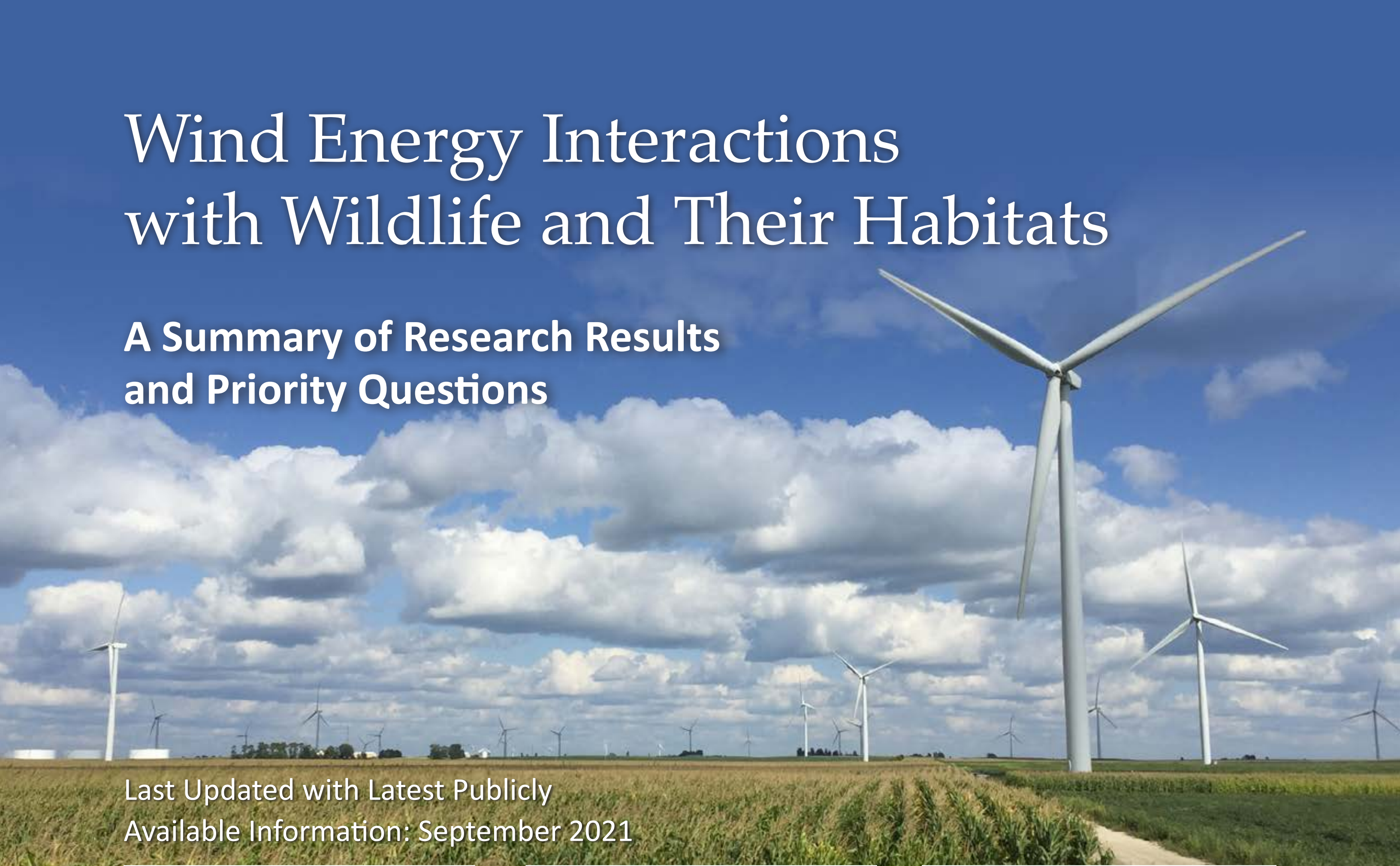

Wind Energy Interactions with Wildlife and Their Habitats

A Summary of Research Results and Priority Questions

Last Updated with Latest Publicly
Available Information: September 2021

This summary reviews publicly available information about the adverse impacts of land-based wind power on wildlife in North America and the status of our knowledge regarding how to avoid or minimize these impacts.

AMERICAN WIND WILDLIFE INSTITUTE

About AWWI

The American Wind Wildlife Institute is a partnership of leaders in the wind industry, wildlife management agencies, and conservation and science organizations who collaborate on a shared mission: to facilitate timely and responsible development of wind energy while protecting wildlife and wildlife habitat.

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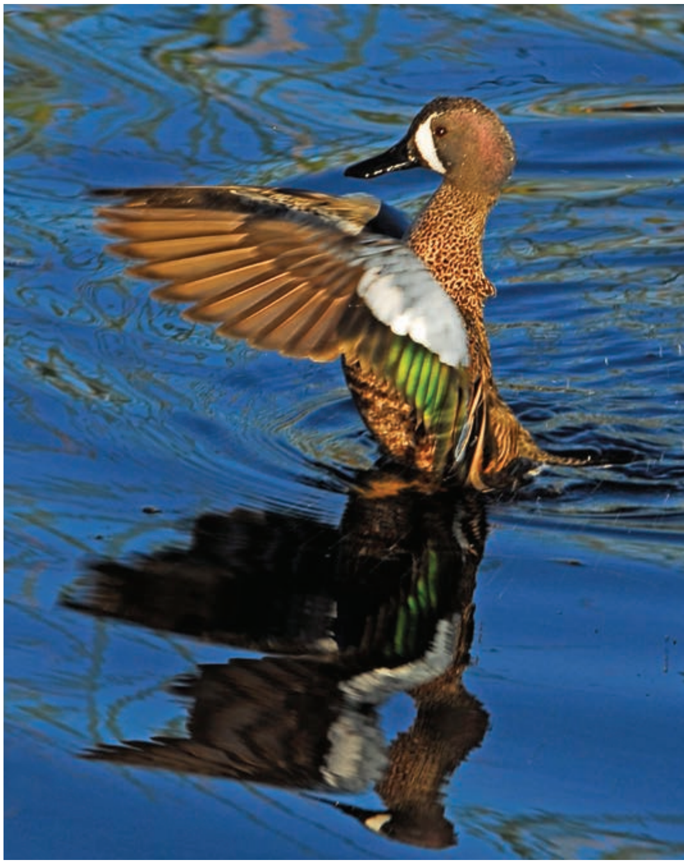
BACKGROUND: COURTESY OF NRG SYSTEMS • INSET, L-R: EASTERN MEADOWLARK, PHOTO BY MATTHEW PAULSON, FLICKR
AMERICAN BALD EAGLE, PHOTO BY USFWS, FLICKR • HOARY BAT, PHOTO BY J. N. STUART, FLICKR

SMOKY HILLS WIND FARM, PHOTO BY DRENALINE, WIKIPEDIA

INTRODUCTION

Electricity from wind energy is a major contributor to the strategy to reduce greenhouse gas emissions from fossil fuel use and thus reduce the negative impacts of climate change. Various scenarios for meeting U.S. carbon emission reduction goals indicate that a four- to five-fold expansion of land-based wind energy from the current 122 gigawatts (GW) by the year 2050 is needed to minimize temperature increases and reduce the risk of climate change to people and wildlife. In addition to near-zero greenhouse gas emissions, wind energy also provides several other environmental benefits including little or no water use associated with electricity production and decreased emissions of mercury and other sources of air and water pollution associated with the burning of fossil fuels (Allison et al. 2019).

The siting and operation of wind energy facilities also pose a risk to some species of wildlife (Arnett et al. 2008; Strickland et al. 2011; Allison et al. 2019). Negative effects may include fatalities resulting from collisions with turbine blades or towers and declines in the availability, quality, or connectivity of habitat caused by construction and operation of wind energy infrastructure. For some species, concern exists that the cumulative effect of impacts from wind energy may contribute to population declines, especially as the installed capacity of wind energy increases.



BLUE-WINGED TEAL, PHOTO BY ANDREA WESTMORELAND, FLICKR

To maximize wind energy's benefits while addressing the risk to wildlife, a first step is to better understand the extent and nature of the risk. This summary seeks to do so by reviewing publicly available information about the adverse impacts of land-based wind power on wildlife in North America and the status of our knowledge regarding how to avoid and minimize these impacts.

The amount of publicly available, peer-reviewed research continues to grow, reflecting the ongoing interest in understanding wind-wildlife interactions. To maintain the highest level of scientific rigor for this summary, we have based our conclusions on research that has been published in peer-reviewed journals or that appears in reports that have undergone expert, technical review.

This summary is updated and undergoes expert review on an annual basis. Literature citations supporting the information presented are denoted in parentheses; full citations can be found online at https://awwi.org/resources/summary-of-wind-power-interactions-with-wildlife/.

Organization of This Summary

This summary organizes statements about what is known and what remains uncertain regarding the adverse impacts of wind energy on wildlife in the following categories:

- Risk factors for collision fatalities
- Population-level consequences of collision fatalities
- Avoidance and minimization of collision fatalities
- Habitat-based impacts on birds and other terrestrial species

Within each section, statements are ordered in decreasing level of certainty. The level of certainty reflects the weight of evidence, which is determined by the consistency of results across studies; the quality of the experimental designs employed; and the relevance of the measured endpoints. So, for example, we have more confidence in conclusions supported by multiple published studies and drawn from experiments with adequate replication and controls than in conclusions based on only a single study. A single study, although informative, is usually insufficient for drawing broad conclusions.

Installed wind energy capacity in the United States continues to grow and was estimated at more than 122,000 megawatts (MW) at the end of 2020. Wind energy accounted for 8.4% of electricity generated in the United States in 2020, more than any other renewable energy source but substantially less than that produced by natural gas (40.3%), coal (19.3%), or nuclear power (19.7%). The power ratings of turbines installed at new projects range from 2-3.6 MW, and turbine towers range in height from 80-100 m (260-325 feet). Turbine blades range in length from 38-60 m (125-200 feet) resulting in a maximum potential height of approximately 160 m (460 feet) and a rotor-swept area of 0.45-1.13 hectares (1.1-2.8 acres). Blade tip speeds range from 220-290 km/hr (140-180 mph) under normal operating conditions. The perimeter of a wind facility may encompass thousands of acres. The most current wind market information can be found at the American Clean Power Association's website.

WOODWARD MOUNTAIN WIND RANCH, PHOTO BY TODD SPINK, NREL 11283

RISK FACTORS FOR COLLISION FATALITIES

At many wind energy facilities, regular searches are conducted for birds and bats that collided with turbines. The number of studies reporting results of collision fatality monitoring at operating land-based wind energy facilities has increased substantially over the years, and studies conducted at more than 100 projects are publicly available (Arnett and Baerwald 2013; Loss et al. 2013a; Erickson et al. 2014; Thompson et al. 2017). Fatality reports for substantially more projects are stored within the American Wind Wildlife Information Center (AWWIC), a cooperative initiative of the American Wind Wildlife Institute (AWWI) and wind energy companies, which includes both public and private data (AWWI 2020a,b). AWWIC also includes data from projects in regions that have few publicly available fatality studies, which should help improve understanding about geographic variation in collision fatalities of both birds and bats. In addition, protocols for carcass searches have become more standardized, and recent advances in estimating fatalities from raw carcass counts should facilitate comparisons of results from separate studies (Dalthorp et al. 2018).

This section outlines what is known and where there is remaining uncertainty about the patterns of bird and bat collision fatalities, particularly in the continental U.S. We first examine patterns that apply to both birds and bats, and then describe patterns specific to either birds or bats.

BLACK THROATED BLUE WARBLER, PHOTO BY KELLY COLGAN AZAR, FLICKR

LITTLE BROWN BATS, PHOTO BY USFWS, FLICKR

Birds and Bats

Fatalities of birds and bats have been recorded at all wind energy facilities for which records are publicly available.

We assume that most bird and bat collisions are with the rotating turbine blades, although collisions with turbine towers and motionless blades may also occur, particularly among birds (Smallwood and Bell 2020). Fatality estimates of individual studies vary in how raw counts are adjusted for known sources of detection error and sampling intensity (Huso et al. 2016). Fatality estimators used to adjust raw counts of carcasses make different assumptions and account for variation in detectability differently, and as a consequence may yield different fatality estimates (Rabie et al. 2021). Comparisons or aggregations of fatality estimates from studies using different estimators should thus be interpreted cautiously. Simulations indicate that GenEst (Simonis et al. 2018) performs better than other commonly used estimators (Rabie et al. 2021) under a wide variety of conditions commonly experienced during fatality monitoring and is recommended for most applications.

For birds, mean estimated fatality rates (i.e., the average estimated number of fatalities after correcting for variation in detectability and sampling intensity) from most studies range from 3 to 6 birds per MW per year[1] for all species combined (Strickland et al. 2011; Loss et al. 2013a; Erickson et al. 2014). In the larger data set contained within AWWIC, 75% of studies reported 2.3 or fewer fatalities per MW per year, with a median fatality estimate of 1.3 birds per MW per year (AWWI 2020b; here, the median is reported instead of the mean because of the right-skewed distribution of fatality estimates).

Estimated bat fatality rates tend to be higher and more variable than bird fatality rates, generally ranging from a mean of 4 to 7 bats per MW per year, but with some individual projects along forested ridgelines of the central Appalachians reporting rates close to 50 bats per MW per year (Arnett et al. 2008; Strickland et al. 2011; Hein et al. 2013). Of the expanded dataset included in AWWIC, 75% of studies reported estimates of fewer than 7.7 bat fatalities per MW per year, with a median of 3.0 bats per MW per year (AWWI 2020a).

The lighting currently recommended by the Federal Aviation Administration (FAA) for installation on commercial wind turbines does not increase collision risk to bats and migrating songbirds.

The FAA regulates the lighting required on structures taller than 199 feet in height above ground level to ensure air traffic safety. The number of bat and songbird fatalities at turbines using FAA-approved lighting is not greater than that recorded at unlit turbines (Kerlinger et al. 2010; Bennett and Hale 2014). One study (Bennett and Hale 2014) recorded higher red bat fatalities at unlit turbines compared to those using red aviation lights; no differences were observed for other bat species between lit and unlit turbines. For wind turbines, the FAA currently recommends strobe or strobe-like lights that produce momentary flashes interspersed with dark periods up to three seconds in duration, and they allow commercial wind facilities to light a proportion of the turbines in a facility (e.g., one in five), firing all lights synchronously (FAA 2007). Red strobe or strobe-like lights are frequently used.

Bat fatality rates may vary substantially among regions in the U.S. while bird fatality rates do not.

Estimated fatality rates of bats are highest at wind energy facilities in the upper Midwest and eastern forests and tend be much lower throughout the Great Plains and western U.S. (Arnett and Baerwald 2013; Hein et al. 2013). Median fatality estimates among studies contained in AWWIC ranged from 0.7 bats per MW per year in the Pacific Northwest to 8.4 bats per MW per year in the Midwest (AWWI 2020a). Regional variation in methodology for conducting fatality studies may be a confounding factor, and thus apparent differences in bat fatality rates among regions or habitats should be interpreted with caution.

There is relatively little geographic variation in the rate of bird fatalities per MW per year for all species combined (Erickson et al. 2014; AWWI 2020b).

The effect of turbine height and rotor-swept area on bird and bat collision fatalities remains uncertain.

The height and rotor-swept area of turbines has been increasing. It has been hypothesized that collision fatalities might also increase due to the greater overlap of taller turbines with flight heights of nocturnal-migrating songbirds and bats (Johnson et al. 2002; Mabee and Cooper 2004; Mabee et al. 2006; Barclay et al. 2007). A larger rotor-swept area also presumably increases the collision risk zone. Some studies show that fatalities of migratory birds and bats are more frequent at taller turbines (Barclay et al. 2007; Baerwald and Barclay 2009; Loss et al. 2013a); however, raptor fatalities were reported to have declined in two studies at Altamont Pass Wind Resource Area following repowering, where smaller turbines were replaced by fewer, taller turbines (Smallwood and Karas 2009; Ventus Environmental Solutions 2016). The importance of turbine height potentially confounded by changes in the type of turbine: typically, lattice-tower turbines were replaced by larger, monopole turbines.

GRASSHOPPER SPARROW, PHOTO BY SHEILA GREGOIRE, FLICKR

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[1] Fatality rates are typically reported on a per turbine basis or per nameplate capacity (MW). We report fatality rates per nameplate capacity to account for differences in turbine capacity, which ranges from 100 kW to 3.0 MW or more. We acknowledge that this reporting format has difficulties, especially when it comes to assessing the effects of repowering and the potential differences in fatalities due to variations in the physical components of the turbines.

GOLDEN-CROWNED KINGLET, PHOTO BY ZANATEH, FLICKR

Birds

The majority of bird fatalities at wind energy facilities are small passerines.

Studies contained within AWWIC reported 307 species of birds discovered during systematic searches for fatalities at wind energy facilities and an additional 13 more that were found incidentally (AWWI 2020b). Raw counts of small passerines (all species in the order Passeriformes except for the larger corvids: magpies, crows, and ravens) account for approximately 57% of fatalities reported in both publicly available and private studies conducted at U.S. wind facilities (Erickson et al. 2014; AWWI 2020b). The representation of small passerines in post-construction fatality studies is less than expected given that this group of birds makes up nearly 90% of all landbirds (Will et al. 2019). However, searcher efficiency trials[2] indicate that small birds have significantly lower detection rates than large birds (Peters et al. 2014) and are removed more quickly by scavengers (Barrientos et al. 2018), and thus raw counts of carcasses may underestimate the proportion of fatalities attributable to small passerines. Modest peaks in fatalities of small passerines occur during spring and fall at most wind facilities, presumably reflecting the passage of migrants during these times (Strickland et al. 2011; Erickson et al. 2014; AWWI 2020b).

Fatalities of diurnal raptors are observed more often than expected given the relatively low abundance of these species.

Diurnal raptors account for approximately 7% of reported fatalities, which is more than expected given their collective population sizes (AWWI 2020b). This may reflect an increased vulnerability to collision among this group of birds or may be an artifact of the higher detectability of carcasses of large birds (Peters et al. 2014). Red-tailed hawk and American kestrel are the most commonly reported raptor fatalities; they are also the two most abundant diurnal raptors in the U.S. and have carcasses that tend to persist longer than those of other species (DeVault et al. 2017; AWWI 2020b).

Reported fatalities of other large bird species are very low.

The vulnerability of prairie grouse to collide with turbines appears low; only greater sage-grouse and sharp-tailed grouse have been reported as fatalities in AWWIC, and numbers for both species were low (four and two carcasses, respectively) (AWWI 2020b). Fatalities of some upland game birds, especially the non-native ring-necked pheasant and gray partridge, are relatively common, accounting for approximately 4% of all bird fatalities (AWWI 2020b).

Fatalities of waterbirds, waterfowl, and other species characteristic of freshwater, shorelines, open water, and coastal areas (e.g., ducks, gulls and terns, shorebirds, loons and grebes) are reported infrequently at land-based wind facilities (Kingsley and Whittam 2007; Gue et al. 2013; AWWI 2020b).

JUVENILE BALD EAGLE, PHOTO BY ELSIE.HUI, FLICKR

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[2] Searcher efficiency trials involve placement of bird and bat carcasses to estimate the number of carcasses missed by field technicians during fatality surveys. This estimate is combined with other sources of detection error, such as scavenger removal of carcasses, to adjust the number of carcasses found during fatality surveys and provide a more accurate estimate of collision fatalities.

The relationship between bird behavior and bird collision risk, especially near the rotor-swept area, is complex and not well understood.

The foraging behavior of some species, such as red-tailed hawk, may take them into close proximity to the rotor-swept zone and possibly explain relatively high fatality rates. Other species, such as common raven, fly around wind turbines and appear to actively avoid collisions with turbines (Kingsley and Whittam 2007; Kuvlesky et al. 2007).

Bats

Migratory tree-roosting bat species are vulnerable to colliding with wind turbines.

At least 25 species of bats have been recorded as collision fatalities in North America, but a large majority of fatalities reported to date are from three migratory tree-roosting species (hoary bat, eastern red bat, and silver-haired bat), which in AWWIC collectively constitute approximately 70% of the reported fatalities at wind facilities for all North American regions combined (Kunz et al. 2007; Arnett et al. 2008; Arnett and Baerwald 2013; Hein et al. 2013; AWWI 2020a). It remains uncertain why these three species appear more vulnerable to collision fatalities than other bat species.

Mexican free-tailed bats account for a significant percentage of bat fatalities in some parts of the U.S.

Mexican free-tailed bat, one of the most abundant bat species in the U.S. (Harvey et al. 2011), constitutes a substantial proportion of the estimated number of bats killed at wind facilities; percentages vary 41-86% across regions that encompass the species' range over most of the southern half of the U.S. (Arnett et al. 2008; Miller 2008; Piorkowski and O'Connell 2010). As with the tree-roosting bats, why Mexican free-tailed bats account for such a high percentage of fatalities remains uncertain.

Bat fatalities peak at wind facilities in the northern U.S. during the late summer and early fall migration.

Several studies in the northern U.S. have shown a peak in the incidence of bat fatalities in late summer and early fall, coinciding with the migration season of tree bats (Kunz et al. 2007; Arnett et al. 2008; Baerwald and Barclay 2011; Jain et al. 2011; Arnett and Baerwald 2013). A smaller peak in fatalities during spring migration has been observed for some bat species at some facilities (Arnett et al. 2008). In the larger sample of projects contained in AWWIC, the incidence of bat fatalities peaks in August in northern areas and September in areas farther south (AWWI 2020a).

EASTERN RED BAT, PHOTO BY MATTHEW O'DONNELL, FLICKR

Some bat species may be attracted to wind turbines.

It has been hypothesized that the relatively high number of bat fatalities that have been observed for some species and locations may be explained by attraction to wind turbines or wind facilities (Horn et al. 2008; Cryan and Barclay 2009; Richardson et al. 2021). Several factors that might attract bats have been proposed, including the sounds produced by turbines, a concentration of insects near turbines, and bat mating behavior (Kunz et al. 2007; Cryan 2008; Cryan and Barclay 2009; Cryan et al. 2012; Cryan et al. 2014; Foo et al. 2017; Bennet et al. 2017). However, definitive tests of these hypotheses are still needed.

Barotrauma does not appear to be an important source of bat mortality at wind energy facilities.

Forensic examination of bat carcasses found at wind energy facilities suggests that the importance of barotrauma, i.e., injury resulting from rapidly altered air pressure caused by fast-moving wind turbine blades (Baerwald et al. 2008; Brownlee and Whidden 2011), is substantially less than originally suggested (Rollins et al. 2012; Grodsky et al. 2011). Theoretical assessments also cast doubt on the importance of barotrauma: fluid dynamics models indicate that there is a low likelihood of bats encountering sufficiently large pressure changes around blades to produce barotrauma (Lawson et al. 2020).

Collision risk for bats varies with the weather.

Bat activity is influenced by nightly wind speed and temperature (Weller and Baldwin 2012), and some studies indicate that bat fatalities occur primarily on nights with low wind speed. Other weather-related variables such as wind direction or changing barometric pressure may also be important (Baerwald and Barclay 2011). Migrating tree bats along a ridgeline in the Appalachian Mountains were more

HOARY BAT, PHOTO BY DANIEL NEAL, FLICKR

active at low wind speeds, high temperatures, and following significant drops in temperature (Muthersbaugh et al. 2019). Activity also varied across the course of a night, albeit in a species-specific fashion (Muthersbaugh et al. 2019). Additional research on weather as a predictor of bat activity and fatalities could support mitigation efforts to reduce bat fatalities (e.g., Arnett et al. 2008; Baerwald and Barclay 2011; Weller and Baldwin 2012; Arnett and Baerwald 2013; Good et al. 2020).

It is uncertain whether collision risk is higher for male migratory tree bats than female migratory tree bats.

In one study, examination of external characteristics of bat carcasses collected at wind energy facilities indicated that the sex ratio of migratory tree bats was skewed towards males (Arnett et al. 2008), although other studies have failed to reproduce this finding in other regions (Baerwald and Barclay 2011). Determining age and sex from a bat's external characteristics can be challenging, especially when carcasses have decomposed or have been partially scavenged (Korstian et al. 2013, Nelson et al. 2018). Studies using molecular methods to sex bat carcasses show no evidence of a consistent sex bias in fatalities of tree bats (Korstian et al. 2013; Nelson et al. 2013), although male bias in fatalities may exist in other species such as evening bats (Korstian et al. 2013).

POPULATION-LEVEL CONSEQUENCES OF COLLISION FATALITIES

Reported levels of fatalities for some bird and bat species have raised concern for potential adverse impacts to populations. While we examine here what is known about the population-level effects of collisions with turbines on wildlife populations, it is important to acknowledge that these effects may operate in combination with other sources of anthropogenic mortality that together could lead to population-level effects. May et al. (2019) and Katzner et al. (2020) review some of the challenges that have limited our ability to understand the population-level consequences of local impacts and offer suggestions for future research.

The estimated total number of collision fatalities of most bird species at wind energy facilities is several orders of magnitude lower than other leading anthropogenic sources of avian mortality.

The number of small passerine birds killed at wind energy facilities is a very small fraction of the total annual anthropogenic bird mortality, and two to four orders of magnitude lower than from other anthropogenic sources of mortality, including feral and domestic cats, power transmission lines, buildings and windows, and communication towers (Longcore et al. 2012; Calvert et al. 2013; Loss et al. 2014a,b,c; Loss et al. 2013a,b; Erickson et al. 2014). Collision fatalities from wind turbines may be relatively more important among the sources of anthropogenic mortality that affect diurnal raptors, including golden eagles (USFWS 2016).

Fatality rates at currently estimated values do not appear likely to lead to population declines in most bird species.

For small passerine species, current turbine-related fatalities constitute a very small percentage of their total population size (typically <0.02%), even for those species with the most

HORNED LARK, PHOTO BY KENNETH COLE SCHNEIDER, FLICKR frequently reported fatalities (Kingsley and Whittam 2007; Kuvlesky et al. 2007; Erickson et al. 2014). However, demographic modeling indicates a potential for population-level impacts at current or projected levels of collision fatalities for some raptor species (Carrete et al. 2010; Bellebaum et al. 2013; Hunt et al. 2017).

The population status of some bat species is poorly understood, and the ecological impact of collision mortality, alone or in combination with other causes of mortality, is not known.

Bats are long-lived, and many species have relatively low reproductive rates, making populations susceptible to localized extinction (Barclay and Harder 2003; Jones et al. 2003). Bat populations of several North American cave-hibernating species have experienced significant declines – up to 90% in some cases – following the emergence of White-Nose Syndrome (WNS), a fungus-caused disease that is estimated to have killed millions of bats in North America since it was first discovered in a cave in New York in 2007 (Frick et al. 2010; Turner et al. 2011; Hayes 2012). Added mortality from wind turbine collisions may exacerbate declines among WNS-vulnerable bat species.

Population sizes for migratory tree bat species are unknown and as such we don’t know whether current or future collision fatality levels represent a significant threat to these species (Kunz et al. 2007; Arnett et al. 2008; Arnett and Baerwald 2013). Demographic modeling indicates a potential for population-level impacts at current or projected levels of collision fatalities for hoary bats (Frick et al. 2017; Friedenberg and Frick 2021). Studies have estimated effective population sizes of tree bats from genetic data, and these estimates might be useful as baselines for evaluating future impacts of collision mortality and other threats to bats (Korstian et al. 2015; Vonhof and Russell 2015; Sovic et al. 2016).

AVOIDANCE AND MINIMIZATION OF COLLISION FATALITIES

Siting

Substantial effort is made to estimate collision risk of birds and bats prior to the siting, construction, and operation of wind energy facilities under the premise that high-activity sites will pose an unacceptable risk to these species and should be avoided. Many wind energy companies choose to apply a tiered decision-making process as outlined in the Land-Based Wind Energy Guidelines issued by the U. S. Fish and Wildlife Service in 2012 (USFWS 2012). This approach, developed with input from multiple stakeholders, outlines a series of steps companies can take to identify potential threats to species thought to be at risk from wind energy development.

DILLON WIND POWER PROJECT, PHOTO BY IBERDROLA RENEWABLES, INC., NREL 16105

Siting individual turbines away from topographic features that attract concentrations of large raptors may reduce raptor collision fatalities at wind energy facilities.

Some analyses have indicated a relationship between raptor fatalities and raptor abundance (Strickland et al. 2011; Carrete et al. 2012; Dahl et al. 2012), although studies also suggest that raptor activity as measured by standard activity surveys may not correlate with the number of raptor fatalities resulting from collisions with turbines (Ferrer et al. 2012). Habitat quality may also be a useful predictor of collision risk in some cases (e.g., Heuck et al. 2019). Large raptors are known to take advantage of wind currents created by ridge tops, upwind sides of slopes, and canyons that are favorable for local and migratory movements (Bednarz et al. 1990; Barrios and Rodriguez 2004; Hoover and Morrison 2005; de Lucas et al. 2012; Katzner et al. 2012; Poessel et al. 2018; Marques et al. 2019)

The ability to predict collision risk for birds and bats from activity recorded by radar and acoustic detectors, respectively, remains elusive.

The use of radar and bat acoustic detectors is a common feature of pre-construction risk assessments for siting wind energy facilities (Strickland et al. 2011). To date, however, studies have not found a relationship between pre-construction activity surveys and post-construction collision risk (Hein et al. 2013; Solick et al. 2020). Predicting bat collision risk using pre-construction activity measures would be further complicated if bats are attracted to wind turbines (see above).

Variation in bat fatality rates may be influenced by landscape features affecting activity and migration routes.

Activity of migratory bats may be influenced by landscape features such as land cover, topography, and presence of water bodies. Variation in bat activity due to these features may be related to the observed variation in fatality rates among projects (Baerwald and Barclay 2009; Santos et al. 2013; Thompson et al. 2017; Peters et al. 2020), although other studies have found no relationship between bat fatality rates and landscape features (Arnett et al. 2008; Arnett and Baerwald 2013). Relating fatality rates to landscape features around a wind energy facility could be useful in siting wind farms to avoid higher-risk areas (Kunz et al. 2007; Kuvlesky et al. 2007; NAS 2007; Arnett et al. 2008; Santos et al. 2013; Davy et al. 2020).

Operations

Wind energy companies are also employing a variety of technologies and operational techniques to minimize fatalities of vulnerable species at operating wind energy facilities.

Curtailing blade rotation at low wind speeds results in substantial reductions in bat fatalities.

An examination of ten separate studies (Baerwald et al. 2009; Arnett et al. 2011; Arnett et al. 2013b) showed reductions in bat fatalities ranging from 50 to 87% at curtailed turbines when compared to normally operating turbines. Further study to identify times when bat collision risk is high could optimize timing of curtailment and minimize power loss (Weller and Baldwin 2012; Martin et al. 2017). For example, a smart curtailment approach that combined real-time data on wind speed and bat activity near turbines reduced estimated fatalities of all bats at a facility by nearly 85% while reducing the overall curtailment time by nearly 50% relative to controls (Hayes et al. 2019). Power generation at treatment turbines was reduced by 3% relative to turbines that were not curtailed (Hayes et al. 2019).

Selective shutdown of high-fatality turbines may be an effective strategy for reducing fatalities of some raptor species.

Some of the highest raptor fatality rates have been observed in southern Spain where raptors congregate to cross the Strait of Gibraltar to Africa during migration (Ferrer et al. 2012). One study (de Lucas et al. 2012) reported a substantial reduction of griffon vulture fatalities (mean of 50.8%) at a facility due to selective shutdown of turbines where the greatest number of fatalities was observed.

The use of ultrasonic transmitters may deter bats away from rotor-swept areas and reduce bat fatalities.

Experimental trials have shown that ultrasonic devices can reduce bat activity and foraging success, and evaluation of similar devices installed on wind turbines has shown that they reduce bat fatalities (Arnett et al. 2013a; Romano et al. 2019; Gilmour et al. 2020; Weaver et al. 2020). Effectiveness of ultrasonic deterrents appears to vary among species for reasons that are unknown.

JUVENILE RED-TAILED HAWK, PHOTO BY KELLY COLGAN AZAR, FLICKR

Automated monitoring may allow for smart curtailment strategies that reduce fatalities of raptors and other large birds.

Automated systems can successfully detect and classify eagles in the vicinity of a wind project and are able to detect large birds at far greater distances than human observers (McClure et al. 2018). Initial tests indicate that these systems are effective in issuing selective curtailment orders: a study in Wyoming reported a 63% decline in golden eagle deaths after installation of an automated detection system (McClure et al. 2021). Additional research will be needed to determine whether this approach is equally effective in different locales or for different species.

Efforts to increase turbine visibility and reduce collision fatalities have shown mixed results.

Impact minimization methods that are assumed to make turbine blades more visible to birds have been proposed to reduce collisions with wind turbines. Ultraviolet (UV) paint, hypothesized to be more visible to birds, did not reduce collisions in one study (Young et al. 2003) and controlled behavioral trials have indicated that some raptor species show little response to UV light (Hunt et al. 2015). In contrast, painting one blade of a wind turbine black reduced annual fatality rates of birds at a Norwegian wind energy facility by more than 70% (May et al. 2020). Although the results were promising, the authors cautioned that replication is needed to determine whether painting blades will reduce fatalities in other locations and for other species.

HABITAT-BASED IMPACTS ON BIRDS AND OTHER TERRESTRIAL SPECIES

Species' use of habitat can be affected by the construction and operation of a wind energy facility. Impacts can include disturbance, displacement from suitable habitat, or demographic effects due to fragmentation of habitat or changes in populations of predators, competitors, or prey. The section below outlines what is known and where there is remaining uncertainty about habitat-based impacts on birds and other terrestrial species.

Construction and operation of wind energy facilities can reduce abundance of some bird species.

Displacement from otherwise suitable habitat in response to wind energy development has been observed in some species (Loesch et al. 2013; Winder et al. 2013, 2014, 2015; Stevens et al. 2013; Shaffer and Buhl 2016; LeBeau et al. 2017a,b; Fernández-Bellon et al. 2019; Coppes et al. 2020; Kirol et al. 2020). Displacement may be temporary, with some species appearing to habituate to the disturbance associated with wind facilities, or persistent (Pearce-Higgins et al. 2012; Shaffer and Buhl 2016; Dohm et al. 2019; Lemaître and Lamarre 2020). The reported extent and magnitude of displacement varies substantially among species and sites and the causes of this variation remain poorly understood. The population-level consequences of displacement due to wind energy development are unknown.

WHOOPING CRANES, PHOTO BY GILLIANCHICAGO, FLICKR

GREATER PRAIRIE-CHICKEN, PHOTO BY WILDRETURN, FLICKR

Studies report few negative effects on survival or reproduction of birds at wind energy facilities.

Demographic studies have not found consistently lower levels of survival or reproduction among birds living near wind facilities (Gue et al. 2013; Hatchett et al. 2013; Bennet et al. 2014; Winder et al. 2014; McNew et al. 2014; Winder et al. 2015; Kolar and Bechard 2016; Mahoney and Chalfoun 2016; Gillespie and Dinsmore 2017; LeBeau et al 2017a; Smith et al. 2017; Harrison et al. 2017; Proett et al. 2019).

It is unknown whether wind energy facilities decrease habitat quality or act as barriers to landscape-level movements by big game and other large terrestrial vertebrates.

There are a small number of studies that have evaluated the hypothesis that land-based wind energy facilities negatively affect non-flying wildlife. Proximity to a wind facility did not affect winter survival of pronghorn in Wyoming (Taylor et al. 2016), but it did change patterns of space use by females (Smith et al. 2020). Female Pronghorn were not displaced by construction of the wind energy facility but, following construction, tended to increase use of those parts of their winter home range that were farther from a turbine. Development and operation of a wind facility in Oklahoma had no measurable impact on radio-collared Rocky Mountain elk (Walter et al. 2006). Long-term studies of desert tortoise at a California wind facility found survival of adult female tortoises was higher within the area of the facility than in an adjacent undisturbed area (Agha et al. 2015). However, fewer tortoises were using the area encompassed by the facility – an effect that became apparent after almost 20 years of monitoring (Lovich et al. 2011; Ennen et al. 2012; Lovich and Ennen 2017).

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