Conservation Biology

Review

Limitations, lack of standardization, and recommended best practices in studies of renewable energy effects on birds and bats

Tara J. Conkling ,[1]* Scott R. Loss ,[2] Jay E. Diffendorfer ,[3] Adam E. Duerr ,[4,5] and Todd E. Katzner[1]

[1]U.S. Geological Survey, Forest and Rangeland Ecosystem Science Center, 970 S. Lusk Street, Boise, ID 83706, U.S.A.
[2]Department of Natural Resource Ecology & Management, 008C Ag Hall, Oklahoma State University, Stillwater, OK 74078, U.S.A.
[3]U.S. Geological Survey, Geosciences and Environmental Change Science Center, Denver Federal Center, Building 25, Room 1719, MS 980, Denver, CO 80225, U.S.A.
[4]Bloom Research Inc., 3611 Hewes Avenue, Santa Ana, CA 92705, U.S.A.
[5]Division of Forestry and Natural Resources, West Virginia University, PO Box 6125, Morgantown, WV 26506

Abstract: Increasing global energy demand is fostering the development of renewable energy as an alternative to fossil fuels. However, renewable energy facilities may adversely affect wildlife. Facility siting guidelines recommend or require project developers complete pre- and postconstruction wildlife surveys to predict risk and estimate effects of proposed projects. Despite this, there are no published studies that have quantified the types of surveys used or how survey types are standardized within and across facilities. We evaluated 628 peer-reviewed publications, unpublished reports, and citations, and we analyzed data from 525 of these sources (203 facilities: 193 wind and 10 solar) in the United States and Canada to determine the frequency of pre- and postconstruction surveys and whether that frequency changed over time; frequency of studies explicitly designed to allow before-after or impact-control analyses; and what types of survey data were collected during pre- and postconstruction periods and how those data types were standardized across periods and among facilities. Within our data set, postconstruction monitoring for wildlife fatalities and habitat use was a standard practice ($n =$ 446 reports), but preconstruction estimation of baseline wildlife habitat use and mortality was less frequently reported ($n = 84$). Only 22% ($n = 45$) of the 203 facilities provided data from both pre- and postconstruction, and 29% ($n = 59$) had experimental study designs. Of 108 facilities at which habitat-use surveys were conducted, only 3% estimated of detection probability. Thus, the available data generally preclude comparison of biological data across construction periods and among facilities. Use of experimental study designs and following similar field protocols would improve the knowledge of how renewable energy affects wildlife.

Keywords: best practices, experimental design, mortality, renewable energy, sampling bias, solar energy, wildlife monitoring, wind energy

Limitaciones, Falta de Estandarización y las Mejores Prácticas Recomendadas en Estudios de los Efectos de las Energías Renovables sobre las Aves y los Murciélagos

Resumen: La creciente demanda global por energía está fomentando el desarrollo de energías renovables como una alternativa a los combustibles fósiles. Sin embargo, las instalaciones de energías renovables pueden afectar de manera adversa a la fauna. Las pautas para la ubicación de dichas instalaciones recomiendan o requieren que los desarrolladores de los proyectos realicen censos previa y posteriormente a la construcción de las instalaciones para pronosticar el riesgo y estimar los efectos de los proyectos propuestos. A pesar de esto, no existen estudios publicados que hayan cuantificado los tipos de censo usados o cómo los tipos de censo están estandarizados para las instalaciones en específico y en general. Evaluamos 628 publicaciones revisadas por pares, reportes sin publicar y referencias y analizamos los datos de 525 de estas fuentes (203 instalaciones: 193 de energía eólica y 10 de energía solar) en los Estados Unidos y Canadá para determinar la frecuencia de los censos previos y posteriores a la construcción y si dicha frecuencia cambió con el tiempo; para determinar la frecuencia de los estudios diseñados explícitamente

*Address correspondence to T. J Conkling, email tconkling@usgs.gov
Article Impact Statement *Many surveys at wind and solar facilities provide limited information on wildlife use and fatality rates.*
Paper submitted June 11, 2019; revised manuscript accepted December 12, 2019.

Conservation Biology, Volume 00, No. 0, 1–13

DOI: 10.1111/cobi.13457

para permitir los análisis antes-y-después o de control-impacto; y para determinar cuáles tipos de datos fueron recolectados previa y posteriormente a la construcción y cómo aquellos tipos de datos estuvieron estandarizados a través de los periodos y entre las instalaciones. Dentro de nuestro conjunto de datos, el monitoreo posterior a la construcción de las fatalidades faunísticas y el uso de hábitat fue una práctica común ($n = 446$ reportes), pero la estimación previa a la construcción de la línea base del uso de hábitat por la fauna y la mortalidad estuvo reportada con menor frecuencia ($n = 84$). Sólo el 22% ($n = 45$) de las 203 instalaciones proporcionaron datos de los censos previos y posteriores a la construcción y el 29% ($n = 59$) contó con diseño de estudios experimentales. De las 108 instalaciones en las que se realizaron censos de uso de hábitat, sólo el 3% incluyó la estimación de la probabilidad de detección. Por lo tanto, los datos disponibles generalmente impiden la comparación de los datos biológicos durante los periodos de construcción y entre las instalaciones. El uso del diseño de estudios experimentales y el seguimiento de protocolos de campo similares mejoraría el conocimiento sobre cómo las energías renovables afectan a la fauna.

Palabras Clave: energía eólica, energía renovable, energía solar, diseño experimental, mejores prácticas, monitoreo de fauna, mortalidad, sesgo de muestreo

摘要: 不断增长的全球能源需求正在促进可再生能源作为化石燃料的替代能源的发展。然而, 可再生能源设施可能对野生动物产生不利影响。设施选址指南通常建议或要求项目开发者对施工前后的野生动物进行调查, 以预测风险并估计拟建项目的影响。尽管如此, 目前还没有已发表研究对野生动物调查类型的选择和设施内部、设施之间如何确定标准化调查类型做过定量分析。本研究评估了 628 篇同行评审文献、未发表报告及引文, 并分析了其中美国和加拿大的 525 篇文献或报告的数据 (涉及 203 个设施, 包含 193 个风能和 10 个太阳能设施), 以确定施工前后调查的频率及其随时间的变化;明确设计进行施工前后或影响控制分析的研究的频率;施工前后收集的调查数据类型, 以及这些数据类型在不同时期和不同设施之间的标准化方法。在本研究的数据集中, 设施建设后的野生动物死亡率和栖息地利用的监测是常规标准做法 (446 份报告), 而在建设前对野生动物死亡率及栖息地利用的基线水平的评估较少 (84 份)。 203 个设施中只有 22% (45 个)同时提供了施工前和施工后的数据, 有 29% (59 个) 提供了实验研究设计。在进行了栖息地利用调查的 108 个设施中, 只有 3% 包含了动物发现概率的估计。因此, 现有数据普遍不能在不同建设时期和不同设施之间进行生物学数据的比较。我们建议使用实验研究设计并遵循类似的野外研究方法, 以提高对可再生能源影响野生动物的认识。【**翻译: 胡怡思; 审校: 聂永刚**】

关键词: 最佳实践, 实验设计, 死亡率, 可再生能源, 采样偏差, 太阳能, 风能, 野生动物监测

Introduction

Rapid development of renewable energy sources has occurred worldwide due to growing interest in mitigating effects of climate change while meeting global energy needs (Dincer 2000; Hoffert et al. 2002; Katzner et al. 2016*a*). Solar and wind energy are the most rapidly growing renewable energy sectors and now constitute >139 GW of total installed generating capacity in the United States (45.4 GW solar and 97.22 GW wind) (National Renewable Energy Laboratory 2017*b*; American Wind Energy Association 2019) and Canada (22.3MW solar and 11.9 GW wind) (Poissant et al. 2016; Canadian Wind Energy Association 2017). Like many other power production plants, renewable energy facilities can have adverse effects on wildlife. At wind facilities, birds and bats collide with wind turbine rotor blades, and at solar facilities, birds collide with panels and are singed at light concentration towers (e.g., Loss et al. 2013; Kagan et al. 2014; ICF International 2016). Additionally, wind and solar energy development may indirectly affect wildlife through habitat loss and fragmentation and by altering foraging, breeding, and migratory behaviors (Drewitt & Langston 2006; Arnett et al. 2007; Cryan et al. 2014; Millon et al. 2015).

Because of these effects on wildlife, state, provincial, and federal, natural resource agencies often recommend or require wildlife risk assessments be conducted prior to the construction of a facility (California Energy Commission & California Department of Fish and Game 2007; U.S. Fish and Wildlife Service 2012, 2013; Katzner et al. 2016*a*). Risk assessment involves, for example, bird point count and nest surveys, bat acoustic surveys, or other site-specific approaches to quantify the presence and activity of species potentially exposed to the proposed energy facility. Guidelines also recommend specific impact-assessment protocols, typically carcass searches to estimate the number of birds or bats killed, be conducted during construction and operation of an energy facility (U.S. Fish and Wildlife Service 2012; Huso et al. 2016*a*; Huso et al. 2016*b*).

Beyond impact assessment, using survey data to inform siting of energy facilities is one of the most common strategies to avoid and minimize the risk to wildlife populations from this activity. Efforts to inform siting have led to several overarching questions of substantial interest to the energy industry, policy makers, and conservation professionals, such as how can negative effects to wildlife species of concern be avoided, how can existing survey data be used to inform siting of renewable energy facilities, are the right data being collected to inform siting, and how do modifications of facility designs alter wildlife behavior, space use, site avoidance, and, ultimately, risk?

Although monitoring to date is only sometimes designed to answer questions such as these, agencies and scientists often want to use monitoring data for this purpose. Rigorous preconstruction risk assessments, and postconstruction fatality monitoring and wildlife-use data could answer these questions and improve siting decisions. However, circumstantial evidence suggests that there is room for improvement in study design and rigor. For example, data collected in pre- and postconstruction surveys are often not directly comparable (e.g., preconstruction wildlife activity or habitat-use surveys vs. postconstruction carcass counts). Further limiting comparisons between data sets, wildlife surveys may be taxon or species specific (e.g., bat acoustic surveys and Golden Eagle [*Aquila chrysaetos*] nest surveys), and each survey type may monitor different variables, such as abundance (e.g., point counts and migration surveys), habitat use (e.g., behavioral observations), and reproductive behavior (e.g., nest surveys). Additionally, carcass counts may incorporate different sampling strategies or fatality estimators to determine total fatalities at a facility (Huso et al. 2016*a*). This wide variety of survey approaches makes it difficult to empirically assess total numbers of animals killed or cumulative impacts across multiple facilities (Loss et al. 2013) and to generate accurate fatality predictions at or across facilities (e.g., U.S. Fish and Wildlife Service 2012; Argonne National Laboratory & National Renewable Energy Laboratory 2015*b*; Huso et al. 2016*a*).

Despite frequent calls for an increase in rigor of data collection and study design at renewable energy facilities (e.g., Kunz et al. 2007*a*; Kunz et al. 2007*b*; Strickland et al. 2011), the degree to which these practices are implemented is unclear, largely because there have been no formal quantitative analyses of the study designs and survey methods employed. We conducted the first such empirical synthesis to determine how the field has progressed in incorporating these practices. We reviewed and quantified the extent to which wildlife fatality and use surveys are standardized across pre- and postconstruction periods and among different energy facilities. We focused on 3 key questions that have, to our knowledge, not been assessed: how frequently were both pre- and postconstruction surveys implemented and has that frequency changed over time, how frequently were studies explicitly designed to allow before-after or impact-control analyses, and what types of survey data are collected during pre- and postconstruction periods and how are those data types standardized across periods and among facilities? Based on our analyses, we devised best practice suggestions for pre- and postconstruction wildlife surveys to increase the utility of future surveys for predicting risk and estimating impacts at individual energy facilities and, thus, for assessing broader-scale impacts on wildlife populations.

Methods

Literature Search

We used online search engines and publicly available document collections to locate peer-reviewed literature and unpublished reports (hereafter referred to as reports) containing pre- or postconstruction wildlife survey data from proposed and operating wind and solar facilities in the continental United States and Canada. We restricted our scope to surveys on birds and bats. In Google Scholar and Web of Science, we used the keywords "*wind turbine,*" *wind*, *solar*, *mortality*, *fatality*, "*wildlife use*," and "*carcass search*" and the names of renewable energy facilities. We compiled as many reports as we could from the period spanning the first installation of wind turbines in North America in the early 1980s through December 2017 from national public databases and, because of funding priorities and the long history of renewable energy there, California-specific public databases (American Wind Wildlife Institute 2017; California Energy Comission 2017; National Renewable Energy Laboratory 2017*a*; Pacific Northwest National Laboratory 2017). We also solicited reports from federal, state, and California county agencies, and we accessed data summarized in previous reviews of renewable energy effects on birds (Loss et al. 2013) and bats (Thompson et al. 2017). We obtained previously compiled and publicly available reports for facilities in California and Nevada, from the U.S. Fish and Wildlife Service (H. Beeler, personal communication), and Alberta, New Brunswick, and Ontario. We also used Google to search for and locate additional reports that were not in other document collections or indexed in scientific literature databases. Finally, we checked published bibliographies (Johnson & Arnett 2004; Argonne National Laboratory & National Renewable Energy Laboratory 2015*a*) and reference lists in our compilation to find other reports.

Most of our data were from facilities on public lands. Regulatory agencies generally have limited monitoring or reporting oversight for privately owned facilities on private land unless they are specifically outlined in state regulations, federal guidelines, or power-purchase agreements. As a result, to the extent they were collected, data from many facilities on private property or developed by private companies were not publicly accessible and thus mostly not included in our data set. These limitations on data availability restricted which samples were available to us and thus may affect the interpretation of results.

Data Organization

We extracted from each document the energy source (wind or solar) and technology type (e.g., turbine models) used at each facility, dates wildlife surveys were conducted (including year), the facility construction period or periods studied (pre- vs. postconstruction), and whether the study used an experimental study design either with reference sites or with a before-and-after construction analyses. We also recorded the type of survey data collected (e.g., fatality [carcass] or wildlife-use surveys) and information about the survey techniques (e.g., search frequency and survey area), including whether studies contained trials to estimate and correct for biases associated with using raw carcass counts (e.g., searcher detection efficiency and carcass removal, proportion of area searched) or ignoring detection probability of live animals in wildlife-use surveys. We recorded the initial operation year for each facility based on reports or publicly available records.

For some facilities, multiple reports provided information on overlapping periods. For example, in some cases, we had monthly and annual summary reports for the same year. To avoid double-sampling in these cases, we excluded the reports covering the shorter period. We also excluded from our analyses preconstruction reports for proposed facilities that were never completed due to the presence of species of conservation concern, lack of permit approval, or shifts in developer funding priorities. Other reports we did not include were for facilities currently under construction or that were so recently completed that postconstruction data had not yet been compiled and publicly reported. Finally, we excluded reports if we were unable to determine which facilities were studied.

We recorded citation data or summary information for 108 reports that we were unable to locate or obtain (hereafter citation-only records and summary documents, respectively). For these reports, whenever possible, we extracted from the title or summary information the construction period, facility name, and survey dates and used these data in our analyses. For example, we included citation-only records when summarizing the number of studies from each facility type and for which wildlife monitoring occurred, but not for analyses that required actual monitoring results.

We assigned each report to the facility concerned and used facility as our unit of replication. Some large facilities had a series of construction periods or multiple operators (e.g., Altamont Pass Wind Resource Area [ICF International 2016]). However, we could not always determine whether data from these within-facility units were statistically independent. Thus, by grouping at the facility level, we were conservative with regard to differences across facilities. In fact, differences among facilities may have appeared larger if we had been able to consider data from these subunits independently.

Data Analyses

To determine how frequently pre- and postconstruction surveys were implemented and whether frequency changed over time, we summarized report data by facility, construction periods monitored, and year of initial operation. We also calculated Fisher's exact test values and pairwise comparisons with adjusted p values ($\alpha = 0.05$) with packages vcd and RVAideMemoire in R 3.4.0 (Meyer et al. 2016; R Core Team 2017; Hervé 2019) to assess whether the construction periods monitored at a facility varied by initial operation year (i.e., whether data existed for only one [pre- or postconstruction] or both periods). Analyses were conducted separately for wind and solar facilities, but in the case of wind facilities, we grouped data into 5-year intervals (e.g., 2006–2010 and 2011–2015) to reduce the size of our contingency table and increase sample sizes for all groups.

To determine how frequently studies were explicitly designed to allow before-after or control-impact analyses, we identified facilities that had both pre- and postconstruction monitoring data, and those that incorporated undeveloped reference sites as controls. We used the same Fisher's exact test analyses as above to determine whether incorporation of experimental design varied by initial operation year. Again, analyses were conducted separately for wind and solar facilities.

To determine what types of survey data were collected and how are those data types were standardized across periods and among facilities, we calculated summary statistics describing use of survey methods in each construction period and among facilities. We categorized survey types as carcass searches, breeding-site surveys (e.g., searches for nests or bat maternal colonies), taxon-or status-specific surveys, and quantification of local populations. We analyzed each survey category separately with a Fisher's exact test to determine whether the frequency with which one (pre- or postconstruction) or both periods were monitored varied by initial operation year. Finally, we quantified the number of facilities incorporating detection probabilities in fatality surveys (e.g., searcher efficiency and carcass persistence trials) and habitat-use surveys (e.g., mark recapture and distance sampling).

Results

Frequency of Pre- and Postconstruction Surveys and Evolution of Survey Methods

We compiled information in 628 reports and citations from 231 facilities in 33 states and provinces (Fig. 1). We excluded 103 that were duplicates, contained no data, or were from facilities that were incomplete or not constructed (Fig. 2). The majority of reports were for wind facilities ($n = 470$ reports, 90%), from the postconstruction period ($n = 446$, 85%), and for both birds and bats ($n = 420$, 80%) (Fig. 3). Only 22% of facilities (4 solar and 41 wind) had data on fatalities or wildlife use for >1 project period (Table 1). The proportion of facilities with data from single or multiple construction periods

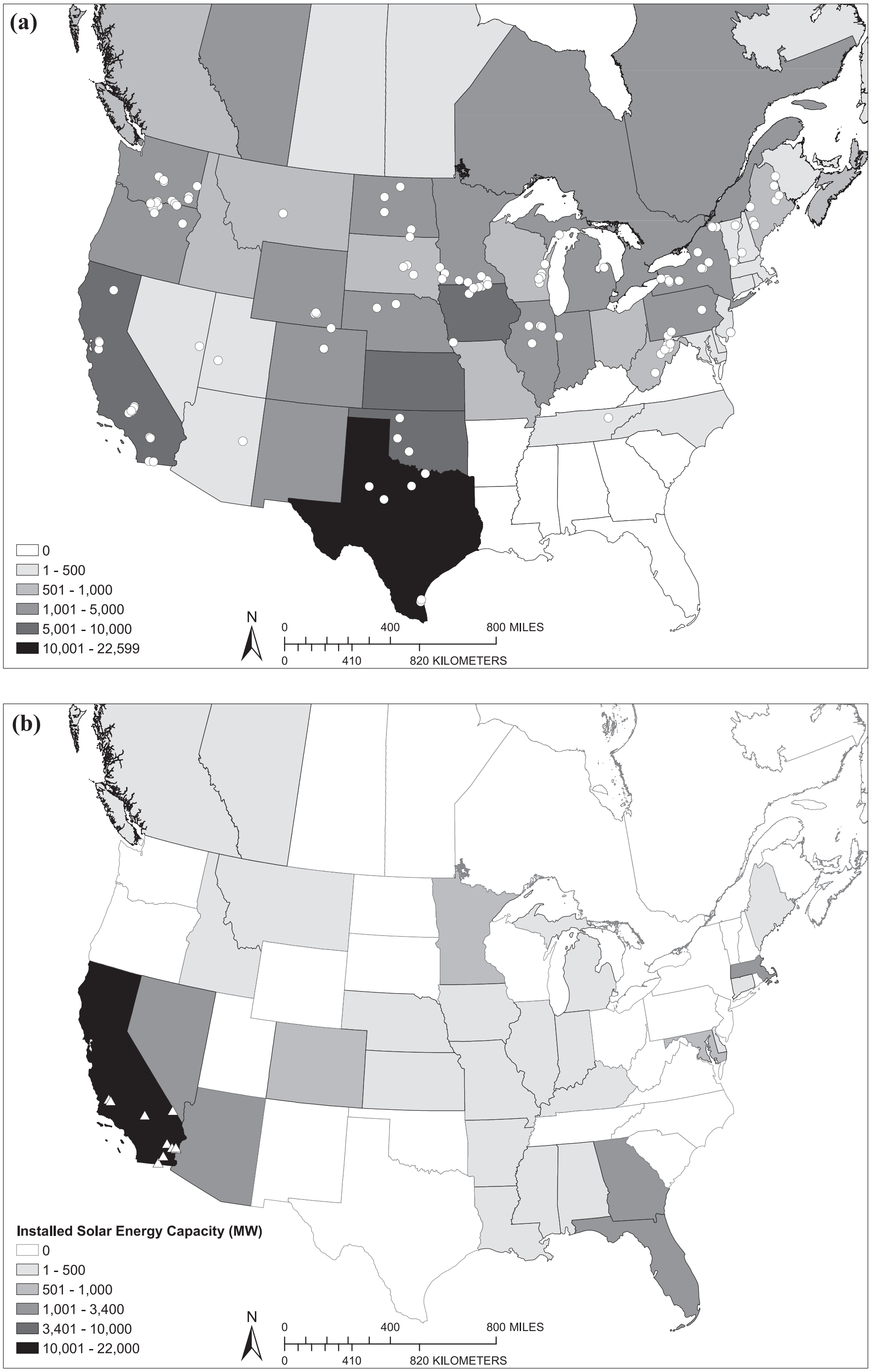

Figure 1. Location of (a) wind and (b) solar energy facilities used in an evaluation of wildlife surveys at such facilities. All solar facilities used in this study were located in California. Also shown is the total energy capacity for both sectors in each state or province as of 2017.

(Fig. 4) did not vary by initial year of facility operation for either wind ($p = 0.55$) or solar energy ($p = 0.49$).

Frequency of Experimental Design in Surveys

Reports from only 29% of facilities ($n = 59$) incorporated some element of experimental survey design. These included before-after ($n = 42$), control-impact ($n = 8$), or a traditional before-after control-impact (BACI) design ($n = 8$). One additional facility used both a before-after and a control-impact design, but not in a traditional combined BACI framework. However, the proportion of facilities including experimental design elements did not vary by initial operation year, for either solar ($p = 0.80$)

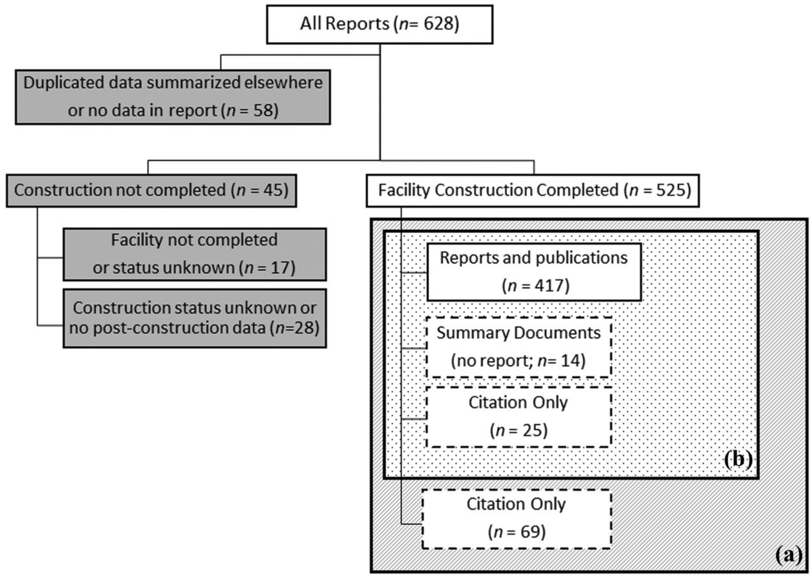

Figure 2. Number of reports evaluated that described pre- and postconstruction monitoring of wildlife at renewable energy facilities (dark gray, report categories not included in analyses; white, report categories included in analyses). Figure also shows which reports addressed our research objectives to (a) determine frequency of pre- and postconstruction surveys and whether frequency changed over time and frequency of studies designed explicitly to allow before-after or control-impact analyses and (b) determine the types of survey data collected and how data types were standardized across periods and among facilities.

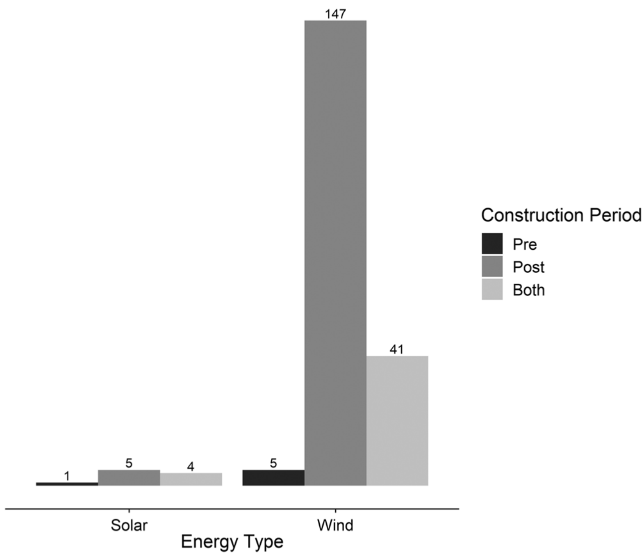

Figure 3. Number of renewable energy facilities in the contiguous United States and Canada (1981–2016) from which we were able to gather monitoring reports on surveys conducted preconstruction, postconstruction, or during both periods. Data are sorted by renewable energy type.

or wind ($p = 0.03$, all pairwise comparisons adjusted $p \geq 0.23$).

Types of Survey Data and Data Standardization

After removing 69 citation-only records that did not contain information about survey methods, our reduced data set contained 456 reports (173 facilities: 163 wind and 10 solar) (Fig. 2). Systematic and incidental fatality surveys ($n = 356$ reports) were conducted almost exclusively (99%) during postconstruction periods. Conversely, use surveys were common during both pre- and postconstruction periods.

Twenty-one survey types were used to quantify habitat use at facilities (Supporting Information). These included point counts ($n = 146$ total reports, 60% of 77 preconstruction reports, 26% of 372 postconstruction reports, 3 reports had both pre- and postconstruction data, and 1 report had data collected during construction), behavioral observations ($n = 39$ total, 12% of preconstruction reports and 8% of postconstruction reports), nest searches ($n = 77$, 36% of preconstruction reports and 13% of postconstruction reports), and acoustic surveys ($n = 54$ total, 18% of preconstruction reports and 10% of postconstruction reports).

Of the 163 wind facilities for which we obtained data on wildlife-use surveys, 25% had data from >1 project period, and 59% of those, which translated into 15% of all facilities, used the same survey approaches during both pre- and postconstruction periods (Tables 1 and 2). At those 24 facilities, where the same survey was used pre- and postconstruction, 79% ($n = 19$) incorporated elements of experimental study design. Of the 10 solar facilities for which we obtained data on wildlife surveys, none included the same data-collection approach for pre- and postconstruction surveys. The type of wildlife-use survey implemented in each construction period (Supporting Information) was not affected by the facility's initial operation year for either wind (breeding site: $p = 0.30$; population counts: $p = 0.88$; and taxon or species-specific: $p = 0.54$) or solar (breeding site: $p = 1.0$; and taxon or species-specific: $p = 1.0$).

Of the 163 wind and solar facilities with information about fatality survey methods, 96% ($n = 156$, 6 solar and 150 wind) incorporated searcher efficiency and carcass persistence data when conducting fatality surveys to account for imperfect detection of carcasses by observers.

Table 1. Total number of reports used for analyses of the frequency with which monitoring at renewable energy facilities in Canada and the United States (1981–2016) occurred during different construction periods (i.e., preconstruction, postconstruction, or both), the names of the renewable energy facilities, the state or province in which the facility is located, the construction period or periods in which fatality or wildlife-use monitoring occurred, and whether or not that facility utilized the same survey method during both monitoring periods.

			Construction period			
Type	*Facility name*	*State or province*	*pre*	*post*	*both*	*Same survey method*
Solar	Blythe (Mesa)	CA	6	1	0	no
	California Valley Solar Ranch	CA	1	3	0	no
	Campo Verde	CA	1	2	0	no
	Genesis Solar	CA	3	3	0	no
Wind	Dry Lake	AZ	2	2	0	yes
	Alta	CA	3	13	0	yes
	Hatchet Ridge	CA	1	2	0	no
	High Winds	CA	0	2	1	yes
	Manzana Wind	CA	2	8	0	yes
	Montezuma Hills	CA	4	0	1	yes
	North Sky River	CA	1	4	0	no
	Ocotillo	CA	3	1	0	yes
	Pine Tree	CA	1	2	0	no
	Rising Tree	CA	1	1	0	yes
	Shiloh	CA	2	9	0	yes
	Tehachapi	CA	1	3	0	no
	Mars Hill	ME	2	2	0	no
	Record Hill	ME	2	1	0	yes
	Big Blue	MN	1	3	0	yes
	Buffalo Ridge	MN	1	17	0	yes
	Judith Gap	MT	1	2	0	yes
	Lempster Mountain	NH	0	2	1	yes
	Spring Valley	NV	2	3	0	yes
	Maple Ridge	NY	1	6	0	yes
	Munnsville	NY	1	1	0	yes
	Biglow Canyon	OR	1	7	0	no
	Eurus Combine Hills Turbine Ranch	OR	2	2	0	yes
	Klondike	OR	2	5	0	yes
	Leaning Juniper	OR	1	2	0	no
	Casselman	PA	1	4	0	no
	Titan I	SD	1	1	0	no
	Wessington Springs	SD	1	2	0	yes
	Searsburg	VT	4	2	0	yes
	Hopkins Ridge	WA	1	2	0	no
	Kittitas Valley	WA	1	1	0	no
	Lower Snake River	WA	2	1	0	no
	Wild Horse Wind Facility	WA	2	2	0	no
	Blue Sky Green Field	WI	2	2	0	no
	Forward Energy Center	WI	0	1	1	yes
	Beech Ridge	WV	1	3	0	yes
	Laurel Mountain	WV	1	3	0	no
	Mount Storm	WV	4	9	0	no
	Foote Creek Rim	WY	1	1	0	no
	Arthur	Ontario	0	2	1	yes
	Wolfe Island Ecopower Centre	Ontario	2	7	0	yes
	Total		73	152	5	24

In contrast, 3% (1 wind and 2 solar) of the 108 facilities that monitored avian habitat use incorporated some measure of detection probability into modeled estimates.

Discussion

Ours is the first analysis to quantitatively illustrate how wildlife risk and impact surveys are conducted at renewable energy facilities. Despite frequent calls for improved rigor of data collection and study design in this field of conservation research (e.g., Kunz et al. 2007*a*; Strickland et al. 2011; Huso et al. 2016*a*;), we found this rigor was only sometimes applied and that pre- and postconstruction surveys were rarely comparable, regardless of the level of rigor. We also documented that study design components, such as control-impact or

Table 2. Wind energy facilities with documented implementation of both pre- and postconstruction surveys and with the same survey method used during both monitoring periods, survey method used, and whether surveys incorporated experimental study designs.

Location	*State or province*	*Area search*	*Acoustic (bats)*	*Behavior observation*	*Migration*	*Mist net*	*Nest searches*	*Nocturnal radar*	*Point count*	*Prey*	*Sensitive species*	*Water fowl*	*Experimental design*
Dry Lake	AZ		X										yes
Alta	CA						X						no
High Winds	CA						X		X	X			yes
Manzana Wind	CA			X									yes
Montezuma Hills	CA			X			X						no
Ocotillo Wind	CA										X		no
Rising Tree Wind	CA						X						no
Shiloh	CA			X			X						yes
Record Hill	ME		X		X								yes
Big Blue Wind Farm	MN		X				X		X				no
Buffalo Ridge	MN		X						X				yes
Judith Gap	MT								X				yes
Lempster Mountain	NH		X		X				X				yes
Spring Valley	NV		X	X			X		X				yes
Maple Ridge	NY							X					yes
Munnsville	NY								X				yes
Eurus Combine Hills													
Turbine Ranch	OR						X		X		X		yes
Klondike	OR						X		X				yes
Wessington Springs	SD								X				yes
Searsburg	VT				X				X				yes
Forward Energy Center	WI			X									yes
Beech Ridge	WV					X							yes
Arthur	Ontario	X			X				X			X	yes
Wolfe Island Ecopower Centre	Ontario			X					X				yes

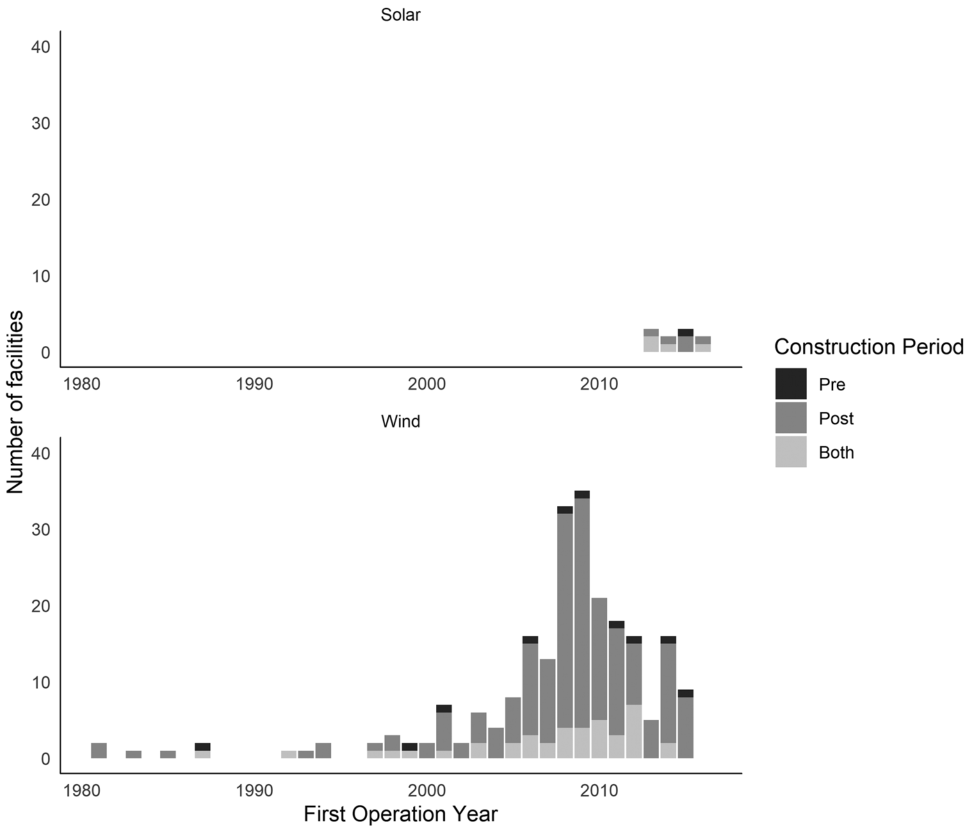

Figure 4. Construction period when wildlife monitoring was conducted at 203 renewable energy facilities in the contiguous United States and Canada for which reports were collected. Data are sorted by year during from 1981 to 2016.

before-after designs, were rarely used at renewable energy facilities.

Although risk assessments are often tailored to specific facilities and species thought to be affected, the data and design concerns we found limit prediction and management of impacts at new energy facilities and estimation of broad-scale, cumulative, and population-level impacts to wildlife. Continued expansion and implementation of more rigorous approaches to study designs within existing monitoring frameworks may lead to additional conservation and research benefits by assuring that funding to study renewable energy impacts not only contributes to meeting facility-specific objectives (e.g., informing turbine siting and estimation of facility-specific collision fatality rates) but also improves the understanding of the cumulative impacts of renewables on specific wildlife populations (e.g., Nichols & Williams 2006; Piorkowski et al. 2012; Sells et al. 2018).

Frequency of Pre- and Postconstruction Surveys and Experimental Design Elements

Postconstruction monitoring for wildlife fatalities was a common component of reports in our data set. However, only one-fifth of reports suggested that data collection of any survey type occurred during both pre- and postconstruction periods. Furthermore, as regulatory agencies have, with time, developed new permitting requirements and monitoring guidelines (California Energy Commission & California Department of Fish and Game 2007; U.S. Fish and Wildlife Service 2012), our results suggest that the frequency of data collection during both periods has not similarly increased. Surveys in both of these periods, or those incorporating reference sites, are important because preconstruction or reference-site data provide context for interpreting postconstruction data (Katzner et al. 2016*a*). This is because species-specific abundance or activity patterns may have shifted following facility construction or an unknown proportion of fatalities in postconstruction surveys may be due to other causes (i.e., background mortality). Without this context, postconstruction surveys may provide a quantitative estimate of wildlife fatalities, but little insight into the biological significance of an energy facility for local or regional wildlife populations (Katzner et al. 2016*a*).

Even in infrequent instances where data were collected during both pre- and postconstruction periods, elements of scientific rigor or experimental design were only sometimes incorporated. The majority of studies appeared designed to meet requirements or guidelines of federal (e.g., USFWS 2012) or state environmental impact statements or reviews (EIS or EIR), which rarely encourage or mandate specific research questions or experimental approaches, despite other monitoring frameworks recommending such procedures (Kunz et al. 2007*a*; Strickland et al. 2011). As such, data collection may be deliberately structured to gather different types of pre- and postconstruction data. This lack of specificity may also occur because BACI studies or other rigorous experimental designs are not always possible due to logistical and financial constraints limiting data collection across multiple seasons or at reference sites (Anderson et al. 1999; Strickland et al. 2011). However, the lack of a rigorous study design may limit the local and general utility of these data (Nichols & Williams 2006; Field et al. 2007; Sells et al. 2018).

Degree of Data Standardization

Of the small number of facilities with both pre- and postconstruction data collection, only half had the same biological information collected in both periods (Table 2). Most of these were the facilities that incorporated elements of experimental study design. A large number of protocols provide guidance on standardized data collection and analyses for postconstruction fatality surveys (e.g., Anderson et al. 1999; Kunz et al. 2007*a*; Huso et al. 2016*a*). However, there are fewer guidelines for preconstruction use surveys (Strickland et al. 2011; Katzner et al. 2016*a*).

Guidance for both pre- and postconstruction studies is important because the rigor of the study design influences the accuracy of fatality predictions (Kuvlesky Jr. et al. 2007; Marques et al. 2014; Schuster et al. 2015). For example, mismatched spatial scales of pre- and postconstruction surveys likely contributed to a poor correlation between predicted risk and recorded fatality of raptors at wind farms in Spain (Ferrer et al. 2012). Similarly, abundance of individuals at a site does not necessarily correlate with collision risk that is driven by biological factors, such as taxonomy or behavior (Hull et al. 2013). We found spatial and temporal mismatches that likely reduced the utility of data for comparing and predicting risk and estimating impacts. For example, preconstruction point counts often were conducted at the broad scale of entire facilities, whereas fatality surveys often focused on local-scale within-facility processes. Likewise, avian abundance surveys were conducted less frequently during migration periods than during breeding or wintering seasons.

Guidance on survey approaches could encourage the use of methods to estimate detection probabilities of live animals. Because detection rates are never 100%, count data should be corrected by detection probability (e.g., p or $\hat{g}$) to account for animals present but undetected. Distance sampling (e.g., Buckland et al. 2001; White 2005; Sollmann et al. 2016), N-mixture models (e.g., Royle 2004; Kéry et al. 2005; Sillett et al. 2012), and an array of other analytical approaches allow estimation of, and adjustment for, detection probabilities to estimate the abundance of both living animals (e.g., point counts) and carcasses. Such approaches have become the norm in peer-reviewed studies of animal distribution and abundance. However, in our review, detection probability was almost universally applied for fatality surveys, yet almost never estimated for wildlife-use surveys.

Fatality estimates have been combined across facilities to explore factors affecting fatality rates for birds and bats. Similar analyses could be done for the abundance of terrestrial species if data were available. However, combining wildlife abundance data across facilities is difficult because detection probabilities were almost never estimated in abundance and use studies and because of substantial among-study variation in both pre- and postconstruction survey approaches. In many cases, data were likely collected with the appropriate sampling intensity and protocols to minimize bias while estimating parameters of interest (Morrison et al. 2008). Little change to existing sampling designs would, therefore, be required to generate estimates of detection probability. Inclusion of raw survey data (e.g., in appendices or online supplements or with links to online data repositories) would allow researchers to generate detection-corrected abundance or use estimates and to link them to fatality data to better elucidate the relationship between predicted and actual impacts from energy facilities.

Increasing Data Quality and Availability

Adding rigor to wildlife-use and impact surveys at renewable energy facilities would enhance the understanding of changes in local mortality, prediction of collision risk, quantification of effects of future energy facilities, and monitoring of mitigation effectiveness (Anderson et al. 1999; Kunz et al. 2007*a*; Ferrer et al. 2012; Huso et al. 2016*a*). Further, if survey monitoring, analytical approaches, and questions addressed were synchronized across facilities, large-scale analyses could be conducted to assess the effects of renewable energy on wildlife populations. Although we acknowledge the challenges of shifting the prevailing monitoring paradigm, increasing scientific rigor may also be cost-effective over the long term for the burgeoning renewable energy industry. This is because improved facility siting, wildlife management, and energy planning and development may have long-term ramifications on ecosystems and wildlife populations (e.g., Katzner et al. 2016*b*; Frick et al. 2017; Katzner et al. 2019). Building scientifically rigorous databases (Romesburg 1981; Reynolds et al. 2011; Sells et al. 2018) on wildlife use and impacts in relation to energy facilities would streamline future development and perhaps reduce the need for future costly research at each energy facility by providing a more comprehensive understanding of the likely impacts of individual proposed facilities and broader energy planning strategies.

The availability of survey data likely influenced our results and constraints on that availability probably occurred due to several factors. First, reporting requirements and report accessibility vary among countries, states, and counties, resulting in geographically variable data availability relative to installed energy capacity (Fig. 1). Second, regulatory agencies often have limited monitoring capabilities or oversight for facilities that are privately owned or on private land. Third, data from one or both construction phases are sometimes not made available due to concerns that they could be used in lawsuits against developers or operators (Dinnell & Russ 2006; Subramanian 2012). Fourth, time lags between data collection and report publication likely contribute to older data being more available than newer data. Fifth, reports may be available in hard copy only and not online or on private computers or intranets not visible to search engines.

Due to these factors, some regions and recent periods were likely undersampled, as were facilities that are privately owned or on private property. For example, a small number of solar facilities on public property in California are regulated by the California Energy Commission (CEC), which requires reports be published on the CEC website at quarterly or annual intervals (California Energy Commission 2010). In contrast, no state agency regulates or archives reports for California wind facilities, thus proportionately fewer reports are available for the large number of wind facilities in the state. Similarly, fewer reports were available in states with a greater proportion of private land. For example, Texas (97% privately owned) has the largest installed wind capacity in the United States (>22,600 MW), but our data set included reports from only 4% ($n = 6$) of the 136 active wind projects in the state (American Wind Energy Association 2018). These limitations on data availability reduced our samples sizes, which may have influenced statistical significance and interpretation of our test results.

A mechanism to address this data availability issue may be through voluntary submission of monitoring records to a central repository. The U.S. Federal Aviation Administration has such a system (National Wildlife Strike Database) that has tracked wildlife-aircraft incidents across the United States since 1990 (Dolbeer et al. 2016; FAA 2017). These data provide opportunities for researchers and managers to identify patterns in aviation risk and to adjust management strategies in ways that would not be possible if data were not collected similarly and aggregated together (e.g., DeVault et al. 2011; Dolbeer 2015; Dolbeer et al. 2016). A publicly available data repository for renewable energy would also have tremendous benefit not only for conservation scientists and wildlife managers, but also for energy developers, who frequently also desire to understand renewable energy impacts on wildlife and to build cost-effective and generalizable mitigation protocols. Both the American Wind Wildlife Institute and National Renewable Energy Laboratory have taken steps in this regard by compiling public document libraries, including peer-reviewed literature and unpublished reports from multiple wind facilities in North America (American Wind Wildlife Institute 2017; National Renewable Energy Laboratory 2017*a*).

Best Practices to Improve Monitoring

Our results identify gaps in the data on wildlife impacts from renewable energy facilities and suggest mechanisms to address these gaps. Specifically, we quantitatively illustrated how current monitoring practices have limited the ability to estimate and minimize local and large-scale risks of renewable energy to wildlife. This limitation arises due to substantial differences in the types of data collected, lack of data collection in all construction and operation periods, and constraints on data availability and accessibility. However, our results also suggest that these limitations can be overcome through widespread implementation of rigorous monitoring practices that will help minimize risk to wildlife, streamline facility siting decisions, and reduce costs of future research and monitoring, thereby providing mutual benefit to both renewable energy and wildlife conservation.

In particular, our results emphasize the following best management practices for study design, implementation, and dissemination. First, it is important to include specific questions and use methods carefully designed to answer those questions. Second, it is important to incorporate the same type of monitoring across locations and periods and account for detection rates for both fatalities and wildlife use. Third, it is important to use reporting protocols that protect confidential data but also allow data to be aggregated for meta-analyses to improve wildlife conservation practices and minimize environmental consequences of renewable energy.

Several of these best practices have been noted in prior work, but our empirical analysis suggests that they are infrequently applied. Implementing these practices may be logistically and financially feasible with existing tools such as the survey and analysis methods used in many published studies, the relatively few examples of rigorous study designs with both pre- and postconstruction, and existing data repositories designed to allow meta-analyses. Application of these tools, in conjunction with continued advances in sampling methods, may allow wildlife managers and the energy industry to more accurately and cost effectively anticipate both the local effects and range-wide cumulative impacts of renewable energy to wildlife.

Acknowledgments

Funding for this work was provided by the California Energy Commission (grant EPC-14-061) and from the U.S. Bureau of Land Management. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

We thank M. Thompson, T. Allison, R. Butryn, H. Beeler, T. Dietsch, T. Borneman, R. Doster, H. Edwards, E. Wrightman, and others who provided reports and other data. We also thank T. Allison, J. Yee, multiple anonymous reviewers, and others for providing constructive comments on earlier drafts of this manuscript. T.E.K., J.E.D., S.R.L., A.E.D., and T.J.C. designed the study, T.J.C. led collection, organizing, and analysis of the data with support from T.E.K. and the other authors, T.J.C. and T.E.K. led writing of the manuscript, and all authors contributed to manuscript revisions.

Supporting Information

A list of all reports used for analyses (Appendix S1), citation-only records (Appendix S2), and summary documents (Appendix S3); a description of wildlife-use survey types (Appendix S4); and the data set used for analyses (Appendix S5) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.
Supplementary Material

Literature Cited

American Wind Energy Association (AWEA). 2018. Wind energy in Texas. AWEA, Washington, D.C. Available from http://awea.files.cms-plus.com/FileDownloads/pdfs/Texas.pdf (accessed February 2018).

American Wind Energy Association (AWEA). 2019. U.S. wind industry first quarter 2019 Market Report. AWEA, Washington, D.C. Available from www.awea.org/2019marketreports (accessed May 2019).

American Wind Wildlife Institute (AWWI). 2017. AWWCI document library. AWWI, Washington, D.C. Available from https://awwic.nacse.org/library.php (accessed December 2017).

Anderson R, Morrison M, Sinclair K, Strickland D, Davis H, Kendall W. 1999. Studying wind energy/bird interactions: a guidance document. National Wind Coordinating Committee, Washington, D.C.

Argonne National Laboratory, National Renewable Energy Laboratory. 2015*a*. Bibliography of literature for avian issues in solar and wind energy and other activities. Argonne National Laboratory, Lemont, Illinois, and National Renewable Energy Laboratory, Golden, Colorado.

Argonne National Laboratory, National Renewable Energy Laboratory. 2015*b*. A review of avian monitoring and mitigation information at existing utility-scale solar facilities. Argonne National Laboratory, Lemont, Illinois, and National Renewable Energy Laboratory, Golden, Colorado.

Arnett EB, Inkley DB, Johnson DH, Larkin RP, Manes S, Manville AM, Mason R, Morrison ML, Strickland MD, Thresher R. 2007. Impacts of wind energy facilities on wildlife and wildlife habitat. Technical review 07-2. The Wildlife Society, Bethesda, Maryland.

Buckland ST, Anderson DR, Burnham KP, Laake JL, Borchers DL, Thomas L. 2001. Introduction to distance sampling. Oxford University Press, New York.

California Energy Commission. 2010. Genesis solar energy project: Commission decision. CEC, Sacramento, California. Available from https://www.energy.ca.gov/2010publications/CEC-800-2010-011/CEC-800-2010-011-CMF.PDF. (accessed February 2018).

California Energy Commission (CEC). 2017. Alphabetical list of power plant projects. CEC, Sacramento, California. Available from http://www.energy.ca.gov/sitingcases/alphabetical.html (accessed May 2017).

California Energy Commission (CEC), California Department of Fish and Game (CDFG). 2007. California guidelines for reducing impacts to birds and bats from wind energy development. Commission Final Report CEC-700-2007-008-CMF.CEC. CDFG, Sacramento, California.

Canadian Wind Energy Association (CanWEA). 2017. Installed capacity. CanWEA, Ottawa, Ontario. Available from https://canwea.ca/wind-energy/installed-capacity/ (accessed December 2017).

Cryan PM, et al. 2014. Behavior of bats at wind turbines. Proceedings of the National Academy of Science of the United States of America **111:**15126–15131.

DeVault TL, Belant JL, Blackwell BF, Seamans TW. 2011. Interspecific variation in wildlife hazards to aircraft: implications for airport wildlife management. Wildlife Society Bulletin **35:**394–402.

Dincer I. 2000. Renewable energy and sustainable development: a crucial review. Renewable and Sustainable Energy Reviews **4:**157–175.

Dinnell AM, Russ AJ. 2006. The legal hurdles to developing wind power as an alternative energy source in the United States: creative and comparative solutions. Northwestern Journal of International Law & Business **27:**535.

Dolbeer RA. 2015. Trends in reporting of wildlife strikes with civil aircraft and in identification of species struck under a primarily voluntary reporting system, 1990–2013. Other Publications in Zoonotics and Wildlife Disease. 188. Available from http://digitalcommons.unl.edu/zoonoticspub/188 (accessed September 2019).

Dolbeer RA, Weller JR, Anderson AL, Begier MJ. 2016. Wildlife strikes to civil aircraft in the United States, 1990–2015. Federal Aviation Administration (FAA) National wildlife strike database Serial Report Number 22. FAA, Washington, D.C.

Drewitt AL, Langston RH. 2006. Assessing the impacts of wind farms on birds. Ibis **148:**29–42.

Federal Aviation Administration (FAA). 2017. FAA wildlife strike database. FAA, Washington, D.C. Available from https://www.faa.gov/airports/airport_safety/wildlife/ (accessed August 2017).

Ferrer M, De Lucas M, Janss GF, Cadaso E, Muñoz AR, Bechard MJ, Calabuig CP. 2012. Weak relationship between risk assessment studies and recorded mortality in wind farms. Journal of Applied Ecology **49:**38–46.

Field SA, O'Conner PJ, Tyre AJ, Possingham HP. 2007. Making monitoring meaningful. Austral Ecology **32:**485–491.

Frick W, Baerwald E, Pollock J, Barclay R, Szymanski J, Weller T, Russell A, Loeb S, Medellin R, McGuire L. 2017. Fatalities at wind turbines may threaten population viability of a migratory bat. Biological Conservation **209:**172–177.

Hervé M. 2019. RVAideMemoire: testing and plotting procedures for biostatistics. R package version 0.9–73.

Hoffert MI, Caldeira K, Benford G, Criswell DR, Green C, Herzog H, Jain AK, Kheshgi HS, Lackner KS, Lewis JS. 2002. Advanced technology paths to global climate stability: energy for a greenhouse planet. Science **298:**981–987.

Hull C, Stark E, Peruzzo S, Sims C. 2013. Avian collisions at two wind farms in Tasmania, Australia: taxonomic and ecological characteristics of colliders versus non-colliders. New Zealand Journal of Zoology **40:**47–62.

Huso MM, Dalthorp D, Miller TJ, Bruns D. 2016*a*. Wind energy development: methods to assess bird and bat fatality rates post-construction. Human–Wildlife Interactions **10:**62–70.

Huso MM, Dietsch T, Nicolai C. 2016*b*. Mortality monitoring design for utility-scale solar power facilities: U.S. Geological Survey Open-File Report 2016-1087, 44 p. U.S. Geological Survey, Reston. Available from https://doi.org/10.3133/ofr20161087 (accessed June 2018).

ICF International. 2016. Altamont pass wind resource area bird fatality study, monitoring years 2005–2013. Alameda County Community Development Agency, Hayward, California.

Johnson GE, Arnett EB. 2004. A bibliography of bat interactions with wind turbines. Western EcoSystems Technology, Inc., Cheyenne, Wyoming and Bat Conservation International, Austin, Texas.

Kagan RA, Viner TC, Trail PW, Espinoza EO. 2014. Avian mortality at solar energy facilities in Southern California: a preliminary analysis. U.S. Fish & Wildlife Service, National Forensics Laboratory, Ashland, Oregon.

Katzner TE, Bennett VJ, Miller T, Duerr A, Braham M, Hale AM. 2016*a*. Wind energy development: methods for assessing risks to birds and bats pre-construction. Human–Wildlife Interactions **10:**42–52.

Katzner TE, Nelson DM, Braham MA, Doyle JM, Fernandez NB, Duerr AE, Bloom PH, Fitzpatrick MC, Miller TA, Culver RC. 2016*b*. Golden Eagle fatalities and the continental-scale consequences of local wind-energy generation. Conservation Biology **31:**406–415.

Katzner TE, et al. 2019. Wind energy: an ecological challenge. Science **366:**1026–1027.

Kéry M, Royle JA, Schmid H. 2005. Modeling avian abundance from replicated counts using binomial mixture models. Ecological Applications **15:**1450–1461.

Kunz TH, Arnett EB, Cooper BA, Erickson W, Larkin RP, Mabee TJ, Morrison ML, Strickland MD, Szewczak JM. 2007*a*. Assessing impacts of wind-energy development on nocturnaly active birds and bats: a guidance document. Journal of Wildlife Management **71:**2449–2486.

Kunz TH, Arnett EB, Erickson WP, Hoar AR, Johnson GD, Larkin RP, Strickland MD, Thresher RW, Tuttle MD. 2007*b*. Ecological impacts of wind energy development on bats: questions, research needs, and hypotheses. Frontiers in Ecology and the Environment **5:**315–324.

Kuvlesky Jr. WP, Brennan LA, Morrison ML, Boydston KK, Ballard BM, Bryant FC. 2007. Wind energy development and wildlife conservation: challenges and opportunities. Journal of Wildlife Management **71:**2487–2498.

Loss SR, Will T, Marra PP. 2013. Estimates of bird collision mortality at wind facilities in the contiguous United States. Biological Conservation **168:**201–209.

Marques AT, Batalha H, Rodrigues S, Costa H, Pereira MJR, Fonseca C, Mascarenhas M, Bernardino J. 2014. Understanding bird collisions at wind farms: an updated review on the causes and possible mitigation strategies. Biological Conservation **179:**40–52.

Meyer D, Zeileis A, Hornik K. 2016. vcd: visualizing categorical data. R package version 1:4–3.

Millon L, Julien J-F, Julliard R, Kerbiriou C. 2015. Bat activity in intensively farmed landscapes with wind turbines and offset measures. Ecological Engineering **75:**250–257.

Morrison M. 2002. Searcher bias and scavenging rates in bird/wind energy studies. National Renewable Energy Laboratory, Golden Colorado.

Morrison ML, Block WM, Strickland MD, Collier BA, Peterson MJ. 2008. Wildlife study design. Springer Science + Business Media, LLC, New York.

National Renewable Energy Laboratory (NREL). 2017*a*. NREL Publications Database. NREL, Golden, Colorado. Available from https://www.nrel.gov/wind/publications.html (accessed December 2017).

National Renewable Energy Laboratory (NREL). 2017*b*. Q2/Q3 2017 Solar Industry Update. NREL, Golden, Colorado. Available from https://www.nrel.gov/docs/fy18osti/70406.pdf (accessed October 2017).

Nichols JD, Williams BK. 2006. Monitoring for conservation. Trends in Ecology & Evolution **21:**668–673.

Pacific Northwest National Laboratory (PNNL). 2017. Tethys wind energy knowledge base. PNNL, Richland, Washington. Available from https://tethys.pnnl.gov/knowledge-base-wind-energy (accessed December 2017).

Piorkowski MD, Farnsworth AJ, Fry M, Rohrbaugh RW, Fitzpatrick JW, Rosenberg KV. 2012. Research priorities for wind energy and migratory wildlife. Journal of Wildlife Management **76:**451–456.

Poissant Y, Dignard-Bailey L, Bateman P. 2016. Photovoltaic technology status and prospects Canadian annual report 2015. Natural Resources Canada, Ottawa, Ontario.

R Core Team. 2017. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Reynolds JH, Thompson WL, Russell B. 2011. Planning for success: identifying effective and efficient survey designs for monitoring. Biological Conservation **144:**1278–1284.

Romesburg C. 1981. Wildlife science: gaining reliable knowledge. Journal of Wildlife Management **45:**293.

Royle JA. 2004. N-mixture models for estimating population size from spatially replicated counts. Biometrics **60:**108–115.

Schuster E, Bulling L, Köppel J. 2015. Consolidating the state of knowledge: a synoptical review of wind energy's wildlife effects. Environmental Management **56:**300–331.

Sells SN, Bassing SB, Barker KJ, Forshee SC, Keever AC, Goerz JW, Mitchell MS. 2018. Increased scientific rigor will improve reliability of research and effectiveness of management. Journal of Wildlife Management **82:**485–494.

Sillett TS, Chandler RB, Royle JA, Kéry M, Morrison SA. 2012. Hierarchical distance-sampling models to estimate population size and habitat-specific abundance of an island endemic. Ecological Applications **22:**1997–2006.

Sollmann R, Gardner B, Williams KA, Gilbert AT, Veit RR. 2016. A hierarchical distance sampling model to estimate abundance and covariate associations of species and communities. Methods in Ecology and Evolution **7:**529–537.

Strickland, MD, Arnett EB, Erickson WP, Johnson DH, Johnson GD, Morrison ML, Shaffer JA, Warren-Hicks W. 2011. Comprehensive Guide to Studying Wind Energy/Wildlife Interactions. Prepared for the National Wind Coordinating Collaborative, Washington, D.C., USA. Available from http://www.nationalwind.org/wp-content/uploads/2018/04/Comprehensive_Guide_to_Studying_Wind_Energy_Wildlife_Interactions_2011_Updated.pdf. (accessed June 2018).

Subramanian M. 2012. An ill wind. Nature **486:**310.

Thompson M, Beston JA, Etterson M, Diffendorfer JE, Loss SR. 2017. Factors associated with bat mortality at wind energy facilities in the United States. Biological Conservation **2015:**241–245.

U.S. Fish and Wildlife Service (USFWS). 2012. U.S. Fish and Wildlife Service land-based wind energy guidelines. USFWS, Arlington, Virginia.

U.S. Fish and Wildlife Service (USFWS). 2013. Eagle conservation plan guidance. USFWS, Arlington, Virginia.

White GC. 2005. Correcting wildlife counts using detection probabilities. Wildlife Research **32:**211–216.