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Utility-scale solar impacts to volant wildlife

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Abstract

To reduce carbon emissions from fossil fuel combustion, United States government agencies, including those in California, initiated aggressive programs to hasten development of utility-scale solar energy. Much of California's early development of solar energy occurred in deserts and annual grasslands, much of it on public land. Measurement of solar energy's impacts to wildlife has been limited to mortality caused by features of solar facilities, and has yet to include impacts from habitat loss and energy transmission. To estimate species-specific bird and bat fatality rates and statewide mortality, I reviewed reports of fatality monitoring from 1982 to 2018 at 14 projects, which varied in duration, level of sampling, search interval, search method, and carcass detection trials. Because most monitors performed carcass detection trials using species of birds whose members were larger than birds and bats found as fatalities, I bridged the monitors' onsite trial results to offsite trial results based on the same methods but which also measured detection probabilities across the full range of body sizes of species represented by fatalities. This bridge preserved the project site's effects on detection probabilities while more fully adjusting for the effects of body size. My fatality estimates consistently exceeded those reported. Projected to California's installed capacity of 1,948.8 MW of solar thermal and 12,220 MW of photovoltaic (PV) panels in 2020 (14,168.8 MW total), reported estimates would support an annual statewide fatality estimate of 37,546 birds and 207 bats, whereas I estimated fatalities of 267,732 birds and 11,418 bats. Fatalities/

MW/year averaged 11.61 birds and 0.06 bats at PV projects and 64.61 birds and 5.49 bats at solar thermal projects. Fatalities/km/year averaged 113.16 birds and zero bats at generation tie-ins, and 14.44 birds and 2.56 bats along perimeter fences. Bird fatality rates averaged 3 times higher at PV projects searched by foot rather than car. They were usually biased low by insufficient monitoring duration and by the 22% of fatalities that monitors could not identify to species. I estimated that construction grading for solar projects removed habitat that otherwise would have supported nearly 300,000 birds/year. I recommend that utility-scale solar energy development be slowed to improve project decision-making, impacts assessment, fatality monitoring, mitigation efficacy, and oversight.

KEYWORDS

bats, birds, carcass detection trials, collision mortality, fatality monitoring, solar energy, wildlife impacts

In response to environmental and economic threats posed by carbon emissions from fossil fuel combustion, state and federal governments embarked on ambitious plans to develop renewable energy in California, USA (California Public Utilities Commission 2008). Plans such as the Desert Renewable Energy Conservation Plan (California Energy Commission et al. 2014) were formulated to overcome regulatory and permitting barriers for utility-scale renewable energy and its transmission to help Californians achieve the goal of obtaining 60% of its energy from renewable sources by 2030 and 100% of it by 2045. Because development of utility-scale renewable energy projects comes with environmental costs, including impacts to wildlife, state and federal agencies collaborated on an Avian-Solar Science Coordination Plan (Multiagency Avian-Solar Collaborative Working Group 2016) to identify and prioritize information needs related to impacts to birds. Just as understanding of impacts to wildlife lagged the rapid expansion of wind energy development (May et al. 2015, 2017), understanding impacts to wildlife also lags the rapid expansion of utility-scale solar energy projects (Multiagency Avian-Solar Collaborative Working Group 2016, Kosciuch et al. 2020). For example, only recently was it learned that many of the animals killed at California's solar projects originated out of state (Conkling et al. 2020), thus elevating the impacts to the regional level.

Deliberation is needed concerning the environmental costs and benefits of utility-scale solar energy compared to other forms of energy generation (e.g., wind, geothermal, hydroelectric, fossil-fuels, nuclear, rooftop solar). Accurate estimates of wildlife mortality would help determine impacts at project and regional levels. Researchers have calculated regional estimates of wind energy impacts to birds (Loss et al. 2013*a*, Smallwood 2013, Zimmerling et al. 2013, Erickson et al. 2014) and bats (Hayes 2013; Smallwood 2013, 2020; Zimmerling and Francis 2016). Researchers have also discussed cumulative impacts (Calvert et al. 2013) and calculated regional estimates of wildlife mortality caused by other anthropogenic sources, such as from collisions with automobiles (Loss et al. 2014*a*), transmission lines (Rioux et al. 2013, Loss et al. 2014*b*), and buildings (Machtans et al. 2013, Loss et al. 2014*c*), and predation from house cats (Loss et al. 2013*b*). Accuracy of these regional estimates depends on representativeness of the monitored projects (or places) relative to the spatial distribution of all projects (Smallwood 2013, Huso and Dalthorp 2014). It also depends substantially on study design and field methods implemented at the project level.

Before 2012, fatality monitoring at utility-scale solar projects was rare, largely because few utility-scale solar projects existed. The only wildlife fatality monitoring performed before 2012 had been at the 10-MW Solar One project in 1982–1983 near Barstow in San Bernardino, California (McCrary et al. 1986). Since monitoring at Solar One, much had been learned about fatality monitoring at wind projects from the late 1980s through the initial fatality monitoring plan for solar projects (Nicolai et al. 2011) and its update in 2016 (Huso et al. 2016). Managers formulated guidance documents to standardize survey methods for the purposes of accurately estimating and comparing fatalities among wind energy projects and to fatalities estimated for other forms of energy generation (Smallwood 2017*b*). Researchers deliberated field methods concerning their support of accurate fatality estimation (Smallwood 2007, Johnson et al. 2016, Reyes et al. 2016, Smallwood et al. 2018, Kitano et al. 2020), and the estimation methods themselves (Korner-Nievergelt et al. 2011, Kitano and Shiraki 2013, Péron et al. 2013, Warren-Hicks et al. 2013, Smallwood et al. 2018). A new framework for testing the efficacy of bat, golden eagle (*Aquila chrysaetos*), and bald eagle (*Haliaeetus leucocephalus*) impact-reduction strategies at wind energy projects (Sinclair and DeGeorge 2016) was also an important step in measuring and responding to utility-scale renewable energy impacts to volant wildlife. Much of what has been learned from research of wind energy impacts to wildlife can contribute to improved fatality monitoring at utility-scale solar projects, but solar projects also pose different risk factors, including to many species less vulnerable to wind energy impacts.

Once constructed, utility-scale solar projects pose multiple fatality risk factors. Volant wildlife can collide with solar collectors, power block structures, project buildings, medium-voltage overhead lines, gen-tie lines (i.e., generator lead or transmission lines), fencing, and automobiles servicing the project. Some birds might collide with photovoltaic (PV) panels because of the lake effect, or the birds' perception of many closely spaced PV panels as a waterbody onto which they attempt to land (Kagan et al. 2014). Polarized light from PV panels might attract prey of insectivorous birds and hence the birds themselves (Horváth et al. 2010), or it might fool birds into trying to lick water from the panel while in flight (Horváth et al. 2009, 2010). Reflected self-images on mirrors of solar thermal projects, or even of PV panels, might elicit aggressive responses of birds motivated to defend territory (Hager and Craig 2014, Kahle et al. 2016). Collisions might result from high-speed predator-prey encounters in which the pursuer or pursued collide with a project feature (Dunn 1993). Bats might fail to detect angled collector panels or mirrors because of reduced echolocation output (Gorresen et al. 2017, Corcoran and Weller 2018) or confused echolocation feedback (P. R. Long, retired military pilot, personal communication). Bats might also misinterpret echolocation-detected flat panels as water bodies from which they attempt to drink while in flight (Greif and Siemers 2010). At power tower projects, birds and bats die because of acute exposure to the zone of solar flux (Kagan et al. 2014). Data summarized herein indicate that birds also perish because of electrocution on energized portions of the project, entrapment or entanglement with project infrastructure such as fencing, and drowning in solar evaporation ponds. Until 2018, however, data needed to test hypothesized causal factors and to estimate regional fatalities were largely unavailable to the public.

Reviews of project-level fatality estimates were reported by those with exclusive access to reports and data (Kagan et al. 2014, Cooper 2016, Walston et al. 2016, Kosciuch et al. 2020). These reviews, along with Harrison et al. (2016), discussed barrier effects, habitat loss, and displacement of wildlife, but they focused on the lesser impacts of mortality caused by operable projects. In the reviews other than Harrison et al. (2016), fatality rates at operative projects were compared mostly as they had been reported, and only Walston et al. (2016) attempted to adjust all project-level fatality counts by carcass detection probabilities. I obtained and reviewed reports, data, environmental reviews, and communications related to bird and bat fatality monitoring at California utility-scale solar energy projects (Table 1). The variety of study designs and methods I observed inspired my own estimations of project-level fatality estimates. I became most concerned over liberal exclusions of fatalities from project-level fatality estimates, use of automobiles in fatality searches, and placements of inappropriate carcasses to measure searcher detection and carcass persistence in carcass detection trials. My first objective was to compare my independent estimates to originally reported estimates of bird and bat

TABLE 1 Solar projects for which fatality data were made available for bats and bird mortalities 1982–2018 at solar projects in California, USA, in response to United States Freedom of Information Act and California Public Records Act requests in 2018.

Project	Ref[a]	County[b]	Features surveyed[c]	MW	Ha	Year(s)	Other surveys[d]
California Valley Solar Ranch	1	SLO	PV, OL, G, F	258	476	2012–2014	Bat, BM
Topaz Solar Farm	2	SLO	PV, OL	550	677	2012–2016	Nest, Use, Bat, BM
Campo Verde Solar Project	3	Imp	PV, G, F	139	584	2013–2016	None
Centinela Solar Energy Project	4	Imp	PV, G, F	170	665	2014–2015	None
Imperial Solar Energy Center South	5	Imp	PV, G	130	383	2014	None
Calipatria Solar Project	6	Imp	PV	20	64	2016	None
Midway Solar Farm II	7	Imp	PV	30	113	2018	None
Desert Sunlight Solar Farm	8	Riv	PV, G, F	550	1,700	2015–2016	None
Stateline Solar Farm	9	SB	PV, G	300	682	2017–2018	None
McCoy Solar Energy Project	10	Riv	PV, G, F	250	914	2016–2017	None
Blythe Solar Power Project	11	Riv	PV, G, F	235	769	2016–2017	None
Genesis Solar Energy Project	12	Riv	SCA, PB, P, G, F	250	728	2015–2017	None
Solar One	13	SB	PT, HM, F, P	10	32	1982–1983	Use
Ivanpah Solar Electric Generating System	14	SB	PT, HM, G, F	377	1,457	2013–2018	Use

[a] References: 1 = H.T. Harvey and Associates (2013, 2015*a*); 2 = Althouse and Meade (2012, 2014); 3 = Heritage Environmental Consultants (2014, 2015*a* 2016); 4 = Heritage Environmental Consultants (2015*b*), Chambers Group (2016); 5 = UltraSystems (2014*a*–*e*); 6 = Heritage Environmental Consultants (2017*a*,*b*,*c*); 7 = Shoener and Barrett's Biological Surveys (2018); 8 = Western EcoSystems Technology (2017*a* 2018*a*); 9 = Dudek (2018*a*); 10 = Martinson et al. (2018*b*); 11 = Doering and Santistevan (2013), Martinson et al. (2018*a*); 12 = Western EcoSystems Technology (2016, 2017*c*); 13 = McCrary et al. (1986); 14 = H.T. Harvey and Associates (2015*b*), Western EcoSystems Technology (2017*b*, 2018*b*, 2019).

[b] SLO = San Luis Obispo, Imp = Imperial, Riv = Riverside, SB = San Bernardino.

[c] PV = photovoltaic panels mounted on ground-based metal frames, OL = medium voltage overhead lines, G = gen-tie, or generation tie-ins to the nearest substation or transmission lines, F = perimeter security fence, SCA = solar collector arrays composed of parabolic mirrors, PB = power blocks, P = solar evaporation ponds, PT = power towers receiving reflected sunlight from heliostat mirrors, and HM = heliostat mirrors arranged to reflect solar energy to receiver on power tower.

[d] Bat = bat activity surveys performed using acoustic detectors; BM = background mortality surveys consisting of fatality searches in adjacent areas lacking solar project infrastructure; nest = nest survey, use = visual scans to detect and count birds during daylight hours.

fatality rates at monitored utility-scale solar projects. I predicted my estimates would usually be higher. My second objective was to estimate statewide fatalities of birds and bats caused by the installed capacity of utility-solar projects in 2020. My third objective was to apportion collision fatality impacts to project features to reveal which features warrant greatest concern. My fourth objective was to compare fatality rates among bird and bat species and among those with special status to identify species in relatively greater need of research and mitigation. My fifth objective was to identify additional sources of error and bias that warrant further research to increase accuracy of fatality estimates.

STUDY AREA

The fatality monitoring studies I reviewed had been performed from 1982–2018 at 14 utility-scale solar energy projects on relatively flat terrain in annual grassland, desert, and agricultural environments within the desert of California (Figure 1; Table 1). Elevations ranged −4 m to 983 m. Climate was Mediterranean, with warmest temperatures and least rainfall during June–August, coolest temperatures and greatest rainfall during November–February, and transitional periods with increasing temperatures and decreasing rain in March–May, and deceasing temperatures and increasing rain during September–October. Twelve projects were located in Mojave and Sonoran deserts, where annual rainfall averaged <10 cm, and natural ground cover was desert scrub including creosote (*Larrea tridentata*). Two project sites were in San Luis Obispo County, where annual rainfall averaged 10–38 cm, and natural ground cover was annual grassland composed of red brome (*Bromus madritensis rubens*), soft chess (*Bromus hordeaceus*), foxtail barley (*Hordeum murinum*), six-weeks fescue (*Festuca octoflora*) and wild oat (*Avena fatua*.). Wildlife typical of the desert sites included coyote (*Canis latrans*), desert kit fox (*Vulpes macrois*), bighorn sheep (*Ovis canadensis*), black-tailed jackrabbit (*Lepus californicus*), canyon bat (*Parastrellus hesperus*), common raven (*Corvus corax*), desert sidewinder (*Crotalus cerastes*), and Agassiz desert tortoise (*Gopherus agassizii*).

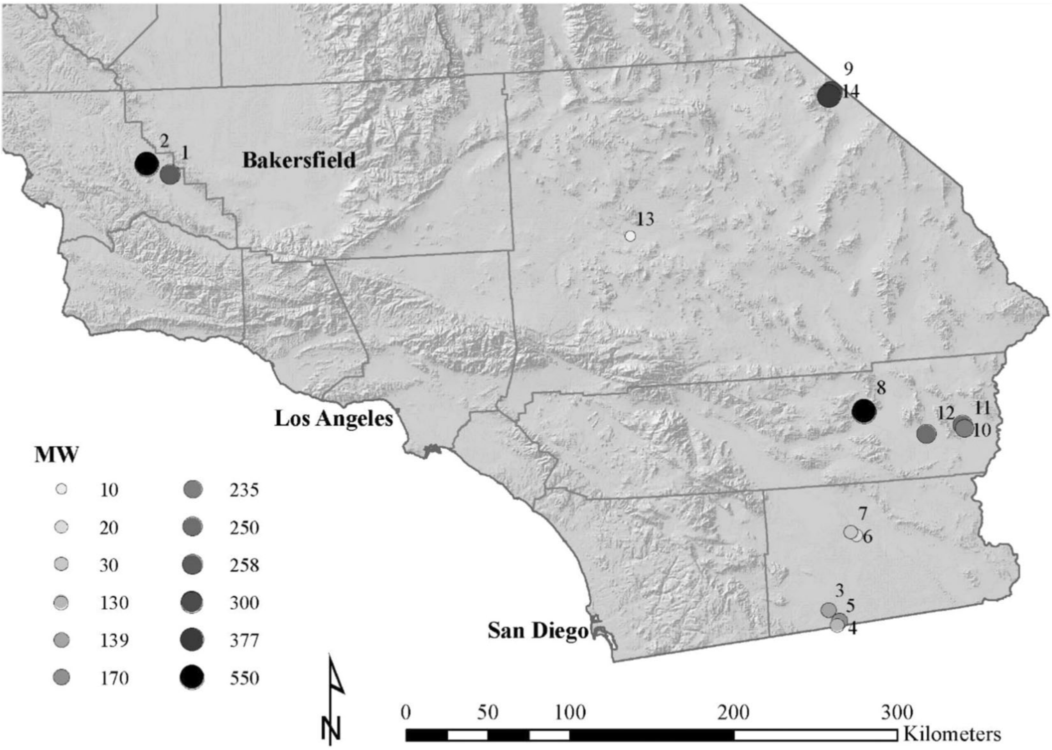

FIGURE 1 Locations and rated capacities (MW) of solar energy project sites that were monitored for wildlife fatalities in California, 1982–2018: 1 = California Valley Solar Ranch, San Luis Obispo County, 2 = Topaz Solar Farm, San Luis Obispo County, 3 = Campo Verde Solar Project, Imperial County, 4 = Centinela Solar Energy Project, Imperial County, 5 = Imperial Solar Energy Center South, Imperial County, 6 = Calipatria Solar Project, Imperial County, 7 = Midway Solar Farm II, Imperial County, 8 = Desert Sunlight Solar Farm, Riverside County, 9 = Stateline Solar Farm, San Bernardino County, 10 = McCoy Solar Energy Project, Riverside County, 11 = Blythe Solar Power Project, Riverside County, 12 = Genesis Solar Energy Project, Riverside County, 13 = Solar One, San Bernardino County, 14 = Ivanpah Solar Electric Generating System, San Bernardino County.

Wildlife typical of the grassland sites included coyote, San Joaquin kit fox (*Vulpes macrotis mutica*), black-tailed jackrabbit, giant kangaroo rat (*Dipodomys ingens*), and northern Pacific rattlesnake (*Crotalus oreganus oreganus*).

All monitored projects had been graded flat and natural vegetation had been removed. Of the 3 solar energy technologies monitored, 1 technology included flat PV panels on ground-mounted frames with solar trackers at most projects. The other 2 technologies were solar thermal, including solar-trough parabolic mirrors referred to as solar collector arrays (SCAs) at Genesis Solar Energy Project, and heliostat mirrors reflecting light to receivers, or boilers, atop power towers at Ivanpah Solar Electric Generating System (Ivanpah) and the since-decommissioned Solar One project. Solar projects connected to the grid via gen-ties, which resemble transmission lines and their towers. Solar projects were also surrounded by perimeter security fences. Some projects also included medium-voltage overhead lines. Monitored projects totaled 3,259 MW, including 627 MW of solar thermal and 2,632 MW of PV. They included 163.35 km of security fence bordering 2,237 MW of solar arrays (0.073 km/MW) and 78.09 km of gen-tie serving 2,237 MW of solar arrays (0.037 km/MW) that were monitored for fatalities.

METHODS

Through use of California Public Records Act (PRA) and federal Freedom of Information Act (FOIA) requests to agencies with regulatory authority over biological resources, I obtained reports, data, environmental reviews, and communications related to fatality monitoring at utility-scale solar projects in California. Field and analytical methods of fatality monitoring varied among reports but all were intended to estimate the number of fatalities caused by the project. Monitors searched for fatalities by following protocols designed to account for proportions of fatalities not found, to extrapolate from sampling units to whole projects, and to compare fatality rates between project features and whole projects. Although monitors used various fatality estimators, the basic form was $\widehat{F} = \frac{F}{\rho}$, where $\widehat{F}$ was the fatality estimate, F was the number of fatalities found, and ρ represented carcass detection probability.

Monitors typically searched by foot or by car for fatalities according to a periodic schedule and along evenly spaced transects across sampled portions or all of a solar project. At 6 projects, monitors applied distance sampling from transects. They usually removed all fatality finds upon discovery. Most performed carcass detection trials, in which testers placed carcasses on the study site to quantify searcher detection rates and carcass persistence time, or the time until the placed carcass was no longer detectable by searchers. Outcomes of carcass detection trials were used to estimate ρ. For fatality estimation, monitors usually omitted fatalities found incidental to scheduled searches or outside search areas. Some monitors set 5 or 10 fatality detections/species as thresholds for species' inclusion, and some separately reported fatality estimates between known and unknown cause of death. A few reports provided estimates for 10 species with the highest fatality rates.

From information I received following PRA and FOIA requests, I constructed data sets I needed to independently estimate fatalities at monitored solar projects (fatality data and their reported attributes, along with definitions of data fields [Table S1], are available in Supporting Information). I recorded each study's start date, duration of monitoring of each project feature, proportion of each project feature searched, whether searched by walking or car, transect width, whether distance sampling was used, fatality search interval, and fatality metric (Table 2). I recorded essential attributes of carcass detection trials that monitors used to represent ρ, including taxa, carcass source, body size classes into which trial carcasses were grouped, trial duration, and metric used to estimate the probability of carcasses persisting to the next search (r), which could be derived from R = proportion of carcasses remaining on the ith day into a trial, R_C = mean daily carcass persistence upon the ith day into a trial, and $\overline{t}$ = mean days to carcass removal (Table S2, available in Supporting Information). Some of the monitors' detection trials included placements of feather piles as a separate class from small and large birds. I did not use the results of such trials because all fatalities found as feather piles began as complete carcasses. Starting a trial from a feather pile, as if the rest of the carcass never existed, was unrealistic.

TABLE 2 Bird and bat fatality search methods reported at utility-scale solar projects in California, USA, 1982–2018.

Project	Feature[a]	Yrs	Sample (%)	Search	Transect (m)[b]	I (days) in spring, summer, fall, winter[c]	$\hat{F}$ metric[d]
CVSR[e]	Gen-tie	2.4	100	Walk	15	7, 7, 7, 7	$F/(S \times r)$
CVSR[e]	MVOH	1.8	100	Walk	18	7, 7, 7, 7	$F/(S \times r)$
CVSR[e]	Fence	2.0	20	Walk	3	7, 7, 7, 7	$F/(S \times r)$
CVSR[e]	PV	2.0	20	Walk	5	7, 7, 7, 7	$F/(S \times r)$
Topaz	MVOH	5.0	3.3	Walk	2.13	1 | 30	F/plot/search
Topaz	PV	5.0	3.5	Walk	2.3	1 | 30	F/plot/search
Campo Verde	Fence	2.5	100	Walk		1 | 30	None
Campo Verde	Gen-tie	2.5	30	Walk	7.5	1 | 30	None
Campo Verde	PV	2.5	30	Walk		1 | 30	None
Centinela	Gen-tie	0.8	50	Walk	5	3.5, 3.5, 3.5, 3.5	$F/(S \times R_C)$
Centinela	Fence	1.0	100	Walk		1 | 30	
Centinela	PV	1.0	10	Walk	4.2	1 | 30	F/0.2 yr
Imperial	Gen-tie	0.4	100	Car		1 | 30	None
Imperial	PV	0.4	10	Car	14.5	1 | 30	None
Calipatria	PV	2.0	100	Walk	35	7, 21, 7, 21	Distance[f]
Midway	PV	0.4		Car	60	7, 0, 18, 0	
Desert Sunlight	Fence	1.0	7	Car		7, 23, 8, 19	$F/(S \times r)$
Desert Sunlight	Gen-tie	1.0	48	Walk	15	7, 23, 8, 19	$F/(S \times r)$
Desert Sunlight	PV	1.0	30	Walk	70	7, 23, 8, 19	$F/(S \times r \times A)$
Stateline	Fence	1.0	100	Car	3	7, 21, 7, 21	$F/(S \times r)$
Stateline	Gen-tie	1.0	50	Car	15	7, 21, 7, 21	$F/(S \times r)$
Stateline	PV	1.0	40	Car	120	7, 21, 7, 21	$F/(S \times r \times A)$
McCoy	Fence	2.0	98	Car	3	7, 21, 7, 21	$F/(S \times r)$
McCoy	Gen-tie	2.0	25	Walk	15	7, 21, 7, 21	$F/(S \times r)$
McCoy	PV	2.0	45	Car	160	7, 21, 7, 21	$F/(S \times r \times A)$
Blythe	Fence	2.0	92	Car	3	7, 21, 7, 21	$F/(S \times r)$
Blythe	Gen-tie	2.0	25	Walk	15	7, 21, 7, 21	$F/(S \times r \times A)$
Blythe	PV	2.0	41	Car	95	7, 21, 7, 21	$F/(S \times r \times A)$
Genesis	Fence	2.0	100	Car	?	7, 20, 7, 19	$F/(S \times r)$
Genesis	Gen-tie	2.0	25	Walk	15	7, 20, 7, 19	$F/(S \times r)$
Genesis	Ponds	2.0	100	Walk		7, 20, 7, 19	$F/(S \times r)$
Genesis	PBlocks	2.0	100	Walk	7.5	7, 20, 7, 19	$F/(S \times r)$
Genesis	SCAs	2.0	30–50	Car	30	7, 20, 7, 19	$F/(S \times r \times A)$

(Continues)

TABLE 2 (Continued)

Project	Feature[a]	Yrs	Sample (%)	Search	Transect (m)[b]	I (days) in spring, summer, fall, winter[c]	$\hat{F}$ metric[d]
Solar One	Heliostats	0.8	100	Walk		7, 0, 7, 7	F/(r)
Solar One	Tower	0.8	100	Walk		7, 0, 7, 7	F/(r)
Ivanpah	Fence	2.0	100	Car	3	7, 25, 7, 25	F/(S × r)
Ivanpah	Gen-tie	2.0	100	Car	15	7, 25, 7, 25	F/(S × r)
Ivanpah	Heliostats	2.0	24	Walk	5	7, 25, 7, 25	F/(S × r)
Ivanpah	Heliostats	2.0	8	Walk		7, 0, 0, 21	F/(S × r)
Ivanpah	Tower[g]	2.0	100	Walk		7, 25, 7, 25	F/(S × r)
Ivanpah	Tower[g]		100	Walk		7, 21, 7, 21	F/(S × r)

[a] PV = photovoltaic panels mounted on ground-based metal frames, MVOH = medium voltage overhead lines, Gen-tie = generation tie-ins to the nearest substation or transmission lines, Fence = perimeter security fence, SCA = solar collector arrays composed of parabolic mirrors, PBlocks = power blocks, Ponds = solar evaporation ponds, Tower = power towers receiving reflected sunlight from heliostat mirrors, and Heliostats = mirrors arranged to reflect solar energy to a receiver on power tower.

[b] Width of search area to one side of transect.

[c] 1 | 30 refers to daily searches for 7 consecutive days beginning again every 30 days.

[d] $\hat{F}$ = estimated number of fatalities, F = number of fatalities found, S = proportion of trial carcasses found, r = proportion of trial carcasses persisting to next search, A = proportion of search area that was searchable; empty spaces indicated the reporting was unclear which metric was used.

[e] California Valley Solar Ranch. Also performed daily searches for 5 consecutive days once every 4 weeks.

[f] Used Program Distance (Miller 2016), but none of the models fit the data well.

[g] Included cleared ground around towers, power blocks, and inner rings of high-density heliostat mirrors.

Where monitors used distance sampling, I derived probabilities of searcher detection of trial carcasses within distance increments from transects, which were reported graphically. I multiplied each distance increment by transect length to calculate the search area, and hence the search area as a proportion of the project area (A) associated with a probability of searcher detection. Because all but the gen-tie at Centinela did not report distances of fatalities from the transect, I usually could not assign fatalities to the distance increment for which detection probabilities had been characterized by trials. I therefore averaged $S \times A$ among the distance increments searched, where S was the proportion of placed trial carcasses found within the ith distance increment (of those available), and A was the searchable area between the car and the farthest point of the ith distance increment. Along with r, $S \times A$ composed ρ: $\hat{F} = \frac{F}{r \times S \times A}$.

Where carcass detection trials were not implemented, insufficiently described, or based on <8 carcass placements/category of bats, small birds, and large birds (i.e., California Valley Solar Ranch [CVSR], Campo Verde, Centinela, Imperial, Solar One), I applied detection rates from my own trials of carcasses as part of 2 3-year fatality monitoring studies in the Altamont Pass Wind Resource Area (APWRA). Given its short-stature annual grassland cover, carcass visibility to scavengers and fatality searchers should be similar between the APWRA and the 5 project sites to which I applied APWRA-derived carcass detection rates, but to minimize differences, I relied solely on trial carcasses that had been placed on open ground to simulate conditions of ground visibility at the 5 solar project sites. The APWRA trials were integrated into routine fatality monitoring with placements that were periodic throughout each study and randomized within fatality search areas. In 1 study, trials included 276 bird carcasses of 79 species that ranged in mass from 2 g to 6,650 g (Smallwood et al. 2017*a*, 2018). In the other study, trials included 764 bird carcasses of 100 species ranging in mass from

3 g to 6,000 g, and 144 bat carcasses of 16 species ranging in mass from 2.3 g to 23.6 g (Brown et al. 2016). Trial carcasses were left indefinitely where placed. Whether searchers ever found the carcass determined each trial outcome. I logit-regressed trial outcomes of found or not found on $\log_{10}$ body mass (g) to estimate overall detection probability $\hat{D}$:

$$\hat{D} = \frac{e^{-a+b\times \log_{10} M}}{1 + e^{-a+b\times \log_{10} M}},$$

where *a* and *b* were fitted coefficients and *M* was body mass (Figure 2). I estimated $\hat{D}$ separately for birds and bats, and among the 3 fatality search intervals that were implemented between the 2 APWRA studies: 5, 7, and 28 days. To simulate a daily search interval, I estimated $\hat{D}$ from carcass trial placements 1 day prior to the next search (Smallwood 2017*a*).

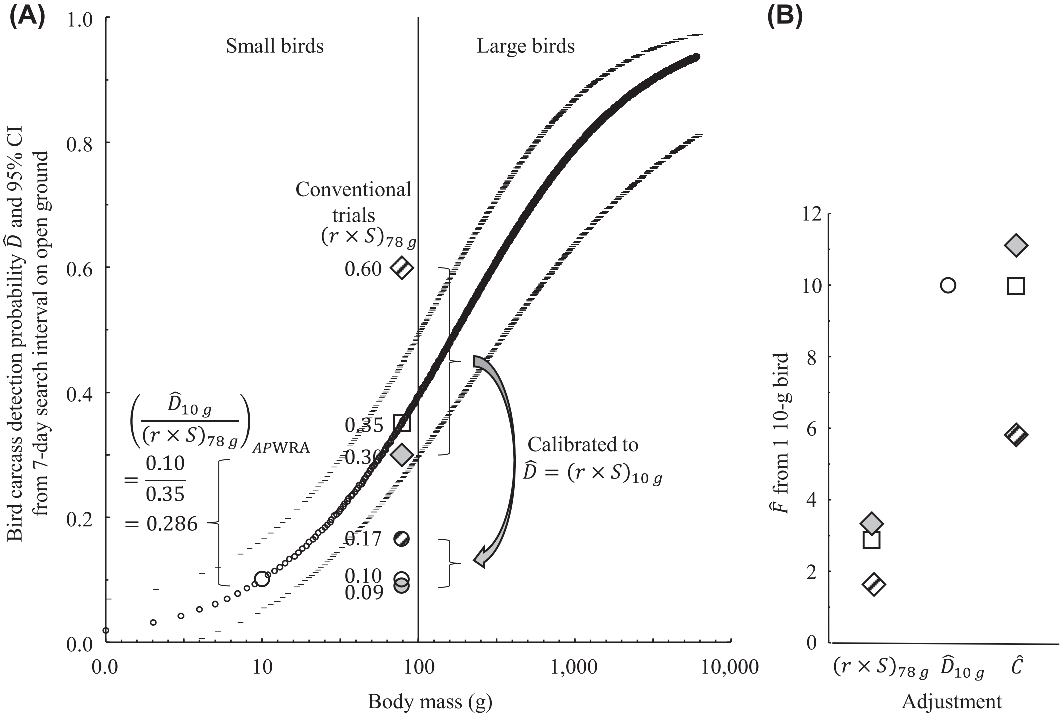

FIGURE 2 Hypothetical fatality estimation from 1 bird of a 10-g species found at a site where monitors used 78-g bird carcasses to represent small birds of ≤100 g body mass in on-site carcass detection trials, and then calibrated to carcass detection trial outcomes on open ground in the Altamont Pass Wind Resource Area (APWRA), California, USA, 2012–2015, where carcass detection probability was modeled to variation in body mass. A) Predicted probability of carcass detection ($\hat{D}$) and 95% confidence intervals based on outcomes of detection trials performed at 7-day intervals and logit-regressed on $\log_{10}$ body mass, and overlayed by overall detection measured for 78-g bird carcasses in on-site trials at 2 sites (shaded and striped diamond symbols) and in the APWRA (open square) and calibrated to $\hat{D}$ of the 10-g bird that was found (oversized circle among mean $\hat{D}$). Also overlaid are the detection probabilities derived from trials with 78-g birds calibrated to that of the 10-g bird (circles patterned to match symbols representing uncalibrated detection probabilities). B) Resulting fatality estimates ($\hat{F}$) derived from 3 types of adjustment: conventional trials for carcass persistence *r* and searcher detection *S* using 78-g birds to represent small birds, $\hat{D}$ of a 10-g bird, and the calibration bridge to introduce the effect of body size on detection probability while preserving the site effect: $\hat{C} = \frac{1}{(r\times S)_{78\,g\ on\ site}} \Big/ \left(\frac{\hat{D}_{10\,g}}{(r\times S)_{78\,g}}\right)_{APWRA}$.

Although logit regression calculates asymptotic confidence intervals along with predicted detection probabilities of each body mass used to develop the model, the body masses of fatality finds can differ from those of the trial carcasses used to develop the model. To extend the model's confidence intervals to fatality finds, I fit nonlinear regression models to logit regression's 95% lower and upper confidence limits (Smallwood et al. 2018).

To the 5 studies at solar projects in need of carcass detection probabilities from my offsite studies, $\widehat{D}$ served as ρ in the fatality estimator: $\widehat{F} = \frac{F}{\widehat{D}}$. I assumed that detection probabilities of carcasses placed on open ground depended more on variation in carcass size than on variation in carcass removal rates among project sites. Spatial variation in carcass removal rates remains unknown, but the effect of body mass on detection probability is strong (Figure 2). Given the strong effect of body mass, $\widehat{D}$ served a second purpose in this study. Because I monitored trial carcasses in the APWRA for availability to be found by searchers so that I could also estimate fatalities using the conventional terms $r \times S$, I had the means to calibrate $r \times S$ to $\widehat{D}$, the importance of which is discussed below.

Most fatality monitors at solar projects deployed birds in detection trials that were larger than most of the birds and bats found as fatalities. This practice emerged as a potential bias because the placed birds represented broad size categories in which the body size-specific detection probabilities of the placed birds would be increasingly discrepant from the detection probabilities of increasingly smaller or larger species found as fatalities in the same broad size category (Figure 2). I therefore adjusted the results of detection trials to account for the effects of variation in body mass. I used integrated, overall detection trials performed in the APWRA to derive a unit-free scaler to adjust for the effects of variation in body mass on trial outcomes. I formulated a body mass scaler $\widehat{C}$ as follows:

$$\widehat{C} = \left(\frac{F}{r \times S}\right)_{ith\ solar\ project} \Big/ \left(\frac{\widehat{D}}{r \times S}\right)_{APWRA,\ open\ ground}$$

With $\widehat{C}$, I adjusted number of fatalities found for overall detection probability $r \times S$ based on the monitors' onsite trials, and then I adjusted fatalities by the ratio of overall detection probability $\widehat{D}$ to overall detection probability $r \times S$ derived from the same conventional trials using the same-sized carcasses as at the solar project. In these cases, $\widehat{C}$ served as ρ. In the dividend, $r \times S$ were from the same-sized species as $r \times S$ in the divisor, thereby serving to bridge the 2 sites, 1 site where $\widehat{D}$ was additionally measured along a continuous range of body mass and the other site where F was additionally measured among species that varied continuously in body mass (Figure 2). This bridge preserved any differences in r and S between the sites. I applied this bridge to onsite detection trials and fatality data from Topaz, Desert Sunlight, McCoy, Midway, Calipatria, Blythe, Genesis, and Ivanpah. I was unable to apply this bridge to data from Stateline, to which I relied solely upon onsite detection trials.

I applied the body mass scaler to bird and bat fatalities where trial outcomes had been lumped into broad size categories. Monitors had performed detection trials for bats at only 1 solar project, but bats were represented by small birds in those trials. The scaling function I used for bats was $\widehat{D}$ for bats relative to $r \times S$ for whichever bird species in my study represented small birds at the solar project, and again I relied only on bats and small birds in my study that had been placed on open ground (no occlusion) at Vasco Winds (Brown et al. 2016) or Sand Hill (Smallwood et al. 2018). To represent trial carcasses at solar projects, I selected APWRA bird trial carcasses ranging in size 24–32 g for house sparrows (*Passer domesticus*), 36–47 g for brown-headed cowbirds (*Molothrus ater*), 50–70 g for Japanese quail (*Coturnix japonica*) chicks, 108–168 g for Japanese quail adults, 260–400 g for rock pigeons (*Columba livia*), 1,050–1,150 g for mallards (*Anas platyrhynchos*), and 1,200–2,300 g for ring-necked pheasants (*Phasianus colchicus*). For application to fatality monitoring based on 21-day search intervals, I averaged $\widehat{D}$ between 7- and 28-day intervals on open ground at Vasco Winds.

Only at CVSR were found fatalities sufficiently assigned to sampling units so that other researchers could estimate standard error attributable to variation among sampling units. Consistent with Smallwood et al. (2020), I used the delta method to estimate confidence intervals at CVSR. Otherwise, I relied on logit-regressed estimates of confidence intervals to represent confidence intervals of fatality estimates. I estimated fatalities of every species represented by ≥1 fatality at operational solar projects. I assumed solar projects caused all fatalities found by monitors, but natural causes likely contributed to a few of the fatalities.

Although I endeavored to reduce the effects of bias on ρ by factoring in fatality detection probability as a function of interspecific variation in body mass, fatality estimates remained amply prone to error and bias (Smallwood 2007). To improve accuracy of fatality estimates going forward, I addressed 3 additional sources of error and probable bias. First, I compared monitoring outcomes between pedestrian and car surveys. I assumed bias would be indicated, though not verified, if estimated fatality rates differed between projects searched by foot and by car. Second, to indicate whether and to what degree wildlife species were represented in fatality monitoring results at solar projects, I related the cumulative number of species represented as detected fatalities by months since monitoring was initiated, similar to the approach used by Beston et al. (2015). To the fatality monitoring data of each project, I attempted to fit a nonlinear model for the purpose of identifying the asymptote of the cumulative number of species represented, and to determine whether the predicted asymptote had indeed been reached. Third, I tallied fatalities that monitors had assigned to taxa or size groups other than the species level.

RESULTS

Attributes of fatality monitoring studies

Fatality monitoring studies varied greatly in attributes that affect fatality estimates (Tables 2, S1). As examples, fatality searches covered 3.3% to 100% of solar project features, and spanned 0.42 to 5 years in duration. Fatality search intervals ranged 1 to 25 days, but at 2 projects searches were daily for 5 to 7 consecutive days beginning at intervals of 28 to 30 days, respectively. Areas searched from transects varied within maximum distances of 2.1 to 160 m—a 76-fold range. Distance sampling was used from a transect along the gen-tie at Centinela, from transects intersecting PV arrays at Centinela, Imperial, Calipatria, Midway, Desert Sunlight, Midway, McCoy, and Blythe, and from transects intersecting SCAs at Genesis. The fatality metric at Topaz was fatalities/plot/search, which was incomparable to fatality metrics reported in other studies. No fatality estimates were reported at Campo Verde and Imperial, and none were reported for bats at Ivanpah.

Studies varied greatly in carcass detection trials needed to accurately represent ρ. Bat detection trials were implemented only at Genesis, where small birds served as surrogates for bats (Table S2). Bird carcasses were placed in all detection trials except for trials along the Centinela gen-tie, where colorful bird-shaped holiday ornaments were placed in searcher detection trials. Source of bird carcasses was unreported at all studies except CVSR, which used carcasses from wildlife rehabilitation facilities and fatalities found during monitoring. Two studies neglected to identify species used in detection trials. Monitors at Solar One and Calipatria did not perform searcher detection trials. Monitors at Centinela and Imperial did not perform detection trials of any type. Duration of carcass persistence trials ranged 5 to 42 days. The carcass persistence metric varied but was usually mean days to carcass removal (Table S2).

The majority of birds killed at solar projects were small-bodied; most were smaller than the bird carcasses used to represent them in detection trials (Figure 3). Of bird species found as fatalities among solar projects, the typical adult body mass of 30% were <22 g, 50% were <42 g, 63% were ≤100 g, and only 22% were at least as large as rock pigeons. Of bird species found as fatalities at 11 PV projects, the typical adult body mass of 30% were ≤25 g, 50% were <56 g, 57% were <100 g, and only 25% were at least as large as rock pigeons. Among 3 projects (McCoy, Blythe, and Desert Sunlight), the smallest species used in small-bird persistence trials was larger than 73% of the small birds found as fatalities (Figure S1, available in Supporting Information). The smallest species used in medium-bird persistence trials was larger than 33% of the medium bird species found. The largest species used in large-bird persistence trials was smaller than 50% of the large birds found as fatalities. Accounting for the detection probabilities of fatalities of species smaller than detection trial carcasses increased fatality estimates of many small-bird

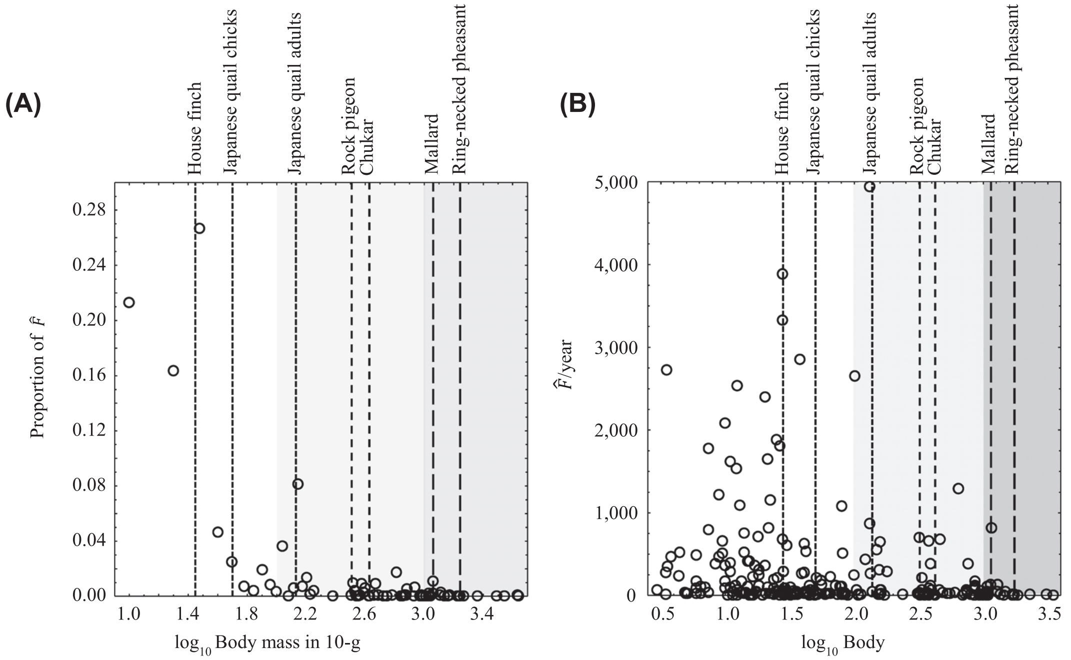

FIGURE 3 Body size-distribution of bird fatalities relative to typical body mass of species used in searcher detection and carcass persistence trials (dashed vertical lines) among 13 California solar projects (Solar One not included) monitored 2012–2018, where the clear zone represents small birds ≤100 g, light gray represents medium birds >100 g to ≤1,000 g, and dark gray represents large birds >1,000 g: A) proportion of estimated number of fatalities ($\hat{F}$) by 10-g increments of typical species' body mass, and B) estimated annual fatalities by body mass on a continuous scale. Carcasses of many found fatalities were smaller than the species used in on-site detection trials.

species, but it reduced estimates of a much smaller number of large-bird species (Figure S2, available in Supporting Information). The onsite-adjusted fatality estimates bridged to the APWRA's integrated overall detection trials related linearly to onsite-adjusted fatality estimates without the bridge, indicative of an unbiased adjustment for interspecific variation in body mass (Figure S3, available in Supporting Information).

Body-size adjusted fatality estimates

My bird fatality estimates exceeded originally reported estimates by factors of 1.07 at Campo Verde, 1.5 at Desert Sunlight, 1.88 at CVSR, 4.59 at McCoy, 6.59 at Blythe, 10.49 at Genesis, 10.5 at Calipatria, and 18–72 at Topaz (Table 3). No project-wide fatality estimates were reported at Ivanpah, but my estimates for birds at Ivanpah's heliostat mirror arrays and in the tower area exceeded originally reported estimates by factors of 10 and 3.8, respectively.

My estimate of bird fatalities among Ivanpah's heliostat mirrors exceed that of the Tower Area by a factor of 6.2 (Table 3; Figure S4, available in Supporting Information). Some unknown portion of the fatalities found among heliostat mirrors was likely caused by exposure to the zone of solar flux. Bird fatality rates among mirrors at Genesis averaged only 20% of those among heliostat mirrors at Ivanpah. Bird mortality was highest at solar thermal projects (Table 3). On a per-MW basis, the gen-tie was the most dangerous project feature to birds at some projects, whereas the PV panels or mirrors were the most dangerous at others. On a project-wide basis, however, more birds died by collision with solar collectors—mirrors and PV panels.

TABLE 3 Reported estimates and my own estimates of wildlife fatality rates at California utility-scale solar energy projects and project features through 2020. I cannot explain the estimates that were not reported by monitors, but I did not estimate fatalities caused by medium-voltage overhead lines and PV at Topaz because these facilities overlapped to a degree that I could not determine which caused the fatalities.

			$\hat{F}$/MW/year (95% CI)	
Project	**Taxa**	**Feature**[a]	**Reported**[b]	**This study**
CVSR	Birds	Gen-tie	0.38 (0.32–0.48)	1.27 (0.89–1.93)
CVSR	Birds	MVOH	0.10 (0.08–0.12)	0.35 (0.26–0.48)
CVSR	Birds	Fence	0.72 (0.60–0.89)	1.15 (0.85–1.64)
CVSR	Birds	PV	8.97 (7.33–11.49)	16.17 (11.98–22.05)
CVSR	Birds	Project	10.07 (8.20–12.92)	18.98 (14.00–26.16)
Topaz	Birds	MVOH	0.0546–0.2159[c]	
Topaz	Birds	PV	0.0491–0.1909[c]	
Topaz	Birds	Project	0.1037–0.4068[c]	7.48 (6.12–11.22)
Campo Verde	Birds	Fence		0.10 (0.08–0.14)
Campo Verde	Birds	Gen-tie		0.50 (0.39–0.78)
Campo Verde	Birds	PV		20.49 (16.52–31.07)
Campo Verde	Birds	Project	19.65	21.09 (16.99–32.00)
Centinela	Birds	Fence		1.82 (1.49–2.77)
Centinela	Birds	Gen-tie	1.68[c]	2.31 (1.7–3.82)
Centinela	Birds	PV	12.93	22.92 (18.52–34.71)
Centinela	Birds	Project		28.64 (23.09–43.76)
Imperial	Birds	Project		9.70 (8.22–14.65)
Calipatria	Birds	PV	2.1	22.09
Calipatria	Birds	Project	2.1	22.09
Midway	Birds	Project		3.22
Desert Sunlight	Birds	Fence	0.015 (0.005–0.042)	0.03 (0.02–0.03)
Desert Sunlight	Birds	Gen-tie	1.86 (0.87–4.99)	2.58 (1.68–4.32)
Desert Sunlight	Birds	PV	1.05 (0.88–1.56)	1.68 (1.24–3.19)
Desert Sunlight	Birds	Project	2.93 (2.03–6.67)	4.39 (3.01–7.70)
Stateline	Birds	Gen-tie	0.457	0.19
Stateline	Birds	PV	0.387	1.94
Stateline	Birds	Project		2.13
McCoy[d]	Birds	Fence	0.096 (0.016–0.20/8)	0.25 (0.17–0.36)
McCoy[d]	Birds	Gen-tie	3.124 (2.36–4.04)	11.68 (7.19–21.13)
McCoy[d]	Birds	PV	0.23 (0.04–0.49)	3.88 (2.58–6.04)
McCoy[d]	Birds	Project	3.45 (2.66–4.39)	15.83 (9.98–27.60)

(Continues)

TABLE 3 (Continued)

Project	Taxa	Feature[a]	$\hat{F}$/MW/year (95% CI) Reported[b]	This study
McCoy[d]	Bats	Project		0.46 (0.01–0.73)
Blythe[d]	Birds	Fence	0.09 (0.03–0.17)	0.38 (0.28–0.55)
Blythe[d]	Birds	Gen-tie	3.32 (2.51–4.30)	16.35 (10.07–28.96)
Blythe[d]	Birds	PV	0.18 (0.009–0.455)	6.67 (4.52–5.75)
Blythe[c]	Birds	Project	3.59 (2.76–4.60)	23.65 (15.04–35.62)
Genesis	Bats	Fence	0.012 (0.002–0.030)	1.67 (0.11–4.27)
Genesis	Bats	Ponds	0.036 (0.008–0.078)	4.82 (0.13–7.90)
Genesis	Bats	PBlocks	0.002 (0.002–0.006)	2.40 (0.09–4.77)
Genesis	Bats	SCAs	0.052 (0.020–0.092)	0.56 (0.09–3.53)
Genesis	Bats	Project	0.106 (0.032–0.198)	10.92 (0.48–22.98)
Genesis	Birds	Fence	0.39 (0.25–0.56)	5.63 (4.21–7.70)
Genesis	Birds	Gen-tie	1.50 (0.66–2.73)	17.62 (11.26–31.09)
Genesis	Birds	Ponds	0.39 (0.14–0.72)	5.57 (3.98–8.09)
Genesis	Birds	PBlocks	0.21 (0.13–0.29)	4.93 (3.51–7.06)
Genesis	Birds	SCAs	2.41 (1.90–3.10)	12.93 (9.77–17.86)
Genesis	Birds	Project	4.56 (3.44–5.84)	47.83 (33.53–73.59)
Solar One	Birds	Heliostats		26.20 (18.70–58.94)
Solar One	Birds	Tower area		16.24 (9.24–92.42)
Solar One	Birds	Project	9.88–11.44	42.44 (27.94–151.36)
Ivanpah	Birds	Fence	0.19 (0.13–0.28)	0.58 (0.41–0.83)
Ivanpah	Birds	Gen-tie	0.005	0.14 (0.09–0.25)
Ivanpah	Birds	Others		0.82 (0.45–5.23)
Ivanpah	Birds	Heliostats	6.41 (4.66–10.38)	63.91 (40.45–141.33)
Ivanpah	Birds	Tower area	2.69 (1.82–4.46)	10.30 (5.79–52.95)
Ivanpah	Birds	Project		75.74 (47.19–200.59)
Ivanpah	Bats	Tower area		1.79 (0.08–3.70)

[a] Project = all features of the project, Fence = perimeter security fence, Ponds = solar evaporation ponds, Gen-tie = generation lead or transmission lines, MVOH = medium-voltage overhead collector lines, PV = solar photo-voltaic panels; and in solar thermal projects, Heliostats = heliostat mirrors, SCAs = solar collector arrays, Tower area = bare ground between SCAs and the power tower, PBlocks = power blocks, and Others = ancillary structures such as operations and maintenance buildings.

[b] 90% CI at California Valley Solar Ranch (CVSR) and Genesis.

[c] I calculated the value based on the reported estimate in terms of a different metric.

[d] I assumed methods remained unchanged in year 2, but the second-year report was unavailable. Martinson et al. (2018*a*,*b*) reported results only for year 1, whereas I report results for both years 1 and 2.

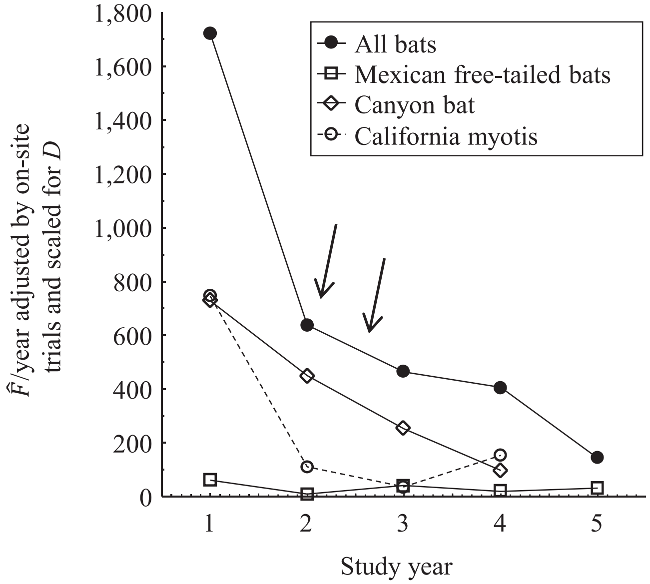

FIGURE 4 Estimates of annual bat fatalities in the tower area of Ivanpah Solar Electric Generating System, San Bernardino County, California, USA, 2013–2018, spanning the cleared ground between the power tower and the mirror arrays and including all bats as a group, Mexican free-tailed bats (*Tadarida brasiliensis*), canyon bats, and California myotis. Arrows point to years following installations of ultrasonic deterrents at power towers, 1 installation after the first year, and 2 more during the second year. Declines in bat mortality preceded installations of deterrents.

Bat mortality was highest at Genesis, followed by Ivanpah and McCoy. At Genesis, the most dangerous project feature to bats was the solar evaporation ponds, followed by power blocks, fences, and SCAs (Table 3). At Ivanpah, bat fatality estimates were possible only in the tower area, where mortality declined over the 5 years of monitoring (Figure 4). Species exhibiting the largest declines were canyon bat and California myotis (*Myotis californicus*). An ultrasonic bat deterrence method was implemented at unit 1 on 10 September 2014, and at units 2 and 3 on 23 April 2015.

California-wide impacts of operative utility-scale solar projects

According to the California Energy Commission, 1,948.8 MW of solar thermal projects operated in California in 2020, and 12,220 MW of PV had been installed by the end of 2019. On average, utility-scale solar energy projects required 3.48 ha/MW for solar thermal and 2.67 ha/MW for PV. Therefore, utility-scale solar thermal projects covered 6,782 ha, and utility-scale solar PV covered 32,627 ha. Projected to California's installed capacity of all utility-scale solar projects in 2020, mean annual fatalities at monitored projects predicted 267,732 (95% CI = 186,071–495,391) bird fatalities and 11,418 (95% CI = 601–23,926) bat fatalities (Table S3). Only 8 studies reported project-wide bird fatality estimates, and only 2 of these reported a confidence interval. Only 2 studies at solar thermal projects reported project-wide bat fatality estimates. Projected to California's installed capacity of all utility-scale solar projects in 2020, originally reported mean annual fatalities would predict 82,471 birds, but original reporting was insufficient for including a 95% confidence interval or for predicting statewide bat fatalities.

At utility-scale solar PV projects, my estimates of $\hat{F}$/MW/year averaged 11.61 (95% CI = 8.37–17.56) birds and 0.06 (95% CI = 0.01–0.10) bats (Table S4, available in Supporting Information). Projected to

California's installed capacity of 12,220 MW of PV in 2019, my fatality rates predicted annual fatalities of 141,811 (95% CI = 102,227–214,593) birds and 716 (95% CI = 124–1,221) bats. At solar thermal projects my estimates of $\hat{F}$/MW/year averaged 64.61 (95% CI = 41.74–149.95) birds and 5.49 (95% CI = 0.25–11.65) bats (Table S4). Projected to California's installed capacity of 1,948.8 MW of solar thermal in 2020, my fatality rates predicted annual fatalities of 125,921 (95% CI = 81,346–292,225) birds and 10,701 (95% CI = 477–22,705) bats.

Along perimeter fences, I estimated $\hat{F}$ /km/year averaged 14.44 (95% CI = 10.88–20.34) birds and 2.56 (95% CI = 0.17–6.54) bats (Table S4). Projected to California's installed 900 km of fencing around solar projects in 2020, these rates predicted annual fatalities of 13,005 (95% CI = 9,802–18,324) birds and 2,304 (95% CI = 156–5,892) bats. I estimated fatalities along fences averaged almost 5% of birds and 20% of bats killed at solar projects.

Along gen-ties, I estimated $\hat{F}$/km/year averaged 113.16 (95% CI = 71.78–198.42) birds and no bats (Table S4). Projected to California's installed 461 km of gen-ties at solar projects in 2020, these rates predicted annual fatalities of 52,162 (95% CI = 33,087–91,463) birds. I estimated fatalities along gen-ties averaged 19% of birds and 0% of bats killed at solar projects.

Projected to the 2019 installed capacity, utility-scale solar PV annually killed more mourning doves (*Zenaida macroura*) than any other species at 17,043, followed by 10,082 horned larks (*Eremophila alpestris*), and 7,628 western meadowlarks (*Sturnella neglecta*), and thousands of other grassland birds (Table S4). The PV panels killed 5,362 American coots (*Fulica americana*), 4,755 soras (*Porzana carolina*) among many other rails, grebes, and waterfowl, and 2,224 burrowing owls (*Athene cunicularia*), 958 American kestrels (*Falco sparverius*), and hundreds of other raptors. They also killed 1,486 common yellowthroats (*Geothlypis trichas*), 1,298 yellow warblers (*Setophaga petechia*), and thousands of additional likely migrants.

Projected to the 2020 installed capacity, utility-scale solar thermal projects annually killed more unidentified small birds than any individual species, at 10,716. Solar thermal killed 8,118 canyon bats and members of ≥8 other bat species (Table S4). It killed likely migrants, including 7,043 yellow-rumped warblers (*Setophaga coronata*), 5,582 yellow warblers, 4,470 Costa's hummingbirds (*Calypte costae*), and thousands of birds of other species. It killed many grassland and desert scrubland birds, including 3,678 white-crowned sparrows (*Zonotrichia leucophrys*), 3,506 American pipits (*Anthus rubescens*), 3,116 western meadowlarks, and 1,498 loggerhead shrikes (*Lanius ludovicianus*).

I estimated that in 2020 fences surrounding solar projects killed 1,783 canyon bats, 1,385 western meadowlarks, 1,174 greater roadrunners (*Geococcyx californianus*), and 476 northern flickers (*Colaptes auratus*; Table S4). Fences also killed an estimated 226 burrowing owls, 172 yellow-headed blackbirds (*Chrysomus icterocephalus*), and 108 northern harriers (*Circus hudsonius*).

I estimated that in 2020 gen-ties of solar projects killed 8,425 Wilson's warblers (*Cardellina pusilla*), 7,144 Brewer's sparrows (*Spizella breweri*), 3,364 common yellowthroats, 2,031 yellow warblers, 899 loggerhead shrikes (*Lanius ludovicianus*), 241 American kestrels, and 195 red-tailed hawks (*Buteo jamaicensis*; Table S4).

Fatalities at operational projects represented ≥8 bat species and ≥192 bird species. Of the 10 species of bats represented by fatalities at solar projects, 3 were California species of special concern. Western Bat Working Group ranked 4 species as high and 2 as moderate conservation priority. Of species of birds represented by fatalities at solar projects, 2 were listed as threatened or endangered under the federal or California Endangered Species Acts. California Fish and Game Code 3503.5 (i.e., birds of prey) protected ≥20 species, and additional statutes protected 8 of these species. Two bird species were California fully protected, and another 36 species were listed as a United States Fish and Wildlife Service bird species of conservation concern or California species of conservation concern, or listed on California's Watch List. Of species listed as California species of special concern, 8 were priority level 3, 9 were priority level 2, and 2 were priority level 1 (2 species were assigned no priority level). Including raptors, 45 special-status species of vertebrate wildlife were documented as fatalities of utility-scaled solar projects, or 23% of all species represented by fatalities.

Additional sources of error and bias

The PV solar projects were searched by foot ($n = 6$) and car ($n = 5$), whereas SCAs at Genesis were searched by car, and power tower projects were searched by foot. Estimated fatalities differed between foot and car searches at PV projects ($t_9 = 2.44$, $P = 0.037$), with respective means of 15.14 $\hat{F}$/MW/year and 5.08 $\hat{F}$/MW/year.

To indicate whether and to what degree wildlife species were represented in fatality monitoring results at solar projects, I fit nonlinear models to the cumulative number of species represented by fatalities with increasing number of months into the study at 5 projects that were monitored more extensively in space and time (Table 4). The monitoring data from Ivanpah served to exemplify not only the asymptotic nature of species representation with monitoring duration, but also the effect of a change in search coverage (Figure 5A). Monitoring effort substantially lessened after 24 months when the monitor terminated fatality searches along the gen-tie and fence and reduced search coverage among heliostat arrays from 24.1% to 8% (0% in the fifth year). Subsequent to the reduced search effort, the increase in number of additional species represented by fatalities was slower than predicted by the pattern in the data through 24 months (Figure 5A). Where fatality monitoring lasted long enough, the pattern in the data revealed how much longer it would have taken at sustained search efforts to achieve asymptotes in species representation by fatalities (Figure 5B). Fatality monitoring at 5 projects was too brief to reveal anything other than a linear increase of species with increasing monitoring duration (Figure 5C). The regression slopes of Blythe and McCoy were nearly identical (Figure 5C). These 2 projects were adjacent to each other, and monitored by the same consulting firm. But even after 2 years of monitoring and documentation of >50 species as fatalities, the pattern of increasing cumulative species represented by fatalities hinted of no imminent arrival to an asymptote. I could not fit a model to the cumulative number of species represented by fatalities with increasing number of months into the study from 4 PV projects. The MW-years sampled among these 4 projects averaged only 11.4% of MW-years at the other 7 PV projects, a significant difference ($F_{1,9} = 22.76$, $P = 0.001$).

Species represented by fatalities were often vulnerable to biased fatality estimates because of misrepresentation. Monitors did not identify nearly 22% of fatalities to species, and identified them instead to coarser levels such as genus, subfamily, small, medium, or large bird, or as unknown bird or bat (Table 5). The coarser the reported level of identification, the more I applied detection probabilities derived from lumped representations of body mass. For example, the degraded carcass of a Pacific-slope flycatcher (*Empidonax difficilis*) found by a weekly

TABLE 4 Best-fit models of cumulative vertebrate species detected as fatalities at California, USA, utility-scale solar projects relative to the number of months since the fatality monitoring began, where model 1 was of the form $Y = a + b \times X$, and model 2 was of the form $Y = \frac{1}{a + b \times c^{\log_{10} X}}$.

		Coefficients				
Project	**Model**	***a***	***b***	***c***	r^2	**RMSE**[a]
California Valley Solar Ranch	2	0.0157	0.4970	0.0490	0.99	51.34
Topaz	2	0.0032	0.2229	0.2548	0.96	266.20
Campo Verde	2	0.0096	0.2435	0.1401	0.97	81.30
Desert Sunlight	1	−2.5714	3.3571		0.96	1.44
Stateline	1	0.8	0.55		0.92	0.67
McCoy	1	3.2029	2.0804		0.96	1.44
Blythe	1	2.0000	2.1700		0.98	1.02
Genesis	2	0.0097	0.2305	0.0017	0.98	311.57
Ivanpah	2	0.0061	0.1762	0.0406	0.99	300.49

[a] RMSE = root mean square error.

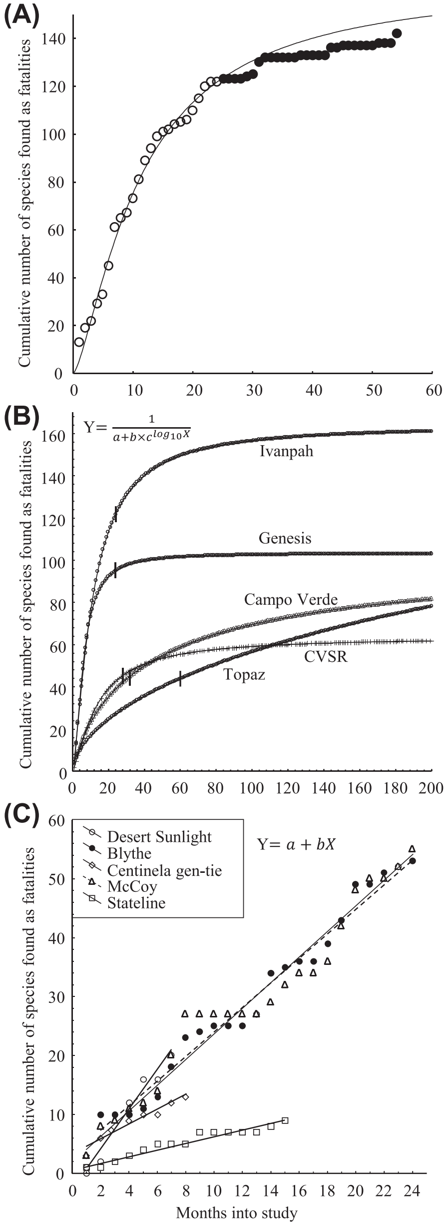

FIGURE 5 Cumulative number of vertebrate species detected as fatalities, California, USA, 2012–2018: A) during the first 2 years of monitoring (open circles) and last 3 years of reduced monitoring effort (filled circles) at the Ivanpah Solar Electric Generating System, San Bernardino County, California, along with best-fit model to the first 2 years of data and projected to the last 3 years of monitoring; B) among solar projects where fatality monitoring lasted long enough to predict an asymptote of species represented by fatalities (vertical bars indicate duration of monitoring used to project the nonlinear pattern in the data); and C) among solar projects where fatality monitoring had not lasted long enough to predict an asymptote, and therefore insufficiently represented species affected. Survey effort largely determined the number of species represented by found fatalities.

TABLE 5 Species of wildlife identified as fatalities among California's utility-scale solar energy projects, USA, 1982–2018, and the percentages of estimated fatalities ($\hat{F}$) that could and could not be identified to species.

Solar project	Number of species represented by fatalities	Percent of $\hat{F}$/MW/year of F	
		Identified	Not identified
California Valley Solar Ranch	43	96.8	3.2
Topaz Solar Farm	17	95.3	4.7
Campo Verde Solar Project	45	81.4	18.6
Centinela Solar Energy Project	24	53.0	47.0
Imperial Solar Energy Center South	4	100.0	0.0
Calipatria Solar Project	13	77.8	22.2
Midway Solar Farm II	4	76.1	23.9
Desert Sunlight Solar Farm	53	83.3	16.7
Stateline Solar Farm	9	100.0	0.0
McCoy Solar Energy Project	49	79.9	20.1
Blythe Solar Power Project	54	82.6	17.4
Genesis Solar Energy Project	97	81.3	18.7
Solar One	25	71.2	28.8
Ivanpah Solar Electric Generating System	147	72.3	27.7
All projects	200	78.3	21.7

search on open ground might have been reported as a small bird. I assigned $D = 0.197$ to small birds, which was the value predicted for house sparrows–the smallest species placed in small-bird detection trials among solar projects. Had the Pacific-slope flycatcher been accurately identified to species, it would have been adjusted by $D = 0.10$, resulting in twice the estimated fatality rate.

The same bias applies to bats. As one of the most often-found bats among solar projects, canyon bats likely contributed most often to bats found and identified as unknown bat. At wind projects, an unknown bat would typically be adjusted using an overall detection probability quantified from the placements of all bats in carcass detection trials. I therefore used the mean from such trials to represent unknown bats with $D = 0.1008$. Overall detection for canyon bat was $D = 0.0485$. Again, had searchers been able to identify canyon bats to species instead of unknown bats, and assuming most of the unknown bats were canyon bats, each of these bats' contribution to bat fatality estimates would have doubled.

At Centinela, 47% of fatalities were not identified to species (Table 5). Other projects where monitors could not identify many fatalities to species included Solar One and Ivanpah at 28.8% and 27.7%, respectively. Projects where all fatalities were identified to species were surveyed briefly by car, including at Imperial where fatalities of only 4 large-sized bird species were found, and at Stateline where fatalities of only 9 species were detected.

DISCUSSION

I largely achieved my study objectives. Original reports of fatality monitoring did not always provide fatality estimates for project features and whole projects, but of those that did, I compared my independent estimates to theirs. From my estimates of project-level fatalities, I estimated statewide fatalities based on the installed capacity of utility-scale solar projects in 2020, and I did so per each project feature. An exception was for medium-voltage overhead lines, which deposited bird carcasses too close to PV solar arrays to discern whether the fatalities were caused by collisions with the overhead lines or the PV solar arrays. I compared fatality rates among species of birds and bats, and among those with special status. I also identified sources of error and bias to alert investigators to research directions needed to improve accuracy of fatality estimation.

To achieve my study objectives, I assumed that the fatality data and carcass detection trial data I obtained from natural resource agencies were accurately reported. I assumed that I accurately interpreted reported study methods and descriptions of solar projects. Data inaccuracies or misinterpretation of methods would have diminished the accuracy of my independent fatality estimates. For biases and large sources of error that I understood from previous research on fatality estimation at wind energy projects, I endeavored to mitigate them by applying adjustment factors. For methods I believed were inappropriate, such as searches for fatalities from cars, I examined the data for evidence of bias and for opportunities to mitigate the effects of bias. I also applied a bridge from my study of the effects of variation in body mass on overall carcass detection probability to account for the disparity I found between carcasses placed in detection trials and those found as fatalities at solar projects. My estimates of fatalities at solar projects were as accurate as I could achieve but undoubtedly inaccurate to some unknown degree. Potential for inaccuracy was greatest for the smallest birds and bats. On the whole, I suspect I more often underestimated rather than overestimated fatality rates. My fatality estimates nevertheless indicate the magnitude of impacts caused by utility-scale solar projects in California, and they can serve as a collective starting point for improving methods to increase accuracy of fatality estimates.

I estimated that by 2020 annual fatalities exceeded a quarter million birds and 11,000 bats at California solar projects. My statewide fatality estimates were based on the available, nonrandom pool of monitored projects, which means they were vulnerable to geographic biases of unknown direction. At the same time, the fatality monitoring performed to date has been prone to substantial biases that largely resulted in underestimation of fatalities. Earlier estimates of regional fatalities were much lower than mine. At PV and solar thermal projects in California, Walston et al. (2016) estimated a weighted mean 9.9 bird fatalities/MW/year, whereas I estimated a weighted mean 18.9 bird fatalities/MW/year. At solar PV projects, Kosciuch et al. (2020) estimated 2.49 bird fatalities/MW/year, whereas I estimated a mean 11.6 bird fatalities/MW/year without adding fatalities caused by perimeter fences and gen-ties. The earlier regional estimates used reported estimates without sufficiently accounting for the effect of body mass on carcass detection probability. They also relied on project-level estimates exclusive of the many species represented by $F < 5$, and because many of these excluded species were small-bodied, under-estimation of $\hat{F}$ had been exacerbated. For these reasons, my fatality estimates were larger, but other biases indicate fatality estimates could be even larger. As examples, the monitors' use of cars for fatality searches and insufficient survey effort both appear to have negatively biased $\hat{F}$. Omitting the 7 fatality monitoring studies that were either based on car surveys or cursory effort, the weighted mean increases 1.25-fold from 11.605 to 14.51 bird fatalities/MW/year among PV projects.

Background mortality (i.e., mortality caused by natural processes) was often suggested as the source of fatalities for which cause of death could not be assigned (Kosciuch et al. 2020), but no reports raised the possibility of crippling bias, the rate of mortally injured animals leaving the search area undetected (Smallwood 2007). Some unknown number of animals mortally injured by exposure to the zone of solar flux, electrocution, or collision likely died, undiscovered, far from study areas. The very background mortality studies discussed by Kosciuch et al. (2020) and reported in (2013) and Althouse and Meade (2012, 2014) likely counted fatalities representative of both crippling bias and background mortality because the background mortality monitoring plots were adjacent to the solar energy projects. These studies could have lessened confounding had they begun monitoring ≥1 year in advance of project construction, and had they located study plots farther from the project to minimize counting of remains of birds that had been displaced by construction and rendered more vulnerable to predation and competition.

Estimates of solar energy's impacts could be more complete by monitoring for fatalities along transmission lines constructed to accommodate the projects. Transmission lines kill many birds, mostly from collisions but also electrocutions. Loss et al. (2014) estimated 29.6 bird collision fatalities/km/year (95% CI = 9.3–66.4) in the United States based on a mix of studies with and without adjustment by ρ. Rioux et al. (2013) estimated 110.4 bird collision fatalities/km/year (95% CI = 43.5–177.2) across Canada after adjusting by ρ. Avian fatality rates along transmission lines have been rarely studied in California. The only study of which I was aware was at Mare Island in Solano County (Hartman et al. 1992). Weighted mean fatality rates along gen-ties servicing solar projects (Table S4) could serve to estimate annual fatality rates along transmission lines that deliver power from solar projects, so long as one knows the length of transmission lines that do so.

Impacts of habitat loss

Estimates of solar energy's impacts could be more complete by also measuring numerical losses of wildlife populations caused by habitat loss. Project sites should be studied prior to construction to estimate densities in breeding and non-breeding seasons, and to measure migratory activity levels, which based on isotopes in feathers collected from dead birds found at solar projects, appears high (Conkling et al. 2020). Wildlife use of the site could be compared before and after project construction and concurrent with studies of wildlife at reference sites.

By 2020 the installed capacity of solar energy projects covered 39,409 ha in California, including 25,453 ha (64.6%) in the Mojave and Sonoran deserts. Construction grading for these projects removed all native vegetation, which continued to be suppressed through project operations. Utility-scale solar projects destroyed habitats of many wildlife species by eliminating breeding sites and forage. No studies were performed to estimate breeding and nonbreeding densities in advance of construction grading at any of the projects I reviewed. No efforts were made to estimate potential reductions in reproductive and numerical capacities of wildlife species.

Estimates of total bird nesting density are available, along with species-specific density estimates, for indicator-level analysis of impacts. Bird nesting densities of 13.27 and 14.19 nest sites/ha were estimated at study sites composed of grassland, wetland, and woodland (Young 1948, Yahner 1982). Assuming 6.94 nest sites/ha, or half the average of Young's (1948) and Yahner's (1982) densities, would more realistically represent California's annual grasslands, this density multiplied against California's 12,414 ha of utility-scale solar in non-desert environments would predict a loss of 86,153 bird nest sites.

Franzeb (1978) provided a basis for applying bird breeding density to areas lost to solar projects in California's deserts. Franzeb (1978) estimated 0.366 breeding birds/ha at a Sonoran Desert site. Projected to 25,453 ha of California's desert environments, this density would estimate 9,316 breeding birds, or 4,658 nest sites, were lost to construction grading for solar projects. Added to the estimate above for non-desert environments, I estimate that California solar projects displaced 90,811 bird nests by 2020. Assuming 25 years of operational impacts, and assuming an average fledging of 2.9 birds/nest/year (Young 1948) and a generation time of 5 years, the lost capacity of breeders and annual chick production would be 7,491,908 birds: {[nests/year × chicks/nest × number of years] + [2 adults/nest × nests/year × (number of years ÷ years/generation)]}. Averaged over 25 years of project operations, this indicator-level approach would estimate an annual loss of 299,676 birds due to habitat destruction to accommodate California's 2020 installed capacity of utility-scale solar.

Burrowing owls, in particular, face significant impacts from habitat loss caused by development of utility-scale solar. Burrowing owls happen to select terrain conditions for breeding and foraging that are also sought by developers of solar projects: flat to gentle southwest- or south-facing slopes. In the 1990s, an estimated 71% of California's entire burrowing owl population resided within the Imperial Valley, after the species had declined throughout the rest of its range in California (DeSante et al. 2007). The average density of breeding attempts was $8.13/\mathrm{km}^2$ (0.081/ha). With 1,488.5 MW of solar PV installed in Imperial County as of 2019, and with an average 2.67 ha/MW, utility-scale solar in Imperial County destroyed 3,974.3 ha of burrowing owl habitat. Assuming the estimate of burrowing owl breeding density from DeSante et al. (2007) still applies, I estimate this level of habitat loss reduced the capacity for breeding attempts by 322 and the number of breeding adults by ≥644. Assuming an average generation time of 8 years and an average 3 chicks produced/breeding attempt, the equation in the preceding paragraph would estimate an annual loss of 1,073 burrowing owls due to habitat loss.

Another form of habitat loss, or habitat degradation, was project-generated wildfires. In June 2019, a bird landed on a power pole at CVSR, sparking a 486-ha fire that removed 84% of the project's generating capacity. The fire reportedly did not damage solar panels, but it likely destroyed many bird nests on the grasslands that were burned next to the project.

Combined impacts to birds from collision mortality and habitat loss

Assuming utility-scale solar projects eliminate breeding habitat within the project footprint, then post-construction collision mortality is largely to migrants or residents of adjacent habitat. If true, then I estimated the installed capacity of utility-scale solar in 2020 removes from California >500,000 birds/year because of combined effects of collision mortality and loss of birds to habitat destruction. Over 25 years of operations of this installed capacity, I estimated California's loss of birds will be >12.5 million. I estimated just over half of this mortality was attributable to habitat destruction (53%), and the rest to operative solar energy projects, but source-specific magnitudes of impacts likely would vary interspecifically.

For burrowing owls in particular, the estimated mean 0.182 collision fatalities/MW/year at solar PV projects applied to 1,488.5 MW of solar PV installed in Imperial County as of 2019 would estimate 271 burrowing owl fatalities/year in Imperial County, where most of California's burrowing owls live. Combined with the estimated impact of habitat loss, I estimate utility-scale solar in Imperial County removed 1,344 burrowing owls annually as of 2020. With an estimated 5,600 burrowing owls in the Imperial Valley in the 1990s, my estimated loss could prove devastating for burrowing owls in Imperial Valley.

Avian mortality at utility-scale solar projects might contribute cumulatively to an ongoing substantial decline of birds in North America (Rosenberg et al. 2019). Bat mortality at solar projects contribute cumulatively to increasingly large nationwide impacts to bats caused by wind turbines (Smallwood 2020). That many of the birds and bats killed at solar projects were special-status species should heighten concern over the ecological and economic impacts of solar energy-caused mortality. A suite of errors and biases suppress understanding of the ecological impacts of solar projects and how to mitigate them.

Additional sources of error and bias in collision fatality estimates

Fatality monitoring efforts not only varied greatly among solar projects, but they introduced biases that resulted in inaccurate fatality estimates. Monitoring that lasted <1 year or covered small portions of a project likely generated incomplete lists of affected species and hence inaccurate fatality estimates. Searches of PV projects by car yielded a third of the fatality estimates of searches of PV projects by foot. No studies performed car surveys simultaneously with pedestrian surveys. Perhaps the most substantial bias was the use of carcasses in detection trials that were larger than many of the birds and bats found as fatalities. I endeavored to offset this latter bias, whereas I identified most others as likely. I also identified additional sources of error and bias that cannot be quantified without further effort on the parts of monitors going forward.

Monitors recorded fatalities of nonvolant wildlife at only 1 project. Either nonvolant animals died only at the 1 project or monitors ignored them at other projects. In another example of potential bias, monitors removed all fatality finds to prevent double counting of fatalities. If this practice altered forage availability and hence scavenger removal rates of carcasses placed in detection trials, then bias was possible. Omissions of fatalities found incidentally to routine searches introduced potential bias when those discoveries occurred on search plots. Also, where monitors searched daily for 5 to 7 consecutive days at beginning of monthly intervals, difficult decisions were necessary over how to treat fatalities found on the first day of each daily search sequence. Another potential bias was the practice of placing feather piles in bird carcass detection trials because doing so increased carcass persistence by offering scavengers inedible body parts that normally would not occur without flesh and bone upon a bird's death.

Monitors could not identify a fifth of all fatalities to species, which means they likely misidentified fatalities such as Allen's hummingbird (*Selasphorus sasin*) and rufous hummingbird (*Selasphorus rufus*). Such errors affect 2 species at once, the species inaccurately assigned the fatality and the species inaccurately denied it. Factors that diminish one's ability to identify fatalities to species include inexperience, insufficient motivation to examine remains carefully enough to identify them, and too much time between fatality searches. As search interval lengthens, more carcasses degrade to the point of becoming less recognizable to species. A related factor is lower detection probabilities of certain search methods. Human searchers miss more carcasses than do scent-detection dogs (Smallwood et al. 2020), and judging from the 3-fold difference in fatality rates between car and pedestrian surveys, searchers in cars likely miss more carcasses than do searchers on foot. Missed carcasses can later be found, but the delay in detection allows carcasses to be scavenged and decay, thereby increasing the likelihood they will not be identified to species. Species identification errors could not be fully quantified without viewing photographic evidence or preserved remains of all fatality finds. Such evidence was not forthcoming in responses to PRA and FOIA requests to state and federal agencies.

Mitigation measures and recommendations

Other than measures implemented to minimize hazards along powerlines, little testing was performed of candidate mitigation measures to minimize or reduce collision fatalities with solar collectors. Nearly all projects implemented mitigation measures to minimize bird collision mortality with gen-ties and medium-voltage overhead lines, and 1 implemented a measure to minimize avian collisions with solar PV panels (Dudek 2018*b*). At CVSR, for example, the gen-tie and medium-voltage overhead lines were fitted with Swan-flight Diverters SFD1520 during fatality monitoring (H. T. Harvey & Associates 2013). An ultrasonic acoustic deterrent was also implemented at Ivanpah's Unit 1 on 10 September 2014 and on 23 April 2015 at both Units 2 and 3 to reduce bat exposure to the zone of solar flux. The deterrent, however, was installed without experimental design elements that would have supported a conclusive hypothesis test of whether the deterrent reduced fatalities. Although bat fatalities declined throughout the study (Figure 4), the largest declines preceded installations of deterrents, which left the possibility that bat numbers were initially depleted by project-caused mortality. Although guidance had been prepared on how to perform experiments to test mitigation efficacy (Sinclair and DeGeorge 2016), none of the mitigation measures were implemented along with sufficient experimental design to convincingly test the measure's efficacy.

Considering the objectives of fatality monitoring and mitigation measures implemented at utility-scale solar projects, and considering what needs to be known of solar energy impacts to wildlife, I recommend the following changes and additions to wildlife studies: 1) perform baseline studies beginning ≥1 year prior to project construction to quantify relative abundance, densities in both breeding and nonbreeding seasons, and behavior patterns of resident and migratory wildlife species; 2) repeat fatality monitoring at projects where it was performed inadequately; 3) either monitor all new utility-scale solar projects for fatalities, or sample projects from the available pool of projects to obtain region-wide fatality estimates; 4) improve scientific access, transparency, and data sharing; 5) introduce peer review as a required standard of report preparation; 6) increase methodological standardization where it is most needed; 7) minimize fatality search intervals or use scent-detection dogs (Paula et al. 2011, Mathews et al. 2013, Smallwood et al. 2020); 8) treat incidental fatality finds just like those found in scheduled searches, so long as they were located on sampling plots; 9) whenever trying a new search method, compare it to the conventional method through concurrent implementation of methods on, minimally, a suitable subsample of the search area; 10) integrate carcass detection trials into routine fatality monitoring, using appropriate species to quantify overall detection probability (Smallwood et al. 2018); 11) quantify and report observer error rates associated with monitoring, such as carcass detection rates and species misidentifications; 12) report species-specific use rates and fatality rates in addition to use rates and fatality rates of all birds and all bats; and 13) implement tenets of experimental design to test hypothesized causal factors and the efficacy of mitigation measures (Sinclair and DeGeorge 2016, Smallwood and Bell 2020*a*).

Based on the impacts I quantified in this review, my first recommendation on performing baseline studies is of high priority. The reports I reviewed were overly focused on collision mortality and paid no attention to impacts of habitat loss. Whereas collision mortality is substantial, more animals are lost to habitat destruction caused by the development of utility-scale solar projects. Resource agencies and permitting authorities need to view the impacts and how to mitigate them more comprehensively. I suggest directing 2 to 3 times more effort into measuring and mitigating habitat impacts than collision impacts. I suggest implementing macro-siting strategies, and I note that I saw amid the data and reports I received via PRA and FOIA requests no evidence of siting to minimize impacts to wildlife. One strategy would be to site projects to avoid migration clusters or locations where rare or declining populations of particular species occur (Ruegg et al. 2020). Another would be to site projects to minimize collision mortality of all birds and bats, and yet another would be to site to minimize loss of breeding sites.

I suggest the formulation of a research fund to assess impacts of habitat loss, explore methodological improvements to more accurately predict and estimate impacts, quantify the effects of causal factors, and test the efficacy of mitigation measures. An example of research that would vastly improve understanding of causal factors of collision mortality would be surveys performed by behavioral ecologists. As in wind energy projects, the most effective means to learn of the circumstances of fatalities is to study animal behavior in the context of the project specific to birds (Hoover and Morrison 2005, Smallwood et al. 2009*a*,*b*; Hull and Muir 2013) and bats (Horn et al. 2008, Cryan et al. 2014). In my experience, careful observation of living animals can determine collision factors more effectively than can collections of dead animals (Smallwood et al. 2017, Smallwood 2017*b*, Smallwood and Bell 2020*a*,*b*). Lastly, I suggest follow-up measures to reduce and compensate for impacts revealed by monitoring.

MANAGEMENT IMPLICATIONS

In light of the magnitudes of solar energy impacts to wildlife, it would be prudent to slow the development of utility-scale solar projects long enough to formulate more accurate impacts assessments and more effective project decision-making, mitigation, and oversight. More than sufficient capacities exist for distributed generation and energy conservation to compensate for the time needed to develop policies and methods for safer development of utility-scale solar energy. Time is needed to develop decision-making frameworks that compare costs and benefits of solar technology, such as solar thermal versus PV, and alternative project locations. Time is needed to improve fatality monitoring and measurement of impacts, including routine implementation of baseline studies. Time is also needed to develop a more transparent oversight process, along with consequences for exceedance of mortality thresholds or for failing to meet standards of baseline studies and fatality monitoring.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data available in article supplementary material and in cited reports. Cited reports of fatality monitoring are also available from the author on request.

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SUPPORTING INFORMATION

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