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Author: Loss, Scott R.

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PERSPECTIVE

Avian interactions with energy infrastructure in the context of other anthropogenic threats

Scott R. Loss

Department of Natural Resource Ecology and Management, Oklahoma State University, Stillwater, Oklahoma, USA
scott.loss@okstate.edu

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ABSTRACT

Continued global expansion in the development of energy and its associated infrastructure is expected in the coming decades. Substantial concern exists about the impacts of this energy infrastructure on bird populations. In this special section, Smith and Dwyer (2016) provide a timely review of interactions between birds and renewable energy infrastructure, and several studies address avian interactions with renewable and nonrenewable energy infrastructure. I briefly summarize these studies and place avian interactions with energy infrastructure in the context of the many anthropogenic threats to birds. There is vast variation in the amount of mortality caused by different man-made threats. Comparing threats in the context of energy development is useful for attracting public, scientific, and policy attention, for highlighting major research gaps, for providing scientific evidence to inform resource allocation decisions, and for developing mitigation strategies whereby mortality risk from one threat can be offset by reducing risk from another threat. However, broad comparisons of mortality should not be used on their own to draw conclusions about population-level impacts, to conclude that low mortality or a paucity of information negates biologically significant impacts or obviates a need for action, or to develop mortality mitigation strategies when little information exists to inform the balancing of risks. To move beyond gross mortality estimates toward comparisons of actual population-level impacts, a balance must be struck between conducting research that produces generalizable results and studies that focus on species, locations, and response variables of interest. Additional information about the many direct and indirect effects of energy infrastructure, such as the research described by the articles in this special section, will be crucial to achieving an optimal tradeoff between energy development and wildlife conservation.

Keywords: anthropogenic bird mortality, energy infrastructure, incidental take, mitigation, population ecology, renewable energy

Interacciones de las aves con infraestructuras de energía en el contexto de otras amenazas antropogénicas

RESUMEN

Se espera para las próximas décadas una continua expansión global en el desarrollo de energía y su infraestructura asociada. Existe bastante preocupación sobre los impactos de estas infraestructuras de energía en las poblaciones de aves. En esta sección especial, Smith y Dwyer (2016) brindan una revisión oportuna de las interacciones entre las aves y las infraestructuras de energía renovable, y varios estudios se centran en las interacciones de las aves con las infraestructuras de energía renovable y no renovable. Aquí sintetizo brevemente estos estudios y enmarco las interacciones de las aves con las infraestructuras de energía en el contexto de las muchas amenazas antrópicas hacia las aves. Hay una enorme variación en la cantidad de mortalidad causada por diferentes amenazas vinculadas al hombre. Es útil comparar las amenazas en el contexto de los desarrollos energéticos para atraer la atención pública, científica y política; para subrayar los principales huecos de investigación; para brindar evidencia científica que guíe las decisiones de asignación de recursos; y para desarrollar estrategias de mitigación en donde el riesgo de mortalidad proveniente de una amenaza puede ser compensado por la reducción del riesgo de otra amenaza. Sin embargo, las comparaciones generales de mortalidad no deben ser usadas por sí solas para sacar conclusiones sobre los impactos a nivel poblacional; para concluir que la baja mortalidad o una escasez de información permite evitar los efectos biológicamente significativos o una necesidad de acción; o para desarrollar estrategias de mitigación de la mortalidad cuando existe poca información para balancear los riesgos. Para ir más allá de las estimaciones generales de mortalidad hacia comparaciones del impacto real en la población, se debe realizar un balance entre realizar investigaciones que produzcan resultados generalizables y estudios que se enfoquen en especies, ubicaciones y variables de respuesta de interés. Será crucial contar con información adicional sobre los muchos impactos directos e indirectos de las infraestructuras de energía, como la información brindada por los artículos en esta sección especial, para alcanzar una solución de compromiso óptima entre el desarrollo de energía y la conservación de la vida silvestre.

Palabras clave: ecología de poblaciones, energía renovable, infraestructuras de energía, mitigación, mortalidad de aves por causas antropogénicas, toma imprevista

Introduction to Special Section on Avian Interactions with Energy Infrastructure

In this special section, Smith and Dwyer (2016) review interactions between birds and renewable energy infrastructure, and several studies empirically address bird interactions with both renewable and nonrenewable energy infrastructure (Bayne et al. 2016, Luzenski et al. 2016, Mahoney and Chalfoun 2016, Pearse et al. 2016). This special section is timely due to the rapidly evolving North American and global energy arenas, and associated interest in understanding and minimizing any adverse environmental effects of this energy boom. Global energy demand is currently on the rise and expected to increase 37% by 2040. As a result, a substantial rise in the use and output of natural gas, solar, and wind energy is anticipated, along with continued development of oil resources (International Energy Agency [IEA] 2014, U.S. Energy Information Administration [USEIA] 2014). By 2040, natural gas will be the second-largest global energy source behind oil (IEA 2014), and rapid expansion of renewable energy sectors—primarily wind and solar, but also geothermal, hydroelectric, and biomass—will lead to renewable energy sources ("renewables") contributing at least 16% of all U.S. power generation (USEIA 2014). Along with this increase in energy development, an expansion of ~5% per year in the already millions-of-kilometers-long global network of electrical lines is expected (Jenkins et al. 2010).

Substantial concern exists about the impacts of this rapidly expanding energy infrastructure on wildlife populations, especially in the context of the many other global anthropogenic threats to the environment, including climate change, habitat loss, disease, pollution, and invasive species. In particular, the direct and indirect effects of energy infrastructure on birds are receiving significant research, management, and policy attention, as are several other sources of direct human-caused bird mortality (e.g., predation by domestic cats, collisions with various man-made objects). For example, a growing body of research has addressed the impacts of wind energy, including direct mortality from collisions with turbines (Loss et al. 2013a), and indirect effects of wind energy facilities on bird movements, distribution, and breeding performance (Pearce-Higgins et al. 2012, Stevens et al. 2013, Shaffer and Buhl 2015). Research has also begun to examine the impacts of oil and natural gas infrastructure on bird–habitat associations, including the impacts of conventional technologies, such as oil and gas extraction with vertical wells, and those of rapidly expanding unconventional technologies, such as oil extraction from tar sands and oil and gas extraction from shale deposits with horizontal drilling and hydraulic fracturing (Naugle 2011, Northrup and Wittemyer 2012, Butt et al. 2013, Thomas et al. 2014). For example, a recent study showed that several songbird species of conservation concern avoided unconventional oil development sites in North Dakota (Thompson et al. 2015). However, the ecological effects of using unconventional methods to extract oil and gas remain largely unknown (Souther et al. 2014).

An increasing focus on the impacts of solar energy also is expected because of the rapid growth of this sector, and because of recently publicized avian mortality events at solar facilities in the southwestern U.S. due to birds being burned at light concentration towers and colliding with reflecting mirrors (Kagan et al. 2014). As with unconventional methods of oil and gas development, few peer-reviewed studies of solar energy impacts have been conducted (Smith and Dwyer 2016). Bird collisions and electrocutions at power lines are relatively well studied in many countries (Barrientos et al. 2011), and effective risk assessment and mitigation approaches have been developed (Avian Power Line Interaction Committee [APLIC] 2006, Dwyer et al. 2014). Yet, much remains to be learned about the direct and indirect effects of power lines on avian populations (Rioux et al. 2013, Loss et al. 2014a).

In this special section, both Pearse et al. (2016) and Mahoney and Chalfoun (2016) further advance our understanding of interactions between birds and wind energy infrastructure. In southeastern Wyoming, Mahoney and Chalfoun (2016) show that the impacts of wind turbines can be highly complex, with bird reproductive performance depending on the species, time period, breeding parameter, and metric of turbine development studied. For example, measures of turbine density at broad spatial scales (1–5 km) were the best turbine-related metrics for explaining nesting productivity. Size-corrected mass of Horned Lark (*Eremophila alpestris*) nestlings and nest success (but only in 1 of 2 yr studied) were both inversely associated with turbine density. No relationship was found between turbine density and either nest success or nestling mass for McCown's Longspur (*Rhynchophanes mccownii*), and no wind energy–related metrics predicted clutch size or number of fledglings for either species. The authors conclude that turbine density should be used along with more commonly used metrics (e.g., distance to turbines) to test for associations between bird populations and wind turbines, and that long-term studies are needed to clarify temporal variation in the impacts of energy infrastructure.

Pearse et al. (2016) approach bird interactions with infrastructure at a much different scale from that of Mahoney and Chalfoun's (2016) study of breeding parameters. Pearse et al. (2016) assess broad-scale space and habitat use of Sandhill Cranes (*Grus canadensis*) in relation to turbine locations during winter and migration. Their study in the Great Plains of the U.S. illustrates that broad-scale spatial overlap between crane use locations and wind turbines is currently relatively low. However, they also find a large amount of overlap between core crane wintering and migration ranges and areas projected to be suitable for future wind development. Furthermore, a high percentage of the region's cranes use locations in close proximity to turbines during at least a portion of their wintering and migration periods. The authors' data from GPS-marked cranes illustrate potential avoidance of wind turbines. However, as illustrated by resource selection functions, this apparent avoidance could have resulted from cranes selecting vegetation types (e.g., wetlands) that are generally far from turbines. Pearse et al. (2016) conclude that a large number of cranes could be exposed to turbines at a small number of locations, a finding with clear ramifications for siting wind turbines and other infrastructure.

Bayne et al. (2016) analyze 13 yr of data from 1,852 point count locations in the boreal forest of Canada to assess interactions between birds and infrastructure associated with conventional oil and gas extraction (pipelines, seismic lines, and well pads). They find that bird abundance responses to disturbance vary by species, and that abundance is more likely to decrease for mature forest species and more likely to increase for open land, shrubland, and early successional forest species. Bayne et al. (2016) also illustrate that the radius used for point counts can interact with the type of infrastructure studied to influence the magnitude, direction, and uncertainty of disturbance response estimates. This finding is broadly important for studies of avian interactions with energy infrastructure because it suggests that variation in data collection methods can obfuscate comparisons of the impacts of different disturbance types. Bayne et al. (2016) highlight the need to incorporate behavioral data and large-scale assessments of bird abundance patterns into studies in order to quantify population-level impacts of energy infrastructure.

Finally, Luzenski et al. (2016) add to our understanding of avian–power line interactions by illustrating that well-marked power lines may pose relatively little collision risk for diurnal raptors, even in important migration corridors. They conduct a before-and-after analysis of raptor flight heights in the Appalachian Mountains of western New Jersey relative to the construction of a high-voltage transmission line with flight diverter markers. Based on the novel approach of using geographic information systems (GIS) and Power Line Systems – Computer Aided Design and Drafting (PLS-CADD) to visually display the spatial locations of raptors during line crossings, the authors illustrate that raptors largely avoid the new power line by flying above it. The analytical approach of Luzenski et al. (2016) combined with a before-and-after sampling design is likely to be broadly useful in the future for assessing impacts of energy infrastructure on avian movements.

These studies of avian interactions with energy infrastructure provide crucial information that can be used to inform energy development decisions and direct future research objectives. Questions that may be raised by these and similar studies include: What are the absolute and relative impacts to bird populations for each type of energy infrastructure, and, more broadly, for all anthropogenic threats? How can researchers move from individual studies toward generalizations across species and systems, and therefore toward a more comprehensive understanding of population-level impacts?

Such comparisons and assessments of population-level impacts are complicated in part by the use of different response variables in different studies (e.g., direct mortality rates for different spatial scales and time periods; indirect effects on different breeding parameters and habitat and space use at different scales). However, several recent quantitative syntheses offer large-scale estimates of direct mortality for various man-made threats that allow the above types of questions to begin to be addressed. Such mortality comparisons are possible because counting dead birds and extrapolating counts to large scales is more straightforward than measuring and extrapolating more subtle indirect effects. Studies in the U.S. and Canada have assessed the total amount of national bird mortality from collisions with buildings (Machtans et al. 2013, Loss et al. 2014b), automobiles (Bishop and Brogan 2013, Loss et al. 2014c), communication towers (Longcore et al. 2012), and wind turbines (Loss et al. 2013a, Zimmerling et al. 2013); from electrocutions and collisions at power lines (Rioux et al. 2013, Loss et al. 2014a); and from predation by domestic cats (*Felis catus*; Blancher 2013, Loss et al. 2013b), among other threats (reviewed by Calvert et al. 2013, Loss et al. 2015).

In the remainder of this article, I use the large-scale perspective afforded by current research to frame what we know about the impacts of energy infrastructure on bird populations. First, I compare estimated amounts of mortality for different man-made mortality sources and highlight how estimates and comparisons should and should not be used in the context of energy development.

Because the conservation of species affected by multiple anthropogenic threats requires going beyond gross estimates of bird body counts, I close by outlining research needs and approaches that will facilitate a move toward comparing actual population-level impacts of different threats to birds.

The Context of Other Anthropogenic Sources of Bird Mortality

There is vast variation in the amount of mortality caused by different man-made threats. Even so, there is general agreement in the ranking of mortality sources for the U.S. and Canada; this concordance of findings increases confidence in the individual assessments and points to opportunities for conservation intervention. In both countries, predation by free-ranging domestic cats is estimated to be the top source of human-caused mortality—excluding indirect drivers such as habitat loss and climate change—with between 1.4 and 4.0 billion birds killed annually in the U.S and between 204 and 348 million in Canada. The next-biggest threats are similar for both countries, including (estimates in birds per year and for the U.S. and Canada, respectively) collisions with buildings (365–988 million; 16–42 million), automobiles (200–340 million; 9–19 million), and power lines (8–57 million; 10–41 million). Other mortality sources with systematically derived estimates include collisions with communication towers (6.6 million; 220,000), electrocutions at power lines (0.9–11.6 million; 160,000–802,000), and collisions with wind turbines (140,000–328,000; 13,000–22,000). Threats with systematically derived estimates for Canada but not the U.S. include agricultural chemicals (1.0–4.4 million), marine fishing activities (2,700–45,600 for gill nets, longlines, and trawls combined), and marine oil and gas activities (2,000–4,100). Some Canadian estimates are only for numbers of destroyed nests (i.e. not independent nonjuvenile birds), including commercial forestry operations (0.6–2.1 million) and terrestrial oil and gas development (9,900–72,000 total for well sites, pipelines, oil sands, and seismic exploration).

Perhaps even more important than current mortality is the trajectory of these figures. Most mortality sources are increasing as human populations and energy demand grow, but the rate of increase probably varies considerably among categories. Numbers of bird–wind turbine collisions may rise quickly due to the rapid growth of this energy sector and projected increases in turbine size (Loss et al. 2013b). Similarly, extraordinary proliferation of energy extraction infrastructure potentially affects vast areas of North America that to date have been relatively undisturbed. For example, oil and gas exploration and extraction infrastructure is increasingly affecting the boreal forest, and oil, gas, and wind energy developments are rapidly expanding in western North American grassland and sagebrush steppe (Leu et al. 2008, Copeland et al. 2011, Souther et al. 2014).

For most mortality sources, data limitations (e.g., inconsistencies in the response variables measured, and a lack of species- and location-specific information) prevent systematic assessments of impacts at the population level, factors driving variation in mortality rates, and spatiotemporal and taxonomic variation in mortality. However, broad comparisons among different categories of a single threat are often possible. For example, unowned feral cats kill more birds than free-ranging pets, both individually (roughly twice as many birds per cat) and cumulatively (roughly 2.4 times more birds across all cats; Loss et al. 2013b). Each low-rise and high-rise office building kills more birds (~10.3 and ~24.3 times more, respectively) than each detached residential building. However, because of the large number of residential buildings, U.S. residences cumulatively kill about the same number of birds as low-rises and 100 times more birds than high-rises (Loss et al. 2014b). For wind turbines, average mortality rates increase 10-fold with an increase in turbine hub height from 36 m to 80 m, and collision rates also vary regionally, with annual per-turbine mortality averaging 2.4 in the Great Plains and 8.2 in the eastern third of the U.S. (Loss et al. 2013a). Species-level analyses illustrate that long-distance migratory species (e.g., vireos, thrushes, warblers, and sparrows) are especially prone to collisions at communications towers and buildings (Longcore et al. 2013, Loss et al. 2014b).

Uses of Mortality Estimates and Comparisons in the Context of Energy Development

Two questions are likely to be asked by researchers, managers, and policymakers based on current knowledge of man-made mortality sources: (1) In lieu of a complete understanding of relative impacts on populations, how can broad comparative information be used to successfully manage bird populations? (2) How is this information useful for future development of energy infrastructure? In the context of these questions, I argue that comparisons of direct mortality are useful for at least 4 general purposes.

First, national estimates of mortality and comparisons of man-made threats are valuable for attracting public, scientific, and policy attention (Calvert et al. 2013, Machtans and Thogmartin 2014). This interest can lead to increased research activity and the development of strategies and management steps for addressing mortality sources. For example, after publishing an estimate of cat predation mortality for U.S. wildlife (Loss et al. 2013b), the authors received inquiries from federal, state, and municipal agencies seeking to use the report to garner interest in reducing cat impacts on wildlife and to initiate discussions about how to effectively manage cat populations. Likewise, large-scale assessments of the effects of energy infrastructure can stimulate research, management, and policy directed at developing infrastructure in a way that minimizes population-level impacts on birds and other wildlife.

Second, mortality estimates and comparisons are valuable for highlighting major research gaps and identifying the types of research and response variables that will allow inductive conclusions to be made about other species and energy development scenarios, ultimately linking energy development to population processes. For example, a comprehensive review of both publicly available and privately held data on bird–wind turbine collisions revealed that additional data collection on the age and sex of species killed was necessary for understanding the population-level impacts of this mortality source (Loss et al. 2013a). In a study of avian nest loss associated with oil and gas exploration and extraction in Canada (Van Wilgenburg et al. 2013), the authors concluded that understanding energy development impacts on bird carrying capacities required assessment of the long-term effects of development-related habitat disturbance, collection of multiyear and season-specific disturbance data that covers the breeding season, and improved approaches to generating bird density estimates. The papers in this special section include examples of the variety of data that can be applied to examining direct impacts at the population level, ranging from straightforward assessment of behavioral flexibility (Luzenski et al. 2016) to regional-scale evaluations that include the synergy of infrastructure siting and bird habitat selection (Pearse et al. 2016). Indirect effects are much more difficult to scale up to population processes. As papers in this section by Mahoney and Chalfoun (2016) and Bayne et al. (2016) illustrate, local performance metrics can reveal subtle indirect effects, but not population processes.

Third, mortality estimates and comparisons can serve as an evidence base to inform decisions about the allocation of resources for management and policy (Calvert et al. 2013). An immediate conclusion from comparing mortality with potential policy and management implications is that there is currently a major lack of resources and science-based management and policy directed at the 2 largest estimated sources of bird mortality in North America, predation by cats and collisions with buildings. Directing additional resources toward these mortality sources could limit widespread impacts on bird populations (DeVault 2015). Decisions to direct resources *away* from threats should be made with caution, given the possibility that even small amounts of mortality may cause population-level effects (see following section). Resource allocation decisions should ideally account for a variety of factors, including: (1) the full range of uncertainty around estimates of mortality and population-level impacts; (2) caveats and limitations that may contribute positive or negative bias to estimates; (3) the need for adaptation of resource allocation, management, and policy in light of updated information; and (4) desired levels of precaution regarding unintended adverse consequences to bird populations (Loss et al. 2012, 2015, Machtans and Thogmartin 2014).

Fourth, mortality estimates and comparisons are a first step toward a deep enough understanding of mortality sources and population processes to allow risk from one source to be balanced correctly against risk from another source when developing mortality mitigation strategies. Currently, there are few species and mortality sources with enough data to allow the careful resource equivalency analyses needed to direct effective mortality mitigation strategies (U.S. Fish and Wildlife Service [USFWS] 2013). However, one promising, data-informed strategy is the use of electrical pole retrofitting to reduce eagle electrocution risk as a way to offset eagle–wind turbine collisions (Cole and Dahl 2013, USFWS 2013). Care must be taken to ensure that enough data is available to inform equivalent tradeoffs between mortality sources and to prevent unintended impacts to bird populations (see following section for limitations of mitigation strategies). The studies in this special issue provide excellent examples of the types of species- and location-specific information needed to build this information base.

Limits of Mortality Estimates and Comparisons in the Context of Energy Development

Although large-scale mortality estimates and comparisons have useful applications for managing bird populations and moving toward assessments of population-level impacts, there are also several purposes for which this information cannot be reliably used. First, unless paired with detailed demographic data collected at spatially and temporally relevant scales, mortality estimates and comparisons should not be used to conclude whether a mortality source has a biologically significant impact on bird populations. Intensive local studies can provide evidence that man-made threats contribute to local population declines (e.g., Dahl et al. 2012, Borda-de-Água et al. 2014), and large-scale multispecies analyses may provide simple comparisons of estimated mortality relative to population size (Longcore et al. 2013, Erickson et al. 2014). However, data limitations in these large-scale analyses obscure demographic details (e.g., mortality effects on age- and sex-specific survival). An additional challenge is determining the degree to which human-caused mortality is compensatory vs. additive (i.e. in simplest terms, whether at least some of the individuals killed would have died due to other causes; Sinclair and

Pech 1996, Péron 2013). Even when detailed demographic data are available, caution should be taken when concluding that there is no population-level impact of a mortality source, because a lack of effective, long-term, and high-resolution monitoring data creates uncertainty in estimates of population responses. Additionally, indirect impacts—including impacts on breeding performance (Mahoney and Chalfoun 2016), broad-scale habitat and space use (Pearse et al. 2016), and fine-scale abundance (Bayne et al. 2016) and movement (Luzenski et al. 2016)—may contribute to population declines even when little or no mortality is observed (Longcore and Smith 2013). Integrating direct and indirect effects remains a major challenge that must be addressed to gain a comprehensive understanding of the factors regulating avian populations.

Second, an overall small magnitude of estimated mortality compared with other threats should not be used to conclude that there is a low probability of population-level impacts, that no further research is needed, or that energy development or other activities can proceed without precautions. Natural gas, oil, and wind energy infrastructure in Canada is estimated to cause fewer bird deaths than many man-made threats (Calvert et al. 2013). However, using this information to conclude that research, management, and policy attention are not needed for these energy sectors could be misguided because even a small absolute amount of mortality (Carrete et al. 2009, Dahl et al. 2012), or the idiosyncrasies of where infrastructure is sited (Schaub 2012), can cause population-level impacts for some species. Extensive popular media attention directed at energy infrastructure and other anthropogenic threats may further increase the likelihood of misguided conclusions about population-level impacts. Statements comparing the relative impact of 2 or more mortality sources based on gross mortality figures pervade popular outlets (e.g., Gore 2009, Neuhauser 2014, Sibley 2016). These comparisons often include data that were not systematically derived or peer-reviewed, and can even result in headlines that directly contradict the science. For example, the headline "Stop blaming cats: As many as 988 million birds die annually in window collisions" (The Washington Post 2014) ignores evidence that cats kill more birds than windows, and even contradicts content within the article.

Third, a complete lack of information should not be taken to indicate that there is no effect of a potential mortality source. As described above, some types of energy infrastructure lack systematically derived mortality estimates or have received little scientific attention overall (e.g., solar, coal, and unconventional oil and gas). A lack of information and analysis for these mortality sources is not equivalent to careful, data-intensive research that documents a lack of impact for the system of interest nor to generalizable research from other systems that allows for reasonable inferences to be made. Instead, qualified conclusions about the likelihood of population-level impacts, along with a highlighting of the quantitative data needed to increase the confidence of these conclusions, will be most useful for policy and management efforts.

Fourth, despite the potential use of mortality comparisons for developing mortality mitigation strategies (previous section), the "apples-to-apples" comparisons that will allow for the correct offsetting of risks will not always be possible. Controlling feral cat populations to offset mortality from power lines, for example, would be unlikely to achieve desired objectives because the bird species, seasonal periods, and regions experiencing mortality vary between the 2 threats. Power lines appear to disproportionately affect raptors and large waterbirds, while cats disproportionally kill passerines and other small- to medium-sized birds. Therefore, even with data about which species are killed in what number, it may be impossible to use cat population control to directly offset mortality for species and locations affected by power lines. A corollary is that reducing mortality from the threat that is easiest to manage may be desirable, but is unlikely to address the entirety of anthropogenic mortality affecting avian populations. Several criteria in addition to feasibility must be weighed when deciding how to distribute resources among threats, including cost, societal resistance, and expected population-level benefits.

Toward an Understanding of Energy Infrastructure Impacts on Bird Populations

Placing the impacts of energy infrastructure in the context of other man-made threats to birds must be done carefully. To increase the validity of these comparisons, a balance must be struck between conducting research that produces generalizable results and broad inferences and studies that focus on species, locations, and infrastructure types of interest. Comparisons among direct mortality sources are fairly straightforward but provide limited inference about population-level effects. Unfortunately, comparisons of the full range of direct and indirect impacts of anthropogenic threats to birds, including energy infrastructure, are not currently possible due to the relatively nascent state of research into indirect effects for most threats and direct effects for some threats. However, rapid growth in the number and diversity of studies addressing the impacts of energy infrastructure, as epitomized by the wide range of topics covered in this special section, should allow such comprehensive assessments in the future.

In the meantime, several specific steps will facilitate a clearer understanding of the impacts of energy infrastructure on bird populations. For well-studied infrastructure types (wind energy and power lines), further study is needed to increase randomization, replication, and duration of studies, and to assess and account for biases that limit the accuracy and precision of mortality estimates (e.g., scavenger removal, searcher detection, and bias related to injured birds dying outside of searched areas). Comparisons of relative impact also will require the development and implementation of modeling approaches that capture the full annual cycles of species (Hostetler et al. 2015) and account for complex population processes (e.g., compensation vs. additivity). In cases in which species-level research is not logistically possible or cannot proceed fast enough due to the rapid pace of energy development, inferences about how to manage species or locate infrastructure could be based on research on related taxa. For example, a recent meta-analysis indicated that grouse as a group tend to be displaced by anthropogenic structures (Hovick et al. 2014); this finding could be broadly generalizable to numerous types of man-made structure despite the nuances of grouse responses (e.g., Dinkins et al. 2014, Winder et al. 2015).

For relatively unstudied infrastructure types (e.g., solar and unconventional oil and gas), basic information on direct and indirect impacts is needed to serve as a basis for more sophisticated analyses. In some cases, initial investigative work may even be necessary to gain an understanding of the full range of impact mechanisms. For example, Ramirez (2013) highlights a previously undescribed type of bird mortality associated with oil and gas infrastructure, the entrapment of birds in so-called "heater treaters" (vessels that use heat to break up wellstream emulsions, separating crude oil from water and other foreign materials). As described above, a lack of information should not preclude risk management activities, but such management requires development, implementation, and monitoring to reduce both direct and indirect impacts. For many types of energy infrastructure, data transparency remains a concern (Piorkowski et al. 2012), and gaining a clear picture of the relative impacts of different man-made threats will require increased public availability of privately funded data.

A lack of knowledge about the impacts of energy infrastructure on bird populations need not halt energy development nor, conversely, pave the way for completely unfettered development of energy resources. Striking a balance between energy development and bird conservation will require consideration of the environment and the ecosystem services it provides, as well as the effects of different actions on human livelihoods. Achieving this tradeoff is especially important because renewable energy development may also provide benefits to birds and the environment by reducing the harmful effects of fossil fuel extraction and use. Increased information about the direct and indirect impacts of different types of energy infrastructure, as well as the effects of other man-made mortality sources, will be central to achieving an appropriate tradeoff.

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