created a second imaging polarimeter capable of capturing light only in the ultraviolet range.

Researchers used a Nikon DSLR with a number of modifications: 1) a near-pass optical filter was replaced with a UV-transmitting linearly polarizing filter that blocked the longer visible wavelengths while allowing ultraviolet light to pass through, and 2) 60 millimeter [mm] focal length UV-transmitting crystalline macro lens was attached (after Száz et al., 2016). Processing of all imagery was done using AlgoNet© software using optical data taken in the blue (450 nm), green (550 nm), and red (650 nm) wavelengths.

Solar panels were placed on flat cement ground, horizontally, >100 feet away from the nearest building to avoid additional sources of refracted sunlight off of glass windows. Each of these solar panel types was imaged under four different sunlight conditions: 1) sun affront, 2) sun left, 3) sun behind, and 4) overcast. Sunny conditions constituted 0 to 5 percent cloud cover, and directionality (affront, left, behind) refers to placement of the camera in relation to solar panel, and the sun (Figure A-1). Overcast conditions constituted 100 percent cloud cover. Polarimeters were placed on tripods at half height (0.6 meter) or full height (1.2 meters), and protractors were attached to the side of each camera flush with the backside of the camera at 180o. A black 15 cm (0.3 millimeter width) string was tied taught to a small washer on the backside of the protractor, and then the string was threaded through the middle hole in the protractor and tied to a weight. The polarimeter was attached to a plate on a tripod, and researchers tilted the polarimeter forward until reaching the desired protractor angle. Polarimetric measurements were performed at multiple angles from 31° to 80° to capture all angles at which the degree of polarization, or d value was ≥35 percent. The 35 percent threshold was chosen because when 35 percent ≤ DoLP ≤ 80 percent, the surface is polarizing light within the realm of known values for natural water bodies (reviewed in Horváth, 2014).

Figure A-1: Methodology for Imaging Solar Panels



Diagrammatic representation of the methodological approach to imaging solar panels. Part A shows the approach from the sun-right point of view illustrating the relationship between the direction of photography, the sun and the ground. Part B shows the same from the point of view of the photographer. The angle from the vertical (coinciding with the line representing 'sun left' in part A). Represents the angle of reflection, α. The angle at which the degree of polarization via reflection is maximized is the Brewster's Angle.

Source: Bruce Robertson, Bard College

For each composite polarization image, a mask file was created that focused DoLP measurements within a circular, 32-pixel diameter areas centered on the center of each image at which the angle of reflection-polarization was calibrated. For each image five mask files were created to capture polarization measurements on that same horizontal plane and equally spaced across the horizontal plane of the image. Researchers calculated means (=/- SE) and plotted the degree of polarization versus and angle of reflection.

Imaging polarimetry and spectroscopy of test surfaces in the behavioral study

The DoLP of test surfaces were taken under sunny skies with the optical axis of the polarimeter aimed toward the sun and downward at the Brewster angle at which surfaces maximally polarize reflected light relevant to the reflective surface being used in each experiment (acrylic feeder bases: $\theta_{Brewster}$ = 56°; polyvinylacrylic ground panels: $\theta_{Brewster}$ = 59°. The Brewster angle for these surfaces was 5° higher for ultraviolet light for each object type. An OceanOptics USB2000+ spectrometer was used to measure the relative irradiance (detections /wavelength) in 1/1000th of a second among trays detected two inches above the edge each test surface at its edge and directed parallel to its surface.

See Table A-1 for a list of animal species in the study.

Table A-1: Species Interacting with Experiment

Common Name	Latin name	Ground panel	Bath	Feeder
American Goldfinch	*Spinis tristis*		X	
Black-capped Chickadee	*Peocile atricpillus*	X	X	X
Blue Jay	*Cyanocitta cristata*		X	X
Carolina Wren	*Thyothorus ludovicianus*			X
Common Grackle	*Quaiscalus quiscula*	X	X	X
Dark-eyed Junco	*Junco hyemalis*	X	X	
Downy Woodpecker	*Picoides pubescens*			X
Eastern Bluebird	*Sialia sialis*		X	
European Starling	*Sturnus vulgarus*	X		
Field Sparrow	*Spizella pusilla*	X		
House Finch	*Haemorhous mexicanus*		X	X
House Sparrow	*Passer domesticus*		X	x
Mourning Dove	*Zenaida macoura*	X	X	
Northern Cardinal	*Cardinalis cardinalis*	X	X	X
Purple Finch	*Haemorhous purpurus*			X
Red-bellied Woodpecker	*Melanerpes carolinus*			X
Red-winged Blackbird	*Agelaius phoeniceus*		X	

Common Name	Latin name	Ground panel	Bath	Feeder
Tufted Titmouse	*Baeolophus bicolor*	X	X	X
White-breasted Nuthatch	*Sitta carolinensis*		X	X
White-throated Sparrow	*Zonotrichia albicollis*	X	X	X

Species detected interacting with the bird-feeder, ground panel and bird bath experiments.

Source: Bruce Robertson, Bard College

CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix B: Other Methodology and Results (re Chapter 3)

June 2024 | CEC-500-2024-055

APPENDIX B: Other Methodology and Results (re Chapter 3)

Reorientation Methodology

The following difference equation accounts for background levels of orientation using the control location.

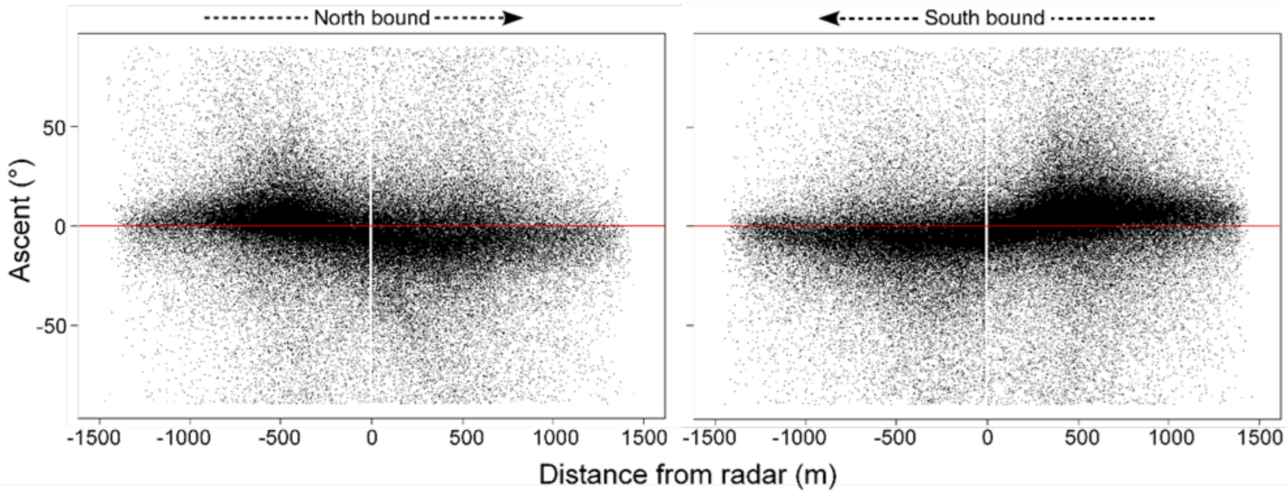
Eq. 1 $$\theta_x = (x_{2t} - x_{1t}) - (x_{2c} - x_{1c}),$$

where θ_x is the difference in direction of flight between treatment and control areas accounting for aspect bias, x refers to sampling areas a, b, or c (see Figure 6), numerical subscripts identify opposing sampling area pairs that represent adjustment for aspect bias, letter subscripts identify treatment (t) and control (c) areas. The predicted results θ_a, θ_b, and θ_c are positive if above background movement toward the solar facility occurs at the treatment location. Likewise, the results are negative if above background movement is away from the solar facility. It is possible for θ_x to be positive even if $x_{2t} - x_{1t} < 0$ as long as response in the treatment area is less negative than that of the control area. It is questionable whether such a scenario constitutes evidence for attraction, therefore, as a precondition to Equation 1 evaluating positive, $x_{2t} - x_{1t}$ must also be positive. For a positive result suggesting attraction, $x_{2t} - x_{1t}$ and θ_x must exceed 2° (or for a negative result suggesting deterrence, the threshold is -2°).

Descent Methodology

As with data collection in the horizontal domain, radars rotating vertically are subject to bias associated with animals' aspect ratios. The bodies of animals flying approximately along the north-south axis of rotation will generally align with the polarization of the radar. Ascending animals flying toward the radar (approaching) will be more detectable than ascending animals flying away (departing) and vice versa. Conversely, departing descending animals flying away will be more detectable than approaching descending animals. This bias poses a challenge when attempting to quantify ascent or descent along the plane of rotation. Figure B-1 shows animals in generally level flight at the control area associated with Desert Sunlight with background levels of variation in ascent and descent. Aspect bias favors detection of ascent and then descent along a north-to-south gradient when animals approach the radar from the north (Figure B-1, right).

Figure B-1: Ascent and Descent Bias



Angles of ascent for animals in flight across the north-south (positive-negative) ground distance from radar. Descent is shown as negative ascent. Data were gathered during October 2018 at the Desert Sunlight control location and are divided into patterns of ascent associated with north bound (left) and south bound (right) animals.

Source: U.S. Geological Survey

The opposite is evident when animals are approaching from the south. Since solar facilities dominate the southern portion of the radar coverage in the treatment area, the ratio of descent south of the radar over descent north of the radar produces a bias favoring detection of descent over solar facilities among southbound animals. Therefore, the ratio of descent south of the radar over descent north of the radar in the control area is used to correct for this bias in the treatment area. The proportion of animals descending owing to the solar facility is represented by the control-adjusted number of animals descending over the southern reach of the radar coverage area, divided by the total number of animals over that reach (Equation 2).

Eq. 2
$$P = \frac{T_i - \frac{T'_i C_i}{C'_i}}{\sum T},$$

where P is the proportion of animals over solar facilities engaged in descent, T is the number of animals in the treatment area south of the radar (i.e., over a solar facility) engaged in descent, T' is the number of animals in the treatment area north of the radar engaged in descent, C is the number of animals in the control area south of the radar engaged in descent, C' is the number of animals in the control area north of the radar engaged in descent, and ΣT is the total number of animals in the treatment area south of the radar (i.e., over a solar facility). Because the correction is based on ratios, differences in animal abundance over treatment versus control areas are accommodated.

The subscript (i) in the above model indicates the variables for which totals are of the number of animals exhibiting angles of descent at or below some threshold. If birds over solar facilities are responding with a wide range of descent angles, shallower angles may be less well represented in treatments relative to controls owing to aspect bias as described above and those animals may not be responding similarly at control locations. This would cause the ratio term in Equation 2 to exceed one and artificially reduce the descent response measure. To identify a descent angle below which descending animals will be enumerated, the ratio term from Equation 2 for each study site was calculated iteratively for a narrow range of increasing descent angles beginning with -90° (descent is negative ascent). The angle at which the ratio transitioned from a somewhat noisy to a smooth increase, -22°, approximately identified the threshold above which descents were more likely caused by background ventral aspect bias. Descent angles at or below this threshold were used for analyses of data from both study sites.

The proportions-based model in Equation 2 was applied to data gathered in the vertical domain to examine descent associated with solar facilities in the following analyses: 1) a broad survey for descent behavior for all combinations of site (Desert Sunlight, Seville), direction of flight (south bound, north bound), and time-of-day (diurnal, nocturnal); 2) a more focused examination of descent with respect to altitude and animal flight speed for diurnal, south-bound animals; and 3) an examination of change in the proportion of descending animals throughout the diel.

Diel variation in the proportion of animals descending were modeled separately for south-bound and northbound animals as a Gaussian function with offset,

Eq. 3 $$P = ae^{-\frac{(t-\mu)^2}{2\sigma^2}} + a',$$

where P is the proportion of animals over solar facilities engaged in descent, a is the value of the Gaussian peak greater than or less than a', a' is the offset in P, t is time within the diel, μ is mean diel, and σ is standard deviation about μ. A non-linear least squares approach was used to fit hourly proportion descent measured to the Gaussian in R (nonlinear least squares function as part of R stats package version 3.6.2).

Unless otherwise indicated, analyses of descent by flying animals were conducted using track durations ≥17.5 seconds for reasons outlined in the Discussion. All statistical analyses were conducted using R stats package version 4.1.1.

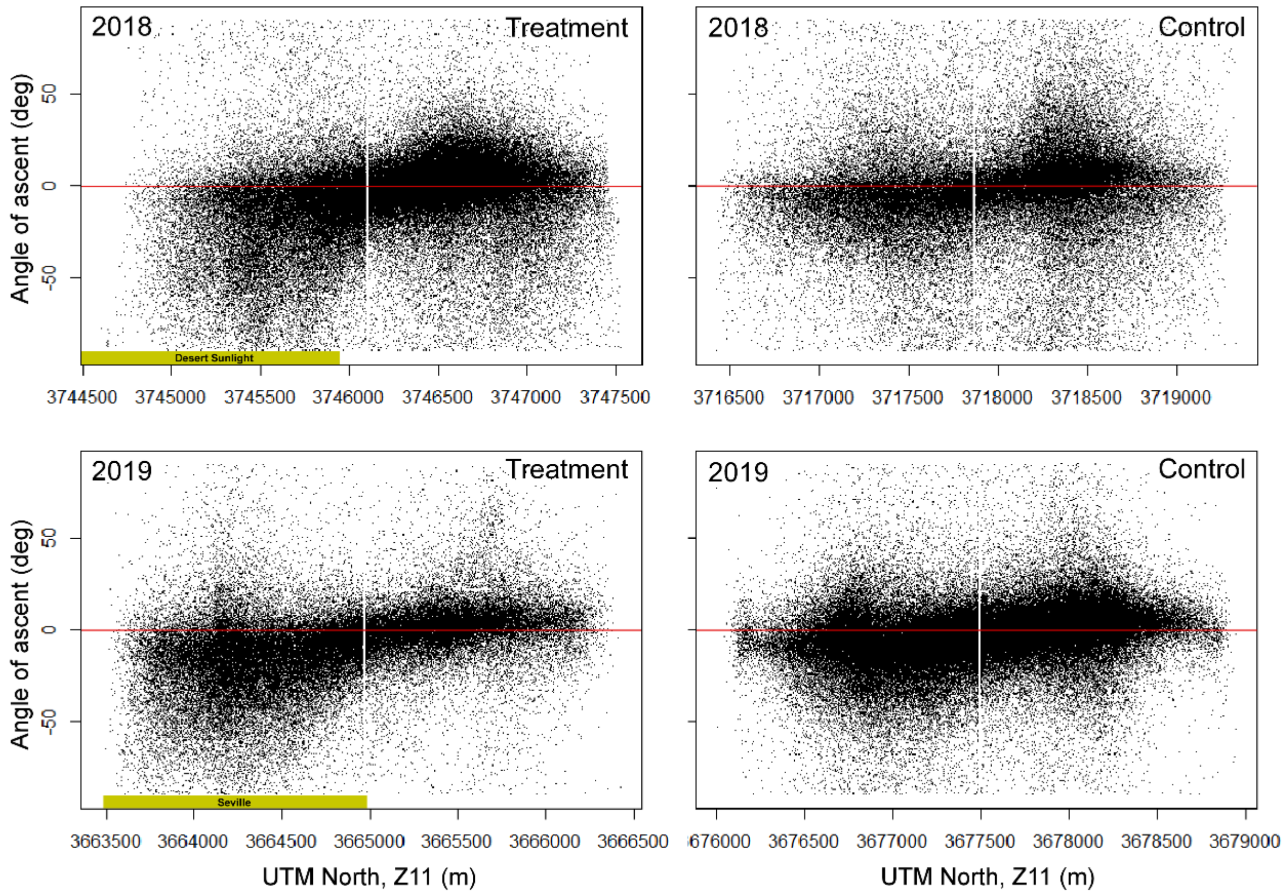
Pitch Angle Bias

All analyses attempt to leverage control spaces within and outside the treatment area to adjust for aspect bias, although this may have resulted in an excessively conservative approach in analyses of descent (see Appendix B, "Descent Methodology"). A minimum angle of descent threshold of 22° may be high, especially for birds, in part owing to further bias associated with positive pitch angle in true flight. In Figure B-1, the distribution of ascending and descending animals is not centered near zero directly over the radar, rather the point where the center mass of ascending and descending animals nears zero is offset ~200 meters north of the radar for southbound animals and ~350 meters south of the radar for northbound animals (this tendency is also visible for the southbound animals in B, "Treatment and Control Descents"). This suggests that animals in level flight fly with positive pitch relative to the horizon (Melnikov et al., 2015) and will, therefore, present their largest surface area to the radar when approaching the radar, not when directly overhead. Descent may not require much if any negative pitch angle, and as departing animals when south bound, these animals may be less detectable over solar facilities.

Treatment and Control Descents

See Figure B-2.

Figure B-2: Animal Descents at Treatment and Control Areas



Angles of ascent at treatment and control areas for both facilities for south bound, ≥17.5 seconds duration tracks for varying distances from the radar over the ground (here in UTM). Descent is shown as negative ascent. Data were gathered during October 2018 and 2019 at the Desert Sunlight and Seville treatment and control locations.

Source: U.S. Geological Survey

Gaussian Model Results

See Table B-1.

Table B-1: Diel Descent Model Results

Track duration ≥7.5 seconds

Desert Sunlight, southbound animals

Parameters:

	Estimate	Std. Error	t value	Pr(>|t|)	
mean hr	15.02112	0.65132	23.062	7.00e-16	***
SD	2.43912	0.76654	3.182	0.004685	**
peak	0.16641	0.04093	4.065	0.000604	***
offset	0.14480	0.01962	7.381	3.96e-07	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.06533 on 20 degrees of freedom

Seville, southbound animals

Parameters:

	Estimate	Std. Error	t value	Pr(>|t|)	
mean hr	11.33541	0.47211	24.010	3.21e-16	***
SD	2.72658	0.57975	4.703	0.000136	***
peak	0.16162	0.02621	6.166	5.04e-06	***
offset	0.01873	0.01411	1.327	0.199319	

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.0435 on 20 degrees of freedom

Track duration ≥17.5 seconds

Desert Sunlight, southbound animals

Parameters:

	Estimate	Std. Error	t value	Pr(>|t|)	
mean hr	14.501340	0.357659	40.545	< 2e-16	***
SD	2.106310	0.406446	5.182	4.53e-05	***
peak	0.230010	0.035431	6.492	2.50e-06	***
offset	-0.007308	0.014913	-0.490	0.629	

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.05336 on 20 degrees of freedom

Seville, southbound animals

Parameters:

	Estimate	Std. Error	t value	Pr(>|t|)	
Mean hr	11.85456	0.36681	32.318	< 2e-16	***
SD	3.45423	0.52195	6.618	1.91e-06	***
peak	0.26213	0.02811	9.324	1.01e-08	***
offset	0.01937	0.02020	0.959	0.349	

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

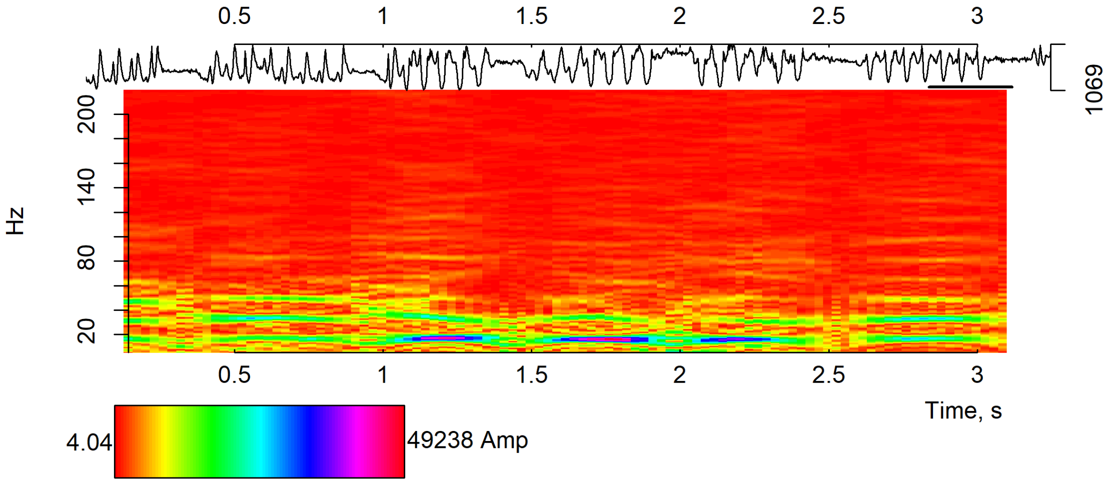
Residual standard error: 0.0487 on 20 degrees of freedom

Source: U.S. Geological Survey

Example Wingbeat Patterns

See Figure B-3.

Figure B-3: Bird Wingbeat Pattern

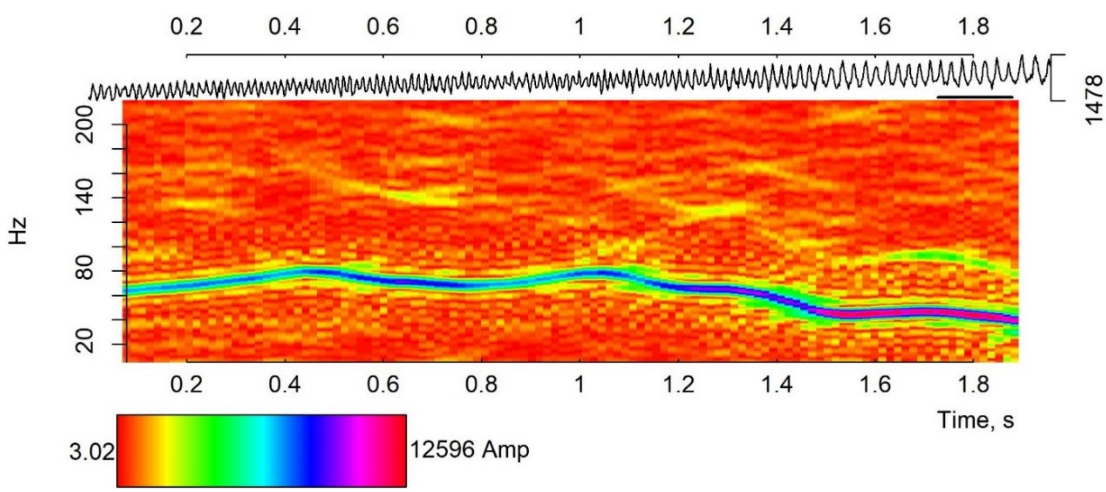


Birds beat their wings at low frequencies relative to insects, in this case ~18 Hz, and in some species the pattern alternates between wing beating and pausing as shown in the oscillogram above.

Source: U.S. Geological Survey

See Figure B-4.

Figure B-4: Insect Wingbeat Pattern



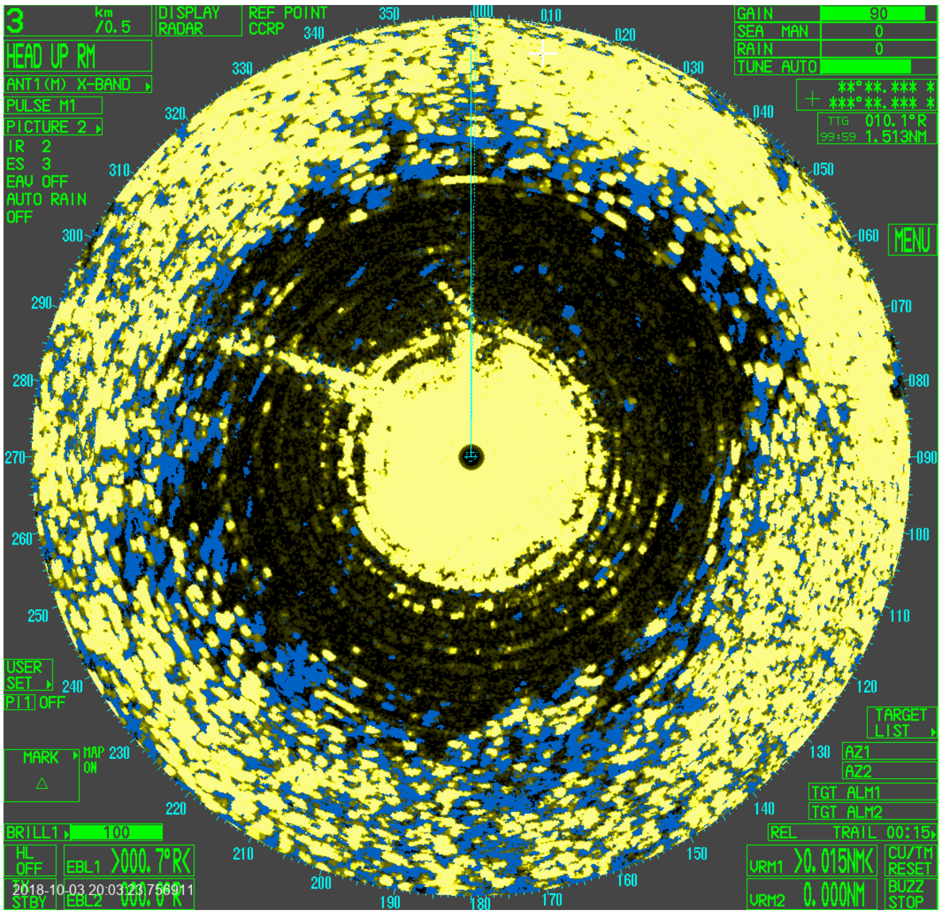
Insects beat their wing at high frequencies, often continuously, and often with substantial variation in frequency.

Source: U.S. Geological Survey

Dense Animal Movement

See Figure B-5.

Figure B-5: Extremely Dense Animal Movement on Radar



This north bound, likely insect-dominated movement was captured on radar near Desert Sunlight (i.e., the treatment location). The radar is located at the center of the image and is surrounded by a yellow halo of ground clutter. Toward the periphery of the radar coverage area (3 km from the radar), each yellow 'point' is the location and an animal in the current radar sweep (blue shows location of animals from previous sweeps going back 15 seconds). Animal densities are so high that the algorithm used to identify individual animal 'blips' and link them into tracks across radar sweeps often fails, especially so in producing long tracks. Most of these animals would not survive the filtering process to become part of the analysis.

Source: U.S. Geological Survey

CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix C: Aquatic Bird Counts (re Chapter 4)

June 2024 | CEC-500-2024-055

APPENDIX C:
Aquatic Bird Counts (re Chapter 4)

Table C-1 provides counts of the aquatic birds at the various solar facilities.

Table C-1: Counts of Aquatic Birds at Solar Facilities

Species	B-F	B-R	H-F	H-R	S-F	S-R	RA-R	LT-R	CVSR-F	CVSR-R	Mt. S-F	Mt. S-R	Total
American coot *Fulica americana*	0	0	0	0	0	0	0	1686	0	0	0 (1)	0 (1)	1686 (2)
white-faced ibis *Plegadis chihi*	0	0	0	0	0	0	0	0	0 (1)	0	300	565 (1)	865 (2)
cattle egret *Bubulcus ibis*	0	0	0	0	0	0	0	0	0	0	315	14 (1)	329 (1)
red-winged blackbird *Agelaius phoeniceus*	0	0	0	0	0	0	0	0	0	0	80 (1)	240	320 (1)
mallard *Anas platyrhynchos*	0	0	0	0	0 (1)	0	0	264	0	0	0	0	264 (1)
ring-necked duck *Aythya collaris*	0	0	0	0	0	0	0	241	0	0	0	0	241
ruddy duck *Oxyura jamaicensis*	0	0	0	0	0	0	0	119	0	0	0	0	119
black-crowned night-heron *Nycticorax nycticorax*	0	1	0	0	0	0	0	60	0	0	0	0	61
tree swallow *Tachycineta bicolor*	4	6	0	0	23	13	0	0	0	5	0	3	54
pied-billed grebe *Podilymbus podiceps*	0	0	0	0	0	0	0	53	0	0	0	0	53
great egret *Ardea alba*	0	0	1	0	0	4	0	6	0	0	6 (1)	31 (1)	48 (2)
northern rough-winged swallow *Stelgidopteryx serripennis*	1	5	0	0	5	2	0	0	0	0	0	0	13
double-crested cormorant *Phalacrocorax auritus*	0	0	0	0	0	0	0	0	0	0	13	0	13
American wigeon *Mareca americana*	0	0	0	0	0	0	0	12	0	0	0	0	12
yellow-headed blackbird *Xanthocephalus xanthocephalus*	0	0	1	10	0	0	0	1	0	0	0	0	12
northern shoveler *Spatula clypeata*	0	0	0	0	0	0	0	9	0	0	0	0	9
cliff swallow *Petrochelidon pyrrhonota*	0	0	0	0	2	5	0	0	0	0	0	0	7

Species	B-F	B-R	H-F	H-R	S-F	S-R	RA-R	LT-R	CVSR-F	CVSR-R	Mt. S-F	Mt. S-R	Total
belted kingfisher *Megaceryle alcyon*	0	0	0	0	0	0	0	5	0	0	0	1	6
great blue heron *Ardea herodias*	0	0	1	0	0	0	0	0	0	0	0 (1)	4 (1)	5 (2)
marsh wren *Cistothorus palustris*	0	0	0	0	0	0	0	4	0	0	0	0	4
American avocet *Recurvirostra americana*	0	0	0	0	0	0	0	2	0	0	0	0	2
lesser yellowlegs *Tringa flavipes*	0	0	0	0	0	0	0	1	0	0	0	0	1
osprey *Pandion haliaetus*	0	0	0	1	0	0	0	0	0	0	0	0	1
California gull *Larus californicus*	0	0	0	0	0	0	0	0	0	0	0	1	1
green heron *Butorides virescens*	0	0	0	0	0	0	0	0	0	0	1	0	1
greater yellowlegs *Tringa melanoleuca*	0	0	0	0	0	0	0	0	0	0	0	1	1
blue-winged teal *Spatula discors*	0 (1)	0	0	0	0	0	0	0	0	0	0	0	0 (1)
common loon *Gavia immer*	0	0	0	0	0 (1)	0	0	0	0	0	0	0	0 (1)
western grebe *Aechmophorus occidentalis*	0	0	0	0	0	0	0	0	0	0	0	0 (1)	0 (1)
sora *Porzana carolina*	0	0	0	0	0	0	0	0	0	0	0 (1)	0	0 (1)
Total	5 (1)	12	3	11	30 (2)	24	0	2463	0 (1)	5	715 (5)	860 (6)	4128 (15)

[1] B = Blythe Solar Energy Center, H = Highlander II, S = Seville 1 and 2, RA = Reference A (desert habitat outside of Desert Sunlight), LT = Lake Tamarisk, CVSR = California Valley Solar Ranch, Mt. S = Mt. Signal 3; F = Solar Facility, R = Reference.

Counts of aquatic habitat birds during 10-minute point count surveys at five photovoltaic solar facilities and paired reference areas, one lake, and one unpaired reference area, 2018 to 2019, in Southern California, U.S. Data are counts of live birds from point counts (counts of bird carcasses from fatality surveys).

Source: Western EcoSystems Technology, Inc