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Bats and Wind Energy: Impacts, Mitigation, and Tradeoffs

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AWWI is a partnership of leaders in the wind industry, wildlife management agencies, and science and environmental 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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Purpose and Scope

Scientific experts widely agree that a rapidly warming climate resulting primarily from the burning of fossil fuels will force major range shifts and substantially increase extinction risk for large numbers of species (e.g., Audubon 2015). Reducing this risk to wildlife as well as to human systems will require major shifts in energy production to non-carbon emitting sources. Wind energy is a major component of the strategy to reduce carbon emissions, and the amount of electricity generated by wind energy has grown substantially in the past 15 years. However, a recent IPCC Report indicates that the pace and scale of emission reductions needs to accelerate to keep temperature increases by the end of the 21st century to a level (1.5 degrees C) that reduces the risk of unmanageable and accelerating temperature increases (IPCC 2018). The IPCC 2018 report indicates that 49%-67% of "primary energy" must come from renewable energy, including wind, by 2050 to avoid a more than 1.5 degrees C increase. Achieving that goal would increase already ambitious targets as outlined in the U.S. Department of Energy Wind Vision, which proposes that 20% of U.S. electricity should come from wind energy alone by 2030 and 30% by 2050 (U.S. Department of Energy 2015). In 2017, 6.3% of energy in the U.S. was generated by wind, and 17% was generated by all renewable sources combined (EIA 2018).

Like all energy sources, wind energy can have adverse impacts to wildlife. Since the early 2000s, surveys at wind facilities have shown that some bat species, such as migratory tree bats, can collide with wind turbines and be killed in large numbers, particularly in the Midwestern and Appalachian regions of the U.S. (Arnett et al. 2008). The magnitude and ubiquity of bat fatalities has raised serious concerns among wind-wildlife stakeholders about the long-term viability of the bat species with the highest estimated fatality rates (e.g., Frick et al. 2017). Uncertainties remain about the impact of wind energy on bats, and substantial efforts are underway to reduce those uncertainties. In a precautionary approach, some permitting authorities are restricting operations of wind turbines to reduce bat fatalities (Alberta, Ontario, Pennsylvania), but some of these restrictions may pose risks to the economic viability of the operations of current and future projects.

Can we develop wind energy at the pace and scale needed to meet emission reduction goals and not imperil bat populations as we do so? Can we protect bats without impeding the contribution of wind energy to emission reduction targets that are needed in the next two decades? The IPCC 2018 report indicates that we have limited time to answer these questions.

To identify a path toward answering these and other questions, the American Wind Wildlife Institute (AWWI) developed a National Wind Wildlife Research Plan to identify and prioritize key areas where additional, strategically targeted research investments were needed to advance:

- Our understanding of **the nature and magnitude of the impacts of wind energy on wildlife** and wildlife habitat
- The **development, evaluation, and widespread application** of strategies to avoid, minimize, and compensate for those impacts when necessary to conserve healthy wildlife populations

The National Research Plan articulates that reducing risk to bats presented the greatest conservation challenge to wind energy development. This bats and wind energy white paper updates the goals of the National Research Plan to reflect the increased urgency in addressing the challenge of bats and wind energy. The revised goals focus recommendations on those topics most likely to reduce key uncertainties regarding understanding of the risk to bats from wind energy and our ability to mitigate that risk. Although scientific research is essential for answering the questions posed above, we also recommend a structured conversation with wind-wildlife stakeholders to achieve a shared understanding of the pace and scale of renewable energy siting needed to help limit the wildlife impacts of climate change as we minimize impacts to bats.

Bats of the U.S. and Canada

Bats are considered an ecologically important group, and conservation concerns about bats in general are long-standing and numerous. Detailed reviews covering bat biology and conservation have been published over the years (Kunz and Fenton 2003, Lacki et al. 2007b). In particular, several reviews have summarized what we know about the impacts of wind energy on bats and potential hypotheses for those impacts (Johnson 2005, Arnett et al. 2007, 2008, 2016, Kunz et al. 2007, Cryan and Barclay 2009, Arnett and Baerwald 2013, Hein and Schirmacher 2016, Barclay et al. 2017). This white paper draws heavily on these reviews; the research literature on bats and wind energy; and published information on bat ecology, distribution, and, when available, population trends.

This section provides a brief overview of bat biology, ecology, and status, focusing specifically on those attributes relevant to understanding the risk that wind energy development and operation poses to North American bat species. Concerns about the risk of wind energy to bats, of course, are not limited to North America, and have been the subject of considerable discussion in other countries and regions. The scope of this white paper, however, is limited to bats and wind energy in the U.S. and Canada.

Distribution and Diversity

Bats are the second-most diverse order of mammals, numbering well over 1,000 species worldwide. Recent reviews describe 45-47 species comprising five families[1] in the continental U.S. and Canada, with the most diverse family being Vespertilionidae, representing 34 species (Harvey et al. 2011, Hammerson et al. 2017; See Appendix A). Bat species diversity is higher in the New World tropics than in more northern latitudes. For example, there are 138 species in Mexico (Medellin et al. 2017), and the northern limit of several North American species' ranges occur in the southwestern or southeastern U.S. (Figure 1).

Life History

Bat species in the U.S. and Canada exhibit diverse behaviors. It is convenient to describe two major groups of bats based on their behavior during the periods of cold temperatures and low food availability characteristic of much of the U.S. and Canada:

1. The first group, commonly referred to as **cave-hibernating bats**, comprises species that undergo torpor and overwinter in caves, mines, and other sheltered areas that have low but stable temperatures. Hibernacula may contain both males and females. These species may undergo arousal from torpor at multiple times throughout the winter, although the function of this arousal is unclear, and it is energetically expensive (Thomas et al. 1990, Halsall et al. 2012). Females of these species may also aggregate in maternity roosts and undergo substantial "regional migrations" of hundreds of miles and back to these roosts over the course of a year (e.g., Loeb and Winters 2013). Cave-hibernating bats tend to be colonial and utilize day roosts during the summer including human-made structures, tree cavities, loose bark, etc. (Carter and Menzel 2007), and some are also known to use human-made structures for winter hibernation (e.g., Halsall et al. 2012).
2. The second group of bat species include foliage-roosting species (e.g., Carter and Menzel 2007) and are often referred to as **migratory tree bats**. Species in this group migrate latitudinally to warmer locations, undergo torpor of varying lengths during cold periods, and arouse frequently to feed during the winter months. The winter ranges of male and female tree bats may be mostly non-overlapping (e.g., Cryan 2003, Cryan and Veilleux 2007, Cryan et al. 2014b). Individuals in this

[1] Bat taxonomy and systematics, like other taxa, undergo revision, especially as new molecular data becomes available. The range in the number of species recognized for North America reflects whether recent species splitting is agreed to, or whether it is agreed that the geographic range of a species occurs in North America.

group tend to be solitary year-round. This group includes the species that are the most common fatality incidents at wind energy facilities.

Several bat species of the deserts of the southwestern U.S. typically don't have freezing temperatures to contend with and don't fall neatly into the two categories above. Some southwestern bat species do roost in caves to avoid the heat and dryness of the desert day. Other bat species in this region can't hibernate and thus migrate during periods of low food availability.

During warm seasons all bats roost during daylight hours for protection from predators (Brigham 2007).

Most North American bat species are insectivorous, typically using echolocation to find and capture flying insect prey, although some bat species may also capture "perched" insects by gleaning them from surrounding surfaces. At least three North American bat species forage on flowers and fruit and undergo seasonal movements to track the availability of their food supply.

Bats have a collection of life history attributes considered unusual for small mammals, including a long life span and low fecundity. These attributes have implications for the consequences of additional mortality from wind turbine collisions. Barclay and Harder (2003) hypothesized that these traits are associated with low extrinsic mortality, reflecting a low predation risk due to a nocturnal flying habit. Most bat species in North America have single litters and single young, although some species have twins. Bats in the genus *Lasiurus* are a general exception to this pattern and are unusual in having four mammary glands (Carter and Menzel 2007). Although also having a single litter, litters in this genus may contain 2-4 young. Survival rate within litters of multiple young is unknown.

The reproductive cycle apparently is not known for all bats in the U.S. and Canada. However, in the bat species that have been examined, delayed fertilization is a common feature, particularly in vespertilionid bats (e.g., Orr and Zuk 2013).

For migratory tree bats and cave-hibernating bats in northern U.S. and Canada that have delayed fertilization, the following describes a "typical" life cycle:

1. **Swarming:**
    a. Mating in late summer-early fall
    b. In cave-hibernating bats this occurs near hibernacula
    c. Fertilization is delayed until spring
    d. "Lekking" may occur in some migratory tree bat species
2. **Over-wintering:**
    a. October-November through April of the following year in hibernating bats
    b. Migration of tree bats occurs earlier, in August through early October
3. **Ovulation and fertilization:**
    a. In spring;
    b. In hibernating bats, when females awaken
4. **Formation of maternity colonies:**
    a. Occurring soon after emergence
    b. Of various sizes in colonial species, but typically individual females in solitary species
5. **Gestation**
    a. Variable, for example, 50-60 days in *Myotis*; 80-90 days in *Lasiurus*
6. **Weaning:**
    a. Occurs 5-6 weeks post-partum
    b. Young may become capable of flight at 3-4 weeks
7. **Reproductive** maturity:

   a. E.g., *Myotis*, 2.5-3 months
   b. Females in many species can breed in their first year

8. Repeat

Bat Population Sizes and Trends

To further understand the ecological significance of collision fatalities for bat species, it is important to understand both bat population numbers and trends, and bat population structure. The latter refers to whether there is structuring of populations into sub-populations – or groups – within a species' range due to limited exchange between sub-populations. One or more of these sub-populations may be at risk while others are not, and increased mortality due to collision fatalities may be more of a threat to sub-populations at risk. Alternatively, a species may represent one well-connected population. Some bat species, such as Townsend's big-eared bat (*Corynorhinus townsendii)*, appear to have discrete, geographically separate populations, while others, such as some species of migratory tree bats, may effectively have one single population (Korstian et al. 2015).

Bat population numbers may range from a few thousand, such as the geographically restricted Ozark big-eared bat (*Corynorhinus townsendii ingens*) to tens of millions, such as the Mexican free-tailed bat (*Tadarida brasliensis*). Unfortunately, there are challenges in accurately assessing numbers and trends in bat populations, even in the more gregarious cave-hibernating species (e.g., Racey and Entwistle 2003). For example, visiting hibernacula to census bats can disturb bats and cause arousal from torpor, which consumes energy and puts the bats at risk (O'Shea et al. 2003). Maternity roosts have been known to be abandoned after visits (e.g., Humphrey and Oli 2015).

Obtaining estimates of population numbers of migratory tree bats is even more difficult because these species tend to be cryptic and more solitary than cave-hibernating bats. Recent studies have used genetic analysis to estimate effective population sizes, N_e, which is defined as the number of individuals contributing offspring to the next generation. For example, genetic analysis indicates that both the eastern red bat (*Lasiurus borealis*) and hoary bat (*L. cinereus*) have "large, well-connected populations, with N_e numbering in the hundreds of thousands to millions" (Korstian et al. 2015, Vonhof and Russell 2015). N_e is assumed to be smaller than the actual population size, and to reflect attributes of the population from the past, rather than the present.

Populations of most North American bat species are thought to have declined due to anthropogenic activity, including habitat loss and persecution, and more recently, direct and indirect impacts of pesticides/insecticides. For example, 19th and early 20th century accounts report large, diurnal flights of eastern red bats, which are not reported today (Barbour and Davis 1969). Long-term mist-netting records and rabies submissions also suggest that many bat species are in decline (e.g., Whitaker et al. 2002, Winhold et al. 2008). In the past 10 or so years, some populations of cave-hibernating bat species are thought to have declined approximately 75 to 95% from White-nose syndrome (WNS; see below).

Recognizing the importance of accurate data on population size and trends for bats, the U.S. Geological Survey (USGS) created the USGS Bat Population Data Project (BPD), defined as "a multi-phase, comprehensive effort to compile existing population information for bats in the United States and Territories" (USGS 2017). The BPD compiles various components of bat population data from 1855-2001, including counts of bats at colony locations and location attributes, while providing a bibliography of bat publications for the U.S. and its Territories. Concerns about declines in bat numbers have continued, and the added threats of WNS and wind energy development have resulted in efforts to update and expand the usability of the BPD.

Efforts to better understand bat population status were expanded further with the launch of the North American Bat Monitoring Program (Loeb et al. 2015), an international, multiagency program to assess changes in bat distributions and abundances using multiple monitoring strategies(NABat 2018).

Legal Protection

Seven species and subspecies of bats occurring in the U.S. are federally endangered, and one species is threatened (see Appendix A). The listing of bat species is often related to current numbers and trends, but also takes into account risk exposure. For example, the listed gray bat[2] (*Myotis grisescens*), although numerous, is thought to be declining due to cave disturbance, and 95% of the population hibernates in only 9-15 caves; one cave in Alabama (Fern Cave) has >1 million individuals. Northern long-eared bat (*M. septentrionalis*) was listed recently as threatened under the Federal Endangered Species Act (ESA), and the U.S. Fish and Wildlife Service (USFWS) agreed that consideration is warranted for listing of at least one other species, tri-colored bat (*Perimyotis subflavus*), because of major declines in numbers of both species due to WNS (see below).

Many bat species were previously considered USFWS Category 2 species, i.e., species for which listing may be warranted, but insufficient data were available (USFWS 2018). The USFWS eliminated this category in December 2016, and many of the species are now categorized unofficially as "Special Concern" (see Appendix A). Several species not listed in the U.S. have legal protection in Canada, including pallid bat (*Antrozous pallidus*), little brown bat (*M. lucifugus*), northern long-eared bat, and tri-colored bat; the latter three were recently listed in Canada as endangered because of declines associated with WNS. In the U.S., several states extend legal protection to bat species. For example northern long-eared bat, a federally threatened species, is listed as threatened or endangered in Illinois, Iowa, Massachusetts, Missouri, New York, Ohio, and Wisconsin, among other states (USFWS 2018).

Two federally listed species, Indiana bat (*M. sodalis*) and northern long-eared bat, have been reported as collision fatalities at wind energy facilities. Fatalities of Hawaiian hoary bat (*Lasiurus cinereus semotus*), a federally endangered subspecies, have been found at wind facilities in Hawaii. Other federally listed species currently have little, if any, geographic overlap with wind energy development.

Threats to North American Bat Populations

As described by Pauli et al. (2017), apparent declines in bat populations prior to wind energy development and WNS were thought to have resulted primarily from cave disturbance and modification (Thomson 1982, USFWS 2007, Hammerson et al. 2017), effects of toxins (O'Shea and Clark Jr. 2001), and the loss and fragmentation of roosting and foraging habitat (Sparks et al. 2005, Barclay and Kurta 2007).

Bats may be particularly sensitive to environmental contaminants (O'Shea and Clark Jr. 2001, Jones et al. 2009), especially those that bioaccumulate. Measured levels of mercury (Hg), a powerful neurotoxin, have been very high in some species (Yates et al. 2014, Korstian et al. 2018), and mercury can be transmitted to young during lactation (Yates et al. 2014). Organochlorines from pesticides are known to accumulate in Myotis species and can cause death or reduced reproductive success when toxins are utilized from fat stores during hibernation (e.g., Eidels et al. 2013). Organochlorines can be passed to young in milk and result in death of juveniles. These chemicals were banned in the 1980s in the U.S., but due to their long persistence time in the environment significant concentrations continue to be found in bats (Kannan et al. 2010, Buchweitz et al. 2018). Current-use pesticides, e.g., organophosphates, carbamates, and pyrethroids, have also been measured in bats, but their effects on bats and bat populations is uncertain.

[2] Members of the genus *Myotis* often incorporate the genus name as part of the common name, e.g., gray myotis. There is not formally accepted convention, and for this white paper we refer to *Myotis* species as "bat", e.g., gray bat.

It is assumed that loss of forest cover due to land-use changes and changes in forest structure from forest management practices have contributed to declines in bat numbers, especially in cavity roosting species (Lacki et al. 2007a). The character of and access to cavity roosts have been a major area of research and are a primary consideration for bat conservation because of the importance of roosts for thermal regulation and energy use, and for protection from predators. Silvicultural practices favor harvesting older forest stands that support more roosting sites and thus may reduce the number and distribution of roosts across the landscape. Proximity of roosts to foraging habitat and water sources is important and may affect commuting times and thus energy use and exposure to predators. Far less is known about the characteristics and availability of foliage roosts and their effect on numbers of foliage-roosting species (Carter and Menzel 2007).

Forest practices may also alter foraging habitat and abundance of insect prey, although the link between the abundance of insect prey and bat numbers remains to be established. There are concerns about declines in avian aerial insectivores (Smith et al. 2015), and broad declines in many bat species that are also aerial insectivores leads to speculation of a common cause. Stable isotope analysis of museum specimens of Eastern Whip-poor-will (*Antrostomus vociferus*) from Ontario suggested that the amount of large insect prey in this bird's diet is declining, and the species has shifted to smaller insect prey that are less nutritious (English et al. 2018). A recent study in Germany indicated a more than 75% decline in insect biomass over 27 years in natural areas (Hallmann et al. 2017). Although causes for possible insect declines are unknown, widespread use of insecticides could be to blame.

Collisions with buildings and towers are major sources of avian mortality, but are not thought to be an important source of bat mortality, although such collisions have been reported (Terres 1956, Timm 1989).

White-Nose Syndrome

White-nose syndrome (WNS) is a disease that affects several North American bat species and is caused by the fungus *Pseudogymnoascus destructans*. It was first discovered in the U.S. in eastern New York in 2006 and has since spread westward and southward. The disease is now confirmed in 33 states and seven Canadian provinces, and in 11 bat species (White-nose Syndrome Response Team 2018). Species affected are primarily cave-hibernating bats. The fungus has been found on individuals of two species of tree bats – eastern red bat and silver-haired bat (*Lasionycteris noctivagans*) – but the disease has not been confirmed in these species. See Frick et al. (2010a) and Blehert et al. (2009) for citations on discovery and spread of the disease.

The USFWS estimates more than six million bats had died from WNS as of 2012 (USFWS 2012). Results of surveys at hibernacula from five eastern states (summarized in Table 1, Turner et al. 2011) indicate substantial variation among species in declines at the sites. The surveys showed the largest declines were in little brown bat and the recently listed northern long-eared bat. The northern long-eared bat seems particularly hard hit, declining approximately 93% in eastern states. Pre-WNS, this species was the second-most commonly recorded species in Vermont, but it is now rarely encountered (Frick et al. 2015). A 2017 survey in Missouri reported only six individuals of northern long-eared bat in more than 300 caves and mines where nearly 2,700 had been reported in 2015 (Winter 2017). Large declines in little brown bat and northern long-eared bat have also been observed in Tennessee between 2010 and 2016 (Campbell 2016). The USFWS Midwest Habitat Conservation Plan Environmental Impact Statement reports one million little brown bat deaths from WNS between 2006 and 2009 (USFWS 2016). Thogmartin et al. (2012), estimated a 10.3% annual decline in little brown bat since the onset of WNS. Substantial declines in numbers of endangered Indiana bat have also been reported (Turner et al. 2011). Surveys of hibernacula and mist-net surveys including big brown bat have shown mixed responses for this species with observations of declines, no change, or increases in numbers since the species exposure to WNS (Frank et al. 2014, Pettit and O'Keefe 2017, Table 1)

The long-term prognosis for the most-affected species is uncertain, although more than one author (e.g., Frick et al. 2010a) has speculated that WNS could result in extirpation of these species. Recent work on little brown bat suggests that the severity of the disease may be declining in this species (e.g., Moore et al. 2018), possibly leading to improved winter survival. In some isolated examples, numbers of some species at some sites may have increased slightly, and individual bats have been known to survive the presence of the disease in hibernacula or summer roosts for several years (Reichard et al. 2014, Maslo et al. 2015). These examples raise hopes that the virulence of the disease may be attenuating in some locations, or that there are individuals in these species that are more resistant to the disease.

Climate Change

That the climate is warming rapidly is beyond dispute, and species are responding by range shifts northward or to higher elevations and by changes in phenology (Parmesan 2006). The extent to which climate change adversely affects North American bat species is largely speculative and likely to vary among bat species, although the ranges of some species, such as the Mexican free-tailed bat and Seminole bat (*Lasiurus seminolus*), may have already shifted northward in the southeastern U.S. (Snyder 1993, Wilhide et al. 1998).

Most insectivorous bats must drink to maintain water balance, and water needs increase considerably during pregnancy and lactation (Adams and Hayes 2008). Changes in water availability, such as in severe droughts exacerbated by climate shifts, may adversely affect reproductive success (Adams 2010). Insect populations may decline during droughts, resulting in increased foraging costs and decreased annual survival for bats (Frick et al. 2010b).

These impacts are most likely to be experienced by bat species in the arid western regions of the U.S. For example, Adams (2010) described reduced reproduction by several bat species in Colorado associated with reduced streamflow, the latter being a predictable outcome of future reductions in precipitation. Adams (2010) found that lactating females drank regardless of ambient conditions, whereas non-lactating females chose times to drink when water loss potential was lower.

There are specific times of year when bats, notably reproductively mature females, have high energy demands, such as during lactation or when preparing for long-distance movements to maternity sites or hibernacula and winter roosts. These periods need to coincide with the availability of insect prey that may also undergo large-scale movements (Krauel et al. 2015). Changing climate and weather patterns could disrupt the synchrony between these periods of energy demand and availability (Frick et al. 2017b). Some species, such as Mexican free-tailed bats, aggregate in the hundreds of thousands and the amount of prey consumed would be enormous. However, this species also can show flexibility in emergence times from roosts in response to weather (Frick et al. 2012, Stepanian and Wainwright 2018) suggesting potential adaptation to the effects of a changing climate.

Warming temperatures could lead to reduced migratory distances as suitable wintering habitat moves north. Stable isotope analysis suggests that migratory tree bats head south and to coastal areas where they can combine periods of torpor in near freezing temperatures with feeding at warmer temperatures (Cryan et al. 2014b). An analysis of preferred hibernation temperatures has led to the prediction that the winter distribution of little brown bats will show a pronounced northward movement (Humphries et al. 2002).

Suitable area for summer maternity colonies of Indiana bat are forecasted to decline, particularly in western and central parts of its range (Loeb and Winters 2013). Frick et al. (2010b). It is hypothesized that summer drought may reduce adult female survival in little brown bat.

Predicting impacts of a changing climate on bats will depend on behavioral adaptability and availability of suitable habitat as shifting climates change the landscape where these species must meet their ecological requirements.

Impacts of Wind Energy on Bats

Collision fatalities at wind energy facilities are considered by many to be one of the greatest threats to bat populations in North America and Europe (O'Shea et al. 2016), and several hypotheses have been put forward to explain this high collision risk (see Barclay et al. 2017 for a recent summary of the status of these hypotheses).

The summary of collision impacts of wind energy on bats in this white paper is based on a detailed review of bat fatality incident and adjusted fatality estimate data contained in the American Wind Wildlife Information Center (AWWIC; Allison and Butryn 2018). AWWIC is a cooperative initiative of AWWI Partners and Friends intended to expand the availability of wind-wildlife data for analysis to improve our ability to predict risk and estimate impacts of wind energy development and operation on wildlife. For more than 20 years, wind energy companies have undertaken hundreds of fatality monitoring studies to assess collision impacts to bats and birds from wind energy projects. Many of the data are publicly available, but other data are confidential, and until recently have been unavailable for analysis. AWWIC stores public and confidential proprietary wind-wildlife data with the intention of increasing the amount of data for analysis while maintaining data confidentiality.

This summary is based on data from the conterminous U.S. only; data from wind facilities in Alaska, Hawaii, and Canada are not included in the database. Most other cumulative assessments of collision fatalities include data from Canada, which may account for some of the differences in the AWWIC data summarized below when compared to previous summaries.

Collision Fatalities

Twenty-four of 47 bat species in the continental U.S. and Canada have been found as fatalities at wind energy facilities (e.g., Arnett and Baerwald 2013). Twenty-two species are recorded as fatality incidents at U.S. wind facilities in AWWIC (Table 2), and two additional species have been reported from wind facilities in Canada. As in previous cumulative assessments, hoary bat, eastern red bat, and silver haired bat account for most collision fatalities. In AWWIC, these species constitute 72% of all fatalities, somewhat lower than the widely cited 78 to 80% cumulative total for these three species (Arnett and Baerwald 2013). The cumulative percentage of fatality incidents for hoary bat, a species considered particularly at risk from collision fatalities, is 32% of all incidents in AWWIC, versus 38% as cited in other reports (e.g., Frick et al. 2017a).

These differences in percentages appear to be due primarily to an increase in the percentage of Mexican free-tailed bat fatality incidents in AWWIC relative to cumulative assessments based on publicly available data only. This species accounted for approximately 3% of all incidents in previous assessments (see also Thompson et al. 2017), but accounts for approximately 10% of all fatality incidents in AWWIC. This reflects the increased representation in AWWIC of wind facilities in regions of the U.S. that overlap with the distribution of Mexican free-tailed bat. Studies from regions that overlap with the range of Mexican free-tailed bat are still underrepresented in AWWIC – for example, the USFWS Southwest Region (Region 2) has 35% of the installed capacity in the U.S. while 19.5% of the installed capacity for this region is represented with studies in AWWIC – so the cumulative percentage of fatality incidents of this species are likely higher.

The four species mentioned (Mexican free-tailed bat, hoary bat, eastern red bat, and silver haired bat) and four additional species (little brown bat, big brown bat, tri-colored bat, and evening bat) collectively account for more than 95% of all recorded bat fatality incidents in AWWIC. Fourteen bat species account for <1% of all reported incidents. The remaining 3.6% of all fatality incidents are unidentified bats.

Fatality incidents of hoary bat are widespread and predominate the data from most regions of the U.S. This is the only bat species found in all 32 EPA Level III Ecoregions represented in the AWWIC database, and there is relatively low regional variation in the proportion of hoary bat fatality incidents within AWWIC. In contrast, some species show both high among- and within-region variation in numbers of fatality incidents in AWWIC. Big brown bat (*Eptesicus fuscus*) and little brown bat, for example, are widespread species that show high geographic variation in fatality incidents. Tri-colored bat fatality incidents are highest in the USFWS Northeast Region (Region 5), and within that region are highest within the Central Appalachians and Ridge Valley Ecoregions. Ecoregions further north, but still part of the range of tri-colored bat, have few reported fatality incidents of this species.

Adjusted bat fatality estimates in the U.S. range from <1 to 50 bats per MW per year. Seventy-five percent of projects had fatality estimates of <5 bats per MW per year, and the median adjusted fatality estimate was 2.6 bats per MW per year. There is substantial and significant variation in adjusted fatality estimates among the USFWS Regions. The Midwest, Northeast, and Southwest regions report higher and wider ranges of estimates than Mountain Prairie, Pacific, and Pacific Southwest regions (Figure 1). This pattern can be observed even when the dataset is limited to estimates adjusted using one estimator, e.g., Shoenfeld or Huso (Allison and Butryn 2018).

Variation in fatality estimates can be seen within regions as well. For example, all studies from the Acadian Plains and Hills Level III Ecoregion were below the Northeast USFWS Region median of 3.5 bats/MW, while nearly all estimates from Central Appalachians and Ridge and Valley Ecoregions were above the Northeast Region median (Figure 3). In the Midwest Region, fatality estimates in AWWIC from the Western Corn Belt Plains Ecoregion are mostly below the Midwest Region median of 6.2 bats/MW, whereas estimates from studies in the Southeastern Wisconsin Till Plains and Central Corn Belt Plains Ecoregions have much greater variation in estimates, and they all fall above the Midwest Region median (Figure 3).

Any estimate of the annual number of bat fatalities at all U.S. wind energy facilities should be made carefully because of the non-random nature of the data, the uneven geographic representation, and the lack of consistency in survey methods and adjustments to raw fatality counts. Arnett and Baerwald (2013) estimated a range of approximately 190,000 to nearly 400,000 bat fatalities in the U.S. and Canada in 2012. Based on the AWWIC composition of fatality incidents, the three migratory tree bats constitute ~70% of those fatalities.

Data continue to be added to AWWIC to further analyze variation as well as other factors that underlie the observed variation in fatality rates among projects and regions. For example, previous assessments of variation in fatality estimates found a relationship between bat fatalities and turbine tower height (Barclay et al. 2007). No relationship between these variables was observed in the AWWIC data, although we are still investigating this relationship.

Barotrauma

Baerwald et al. (2008) described dead bats found around wind turbines that had no physical sign of injury but had ruptured ears and blood in the lungs consistent with injury due to sudden pressure changes, known as barotrauma. Bat scientists speculated that bats would experience sudden pressure changes as they passed through rotating turbine blades. An implication of the barotrauma hypothesis was that bats might avoid collision, but still suffer debilitating injury or die from either over-pressure (damage to tympanic membranes) or under-pressure (damage to lungs) in proximity to the rotating blades, thus adding to the risk of wind energy to bats.

The hypothesis that barotrauma was an important source of bat mortality at wind facilities was quickly accepted, although the evidence was largely circumstantial and there have been few efforts to evaluate this hypothesis empirically. Rollins et al. (2012) observed that many of the symptoms associated with barotrauma were also consistent with traumatic injury as well as post-mortem processes occurring before the carcasses were discovered. Simulations conducted at the National Renewable Energy Laboratory (NREL; presentation at 2015 BWEC Science Meeting) suggested that there is a very limited area along a rotating turbine blade that creates pressure differentials sufficient to cause barotrauma, and that bats would have to be in such close proximity to the blade to experience barotrauma-causing pressure changes that the risk of collision was almost certain. The NREL study has not been published in the peer-reviewed literature.

Barotrauma continues to be cited as an important source of mortality for bats in both the popular and scientific literature (e.g., USFWS 2016, Barclay et al. 2017). Whether it is important to resolve questions around the significance of barotrauma depends on whether it leads to an underestimation of bat fatalities, particularly in some species, from bats flying out of the search area before dying for example, or whether the risk of barotrauma leads to different strategies for mitigating bat fatalities.

Indirect (Habitat-Based) Impacts[3]

There have been few direct studies evaluating the effects of land transformation (as described by Diffendorfer and Compton 2014) on bats. Possible impacts are inferred from landscape changes associated with construction of a wind facility, particularly in forested areas where land is cleared for roads, turbine pads, and feed-in transmission. In theory, these changes may destroy maternity roosts in forested areas or create disturbances leading to abandonment of hibernacula or roosts. However, it has been hypothesized that changes in the landscape, such as the increase in forest edge, increases bat activity and could be a factor contributing to high bat fatalities in the eastern U.S.

Reducing bat activity near wind facilities could lower collision risk. The ecological consequences of bats avoiding wind facilities would depend on whether increased mortality or habitat availability are limiting factors for the population.

Evaluating Risk of Wind Energy to Bats[4]

We assume that fatalities from collisions with turbine blades is the overwhelming source of risk to both individuals and populations of bats. Further, the data suggest that collision risk varies among bat species and for individual bats in some species collision risk is higher than to individuals of most bird species. Why many bats are at presumed greater risk from wind energy development and operation has been the subject of multiple publications over the last ten years (e.g., (Kunz et al. 2007, Cryan and Barclay 2009, Barclay et al. 2017).

Many of the hypotheses (summarized most recently in Barclay et al. 2017) consider that at least some bat species are attracted to wind turbines or the landscape changes associated with wind energy development, particularly in forested landscapes (Diffendorfer and Compton 2014). Attraction would lead to increased bat activity and exposure, particularly in the collision risk zone. Attraction hypotheses include:

- Perceiving wind turbines as a resource for roosting or mating

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[3] see Barclay et al. 2017 for recent review

[4] Risk can be defined as a product of the probability of an occurrence and the consequences of the occurrence. For wind energy development, collision risk can be defined either as the probability of death to individuals or the likelihood of population declines due to the accumulation of individual fatality events.

- Higher concentrations of insects around wind turbines, perhaps drawn to the heat produced at the nacelle
- Turbines are misperceived as a resource, e.g., water (Hale and Bennett, *unpublished data*)
- Openings created by turbine installation in forested landscapes create habitat for species that forage in open areas
- Sounds produced by rotating blades

None of these hypotheses are mutually exclusive, and their importance may vary by species and by landscape. There is some circumstantial support for each of these hypotheses, but there is also counter evidence (Barclay et al. 2017). To date, there are no published studies that have specifically evaluated these hypotheses, although minimization strategies are being studied that draw from these hypotheses, particularly strategies that reduce the potential for turbines being misperceived as a resource.

Previous analyses of collision fatalities, which have been supported by the expanded dataset in AWWIC, indicate that collision fatalities and presumably collision risk vary by species, by region, and by season. Before we consider this variation too deeply it is important to recognize that some of the variation we observe in bat fatality estimates and fatality incidents could be due to differences in detectability or systematic differences in survey protocols both within and among regions (see also “Sidebar – A Note on Detection”). For example, search intervals tend to be much shorter in the Northeast Region relative to other regions, particularly the Pacific Region, and this bias could affect corrections for detection in raw carcass results.

Evaluations of bat fatality impacts, including evaluations of the data in AWWIC, are also based on a non-random collection of studies. Some regions of the country where there are substantial amounts of wind energy development have been underrepresented in analyses, and as the evaluation of the AWWIC data has shown, data representation could affect our assessment of risk to different bat species.

Further, the current distribution of wind energy facilities may not overlap with the occurrences of many bat species in the U.S. (USGS 2018). If wind energy expands into areas where these species occur, then collision fatalities for these species may be reported. The first reports of fatalities of lesser long-nosed bat (*Leptonycteris yerbebuena*) at a wind facility in Arizona highlights this possibility (Davis 2018).

Alternatively, these differences may have a real basis in variation in collision risk among bat species, and the simplest explanation for that variation is that exposure, a function of activity in the rotor swept zone (see, for example, Korner-Nievergelt et al. 2013), is lower for some bat species than others that co-occur in proximity to a project.

Risk exposure for individual species, i.e., presence in the rotor-swept area, may reflect abundance of bats as well as foraging behavior. Many bat species in the U.S. are considered rare (e.g., Harvey et al. 2011), and an absence or low frequency of fatalities may reflect the species’ rarity. This reasoning would suggest that a high frequency of fatality incidents would correspond to widely distributed and abundant species.

Alternatively, a species may be abundant, but its behavior does not take it into the collision risk zone very often. For example, in lower Michigan, mist net captures of big brown bat were one to two orders of magnitude greater than captures of migratory tree bats (Winhold and Kurta 2008). However, the relative number of big brown bat fatality incidents was substantially lower than that of any tree bat species in this same region. These differences reflect that mist-netting occurs at ground level and not at the level of the rotor swept area.

Variation in bat morphology and its influence on how bats use airspace has been hypothesized as a factor influencing collision risk in bats – specifically, wing-loading (defined as body mass divided by wing area) and aspect ratio (a measure of wing shape). Barclay et al. (2017) noted that wing-loading and aspect ratio were significantly higher in species with high proportions of fatality incidents than in species with low proportions of fatality incidents. The rationale is that species with high wing-loading and aspect ratios, such as hoary bat or Mexican free-tailed bat (see Table 2), are fast flyers and forage in the open – potentially putting them more frequently in the rotor-swept area – while species with low wing-loading and aspect ratios, such as species in the genus *Myotis*, can forage lower and slower in and around vegetation, and fly less frequently in the rotor swept area, thus being less at risk of collision.

A Note on Detection

Any discussion of bat collision risk based on data collected during fatality monitoring studies should consider differences in detection error among bat species. Detection error results from failure to find carcasses within the searched area, removal of carcasses by scavengers before they can be discovered, or failure to search the entire area or search during the entire time period where carcasses may be found. Theory and protocols to account for these sources of error have advanced substantially in the past several years (e.g., Strickland et al. 2011, Korner-Nievergelt et al. 2013, Huso and Dalthorp 2014), although these adjustments are applied to the sum of bat fatality incidents and typically not to individual species raw counts.

What we're learning is that large carcasses (raptors, for example) are more detectable than smaller carcasses, and the fall distribution of carcasses differ between birds and bats. Known or potential differences in detectability across species are not usually accounted for in fatality monitoring studies. For example, we don't know whether tree-roosting bats are more detectable than Myotis bats, but differences in the number of fatality incidents by species implicitly assume that differences in detectability are unimportant. Evaluating interspecific differences in detection is hampered by insufficient availability of carcasses of different species to use in detection trials. Mice or small birds are often used as surrogates for bats in carcass persistence trials and searcher efficiency trials, and at least one study estimated a much lower persistence time for bats versus mice (Tidhar et al. 2013).

Mitigating the Impacts of Wind Energy on Bats

The framework for the discussion in this section follows the mitigation hierarchy of avoid, minimize, mitigate, as defined by the U.S. Fish and Wildlife Service in the Land-Based Wind Energy Guidelines (U.S. Fish and Wildlife Service 2012). This mitigation hierarchy is also the underlying framework of the tiered approach described in the Guidelines. These steps are assumed to form a sequence, i.e., project developers should first avoid, then minimize project impacts, and compensate for any impacts that can't be avoided or minimized, often with the goal of reducing wildlife impacts of a project to a net neutral or even a net gain.

This mitigation hierarchy is applied primarily in the context of protected species, such as those listed under the Endangered Species Act. We summarize the application of these steps with respect to bats and wind energy in the discussion that follows.

Avoidance

In theory, siting of wind facilities could avoid high risk sites for bats, and thus could avoid risk of collision fatalities and habitat impacts. If enough low risk sites are still economically viable, then we could theoretically produce sufficient wind energy to mitigate climate change at reduced risk to bats, while reducing reliance on post-construction mitigation.

To avoid developing sites with high collision risk we need reasonably accurate predictions of the variation in collision risk among potential development sites within a region or landscape. Pre-construction risk assessments have collected ultrasonic acoustic data to estimate relative bat activity, and, if appropriate, mist-netting to detect presence of listed species. There is, however, no reliable evidence that acoustic monitoring is a useful predictor of collision risk (see Hein et al. 2013, Lintott et al. 2016). Measuring bat activity "at height" – defined as the rotor-swept area – might more accurately identify risk (Roemer et al. 2017), but assessment of collision risk based on pre-construction data is complicated by the potential attraction of at least some bat species to wind facilities.

An alternative approach to predicting bat collision risk at future projects would be to model variation in fatality estimates from operating projects within the same region. If at-risk bat species are attracted to turbines, or land transformation from project construction increases bat activity in a project's vicinity, then evaluating post-construction fatality data has logical appeal. This approach has been tested and appears to show promise (Santos et al. 2013). Detailed analyses of fatality data and landscape-level attributes found the strongest positive relationship between grassland cover and bat fatalities (Thompson et al. 2017). Further research to evaluate both the explanatory power and utility of this modeling approach for siting wind projects would be very useful.

Avoiding proximity to known maternity roosts and hibernacula (e.g., as described in the Midwest Wind Energy Habitat Conservation Plan) is strongly recommended, and known proximity to these features can affect further mitigation efforts for listed species. However, locations of these features may be unknown for most species, and the effectiveness of suggested distance buffers in reducing impacts has not been evaluated. Avoiding roosting habitat also may be relevant to reducing activity near wind energy facilities, but the relationship between roosting requirements and turbine collision risk is unclear has not been determined.

As will be discussed below, identifying areas that are important for bats, and exploring how to site to avoid these areas are topics that needs more focused attention over the next several years.

Minimization

Minimization strategies are intended to reduce bat fatalities at operating wind facilities. Two broad strategies have been implemented and evaluated at operating wind facilities: 1) curtailment, also referred to as operational mitigation or operation minimization; and 2) deterrence, primarily through the use of ultrasonic acoustic transmitters.

Curtailment

A large proportion of bat fatalities occur at low wind speeds (Arnett et al. 2008). Slowing or curtailing blade rotation at low wind speeds, typically reflected as increasing the "cut-in speed" (the wind speed at which wind turbines begin generating electricity) has been shown repeatedly to be an effective strategy for reducing bat collision fatalities (Arnett et al. 2013c). For example, curtailing blade rotation when wind speeds are less than 5.0 meters per second (m/s) reduces all-species bat fatalities by 50% or more on average, and testing of higher cut-in speeds may result in greater fatality reductions (Table 4).

The use of curtailment as a regulatory or compliance tool has increased. Pennsylvania and the provinces of Alberta and Ontario have instituted threshold levels of bat fatalities, which if exceeded would require curtailment of turbine operation below "designated" wind speeds at the wind facility (Arnett et al. 2013a). The USFWS in Regions 3 and 5 have indicated that curtailing turbines at 6.5 or 6.9 m/s would constitute avoidance of Indiana bat take, thus avoiding the need for a take permit, although collision fatalities of bats will continue to occur at these cut-in speeds (Table 4).

Restricting turbine operation at low wind speeds, however, reduces power production and has an economic impact on the project. The amount of power production lost with curtailment increases with the cube of the wind speed, i.e., reductions in power production increase rapidly with the increase in the wind speed threshold for curtailment. The specific amount of power and revenue loss will depend on the wind speed chosen for curtailment, the wind-speed characteristics of the project location, the turbine model, and the market in which the power is being sold. Further complicating the economic impact of curtailment is that turbines are getting taller and more efficient at lower wind speeds, which would increase power losses with curtailment.

Turbine blades rotate at sufficient velocity below the manufacturer's cut-in speed to pose a collision risk to bats, with no electrical power being generated. A small number of studies indicate statistically significant fatality reductions when turbine blades are feathered (turned parallel to the wind) below cut-in speed (see Table 4). On that basis, member companies of the American Wind Energy Association agreed to voluntarily feather turbine blades below the cut-in speed at night during fall bat migration as a minimization measure (Curry 2015). To date, no formal evaluation of the effectiveness or the level of implementation of this policy is available. Although automatically feathering below cut-in speed is not feasible for older turbine models, many newer machines are programmed to do so.

Because curtailment at higher wind speeds is currently the only demonstrably effective minimization option, there is considerable interest in increasing the efficiency of this mitigation option in an approach often referred to as "smart curtailment." Efficiency could be defined as the reduction in numbers of bats killed per unit of lost power production, meaning that maintaining fatality reduction benefits while minimizing power production losses would constitute high efficiency (Trevor Peterson, *personal communication*). As the number of reported bat fatalities varies substantially among nights even within the peak fall season (Allison and Butryn 2018), a minimization strategy based solely on wind speed could result in turbine shutdown when bats are not present and therefore not at collision risk.

A variety of research approaches are attempting to identify variables in addition to wind speed that could predict peak fatality events or model factors affecting bat activity and collision risk. For example, bat activity has been shown to be highest at a combination of lower wind speeds and higher temperatures (Peterson 2016 NWCC presentation), and movements of migratory tree bats might be influenced by weather fronts that could be predicted by changing barometric pressure. A study at a Vermont wind energy facility defined curtailment rules based on a combination of wind speed and temperature. The reduction in bat fatalities was comparable to that observed in other studies, and lost power production was calculated to be 18% less than power lost from curtailment based on wind speed alone (Martin et al. 2017).

Other experimental curtailment approaches involve shutting down turbines in a wind energy facility according to rules based on wind speed and estimates of acoustic bat activity at the nacelles of a few turbines within the facility (Electric Power Research Institute 2017), or employing different strategies for shutting down turbines based on different rules for measuring wind speeds at which curtailment would be implemented (Schirmacher et al. 2018).

Although these new approaches, and activity based curtailment, in particular, have shown promise in predicting bat activity and collision risk, the relative effects on power production compared to curtailing based on wind speed alone remains unclear. Efficiency gains in applying these models, whether it be reductions in power production losses or increases in bat fatality reductions, will depend on the error associated with the model predictions. A high amount of unexplained variation could result in high error rates in the application of the models.

Deterrence

Even smart curtailment will involve power production losses, and increasing turbine efficiency at low wind speeds could further undermine the financial viability of curtailment. Thus, there has been substantial interest and investment in developing technologies that deter bats from entering the collision risk zone and allow turbines to operate normally (see Table 5).

The approach that has received the most attention is the use of ultrasonic acoustic transmitters (UADs) to deter bats from approaching rotating wind turbine blades. All bat species in the U.S. echolocate by emitting high-frequency (ultrasonic) sounds and interpreting the reflected echoes from objects in their surroundings. These sounds allow bats to orient, capture prey, and communicate in the dark. A two-year evaluation of a UAD device at a wind facility in central Pennsylvania showed significant reductions in fatalities of hoary bats and silver-haired bats at test turbines in the first year (Arnett et al. 2013b).

Different approaches are at various stages of development for the next generation of technologies that generate ultrasonic frequencies and approaches to arraying them on turbines (Table 5), but the effectiveness and durability of these technologies is still being evaluated. Efforts to advance deterrent strategies were helped substantially by in 2015 when the U.S. Department of Energy (DOE) provided funding for five bat deterrent technologies that were in various stages of "readiness." Unpublished preliminary results of initial tests at operating wind facilities in different regions of the U.S. have shown mixed outcomes in reducing bat fatalities overall and in reductions for specific species. Fatality reductions of all bat species have averaged around 50%, but UADs were not effective in reducing eastern red bat fatalities. One study included a combined treatment of deterrence and curtailment at 5 m/s, but there was no additional reduction in all-bat fatalities beyond what was achieved with curtailment alone (Hein et al. unpublished data). Studies are underway that are building on these tests as technology developers continue to enhance their technology and researchers and companies continue to test strategies that improve curtailment efficiency or that combine minimization approaches.

Ultrasound attenuates rapidly with distance and thus a challenge for successful deployment of UAD technology is ensuring that the emitted sounds cover the entire rotor-swept area. Higher frequencies attenuate more rapidly, covering less of the rotor swept area. Video imagery of bats around turbines indicates high levels of activity around the nacelle (Cryan et al. 2014a) where blades turn slowly and might not pose a collision threat. If UADs deployed at the nacelle only cover an interior portion of the rotor-swept area, bat activity may be pushed away from the nacelle to the periphery of the rotor-swept area, where bats may then actually be at higher risk of collision with the fastest moving parts of the blades. Tests on the next generation of the technology, including effects of placement of the UADs and increasing power output, are currently planned.

In addition to UADs, research to evaluate low-intensity ultraviolet light as a bat deterrent is in its early stages (Gorresen et al. 2015). This deterrent is based on the premise that bats are attracted to turbines because they perceive them as tall trees. Illumination of turbines with UV light might provide a signal to bats that turbines are not tall trees, and thus bats would not be drawn in to turbines from a distance, reducing bat activity around turbines, and thus reducing collision fatalities.

Commercial marine radar also has been evaluated as a potential deterrent and was shown to significantly reduce bat foraging activity (Nicholls and Racey 2007, 2009). We are not aware if this option has been evaluated at operating wind facilities.

Another DOE-funded study is evaluating the hypothesis that bats are attracted to turbines because the acoustic signature of the smooth tower is similar to the acoustic signature of water (Amanda Hale, Texas Christian University, unpublished data). Investigators are evaluating whether adding a rough surface texture to turbine towers will reduce bat activity near the tower and reduce bat fatalities. As of this writing, pilot testing on wind turbines is underway.

As of this writing, DOE is providing additional funding to improve the effectiveness of UADs and to develop effective smart curtailment algorithms.

Compensatory Mitigation

Compensatory mitigation is typically applied after all practicable measures to avoid and minimize impacts have been taken, with the goal of offsetting any remaining impacts that cannot be avoided or minimized. This mitigation is typically applied when take (harming or killing) of listed species, such as Indiana bat and other listed bat species in the U.S., is considered likely. In such cases, when an application is made for an incidental take permit, a habitat conservation plan is prepared, and compensatory mitigation measures are proposed to offset the impacts of the predicted take. Offset measures could include cave-gating, which is utilized to reduce disturbance at hibernacula (Crimmins et al. 2014), and mitigation banking that involves third-party protection and enhancement of forested areas containing maternity roosts or swarming habitat. Anticipated collision fatalities of listed bat species at any project are assumed to be low (<1 bat per year).

Although seemingly feasible for offsetting impacts to listed bat species, it has been questioned whether compensatory mitigation would be a viable option for certain species, such as migratory tree bats, that experience an estimated cumulative collision mortality of tens of thousands of bats per year and currently have no protection under state or federal wildlife laws. We lack knowledge of factors that limit population size in these solitary bat species that could be used as targets for compensatory measures. For example, it has been suggested that eastern red bats will roost on the forest floor in their winter range and may enter torpor when temperatures are below ~10° C (e.g., Hein et al. 2005, Morman and Robbins 2007, Perry et al. 2010). If prescribed burns in the winter in southern forests could result in death, injury, or premature arousal from torpor that might have population-level impacts, then changes to forest management practices to limit prescribed burns in winter could be used as compensatory mitigation for eastern red bat. It is not known whether changes to forest management would be an effective compensatory mitigation measure for this bat species.

However, even if such factors were known, the amount of mitigation to completely offset collision fatalities of migratory tree bats, as would be needed for listed species, could be costly and potentially make projects uneconomic. For these reasons this option is not considered feasible as a mitigation strategy for bat mortality at wind facilities (e.g., Arnett and May 2016). Nonetheless, compensatory mitigation may be able to play a role in an integrated mitigation strategy, and this is discussed further below.

Mitigating Current and Future Impacts to Bats – Priorities for Research

Timely expansion of wind energy and other renewable energy sources is considered necessary to offset carbon emissions and avoid the worst effects of climate change on global biodiversity (IPCC 2018). Such expansion may be even greater that the 150% increase in installed capacity called for in the DOE Wind Vision (DOE 2015; from 90+GW currently to 225 GW).

Predictions of the cumulative risk to bats from this future development will be influenced by where wind energy is installed and by advances in mitigation strategies implemented to reduce this risk. We can predict which species will be at risk and where they will be at risk based on the anticipated regional expansion of wind energy as describe in DOE's Wind Vision, projections from the data contained in AWWIC, and our knowledge of seasonal timing of risk.

Such projections require making several assumptions, but the Midwest and Southwest Regions are anticipated to constitute approximately 60% of the installed capacity in the U.S. by 2030, and in the absence of mitigation would lead to increased impacts to several bat species, including Mexican free-tailed bat, hoary bat, and eastern red bat. New species may also be at risk. For example, the southeastern

U.S., where there is currently very little wind energy development, is predicted to grow to ~9 GW installed by 2030. This region has several species, including the federally endangered gray bat, that might have greater exposure to collision risk if more wind energy is developed there. In turn, new federal and state listings of bat species could increase the effects of regulations on operations of both current and future wind facilities.

Much research is underway to minimize the risk to bats from current and future wind energy. For example, as described previously, there is still much to be learned about bat behavior and responses to wind turbines. It also remains uncertain whether the cumulative impacts from wind energy have adverse population-level effects on at-risk bat species. As Barclay and Harder (2007) have described, bat populations are sustained by long life spans and low mortality that compensate for low reproductive potential. This suggests that increased mortality will not be compensated for by increased number or size of litters, and death of breeding bats will not be offset by an influx of non-territorial individuals as has been observed in many bird species, even in large raptors such as eagles (e.g., Katzner et al. 2016).

Efforts over the past decade have substantially increased our understanding of the options for avoiding and minimizing current and future impacts. Currently, curtailment is consistently the most promising approach with the potential to reduce bat fatalities by an average of 50-60% with widely applied 5.0 m/s curtailment across the U.S. However, without more sophisticated integrated mitigation strategies – advancements in technological solutions combined with careful siting to avoid the highest risk areas – we face the prospect that this cumulative reduction would be eliminated if the 2030 goal of DOE's Wind Vision is achieved.

Increasing cut-in speed from 5.0 m/s to higher levels could reduce fatalities further, but as described above, even smart curtailment will result in power losses, and power losses will further increase at higher cut-in speeds, affecting the economic viability of wind projects. Relying on curtailment alone to reduce the risk of population declines would require more turbines to reach wind energy production goals, thus offsetting reductions in cumulative bat mortality, and would make wind energy development economically unviable.

A purpose of this white paper was to further understanding of bats and wind energy to refine AWWI's research priorities; specifically, to identify what our research priorities should be over the next five years to reduce the risk of impacts to bat species in the short-term. As others have noted, it is possible that no single mitigation solution will sufficiently address the challenge of reducing impacts to bats from wind energy. We support research to develop an integrated bat mitigation strategy specific to different geographic regions and bat communities. Specifically, we will support research that:

1. Accurately describes the observed variation in collision risk among bat species and regions
2. Facilitates the siting of turbines and wind energy facilities away from high risk locations, or high-quality habitat of at-risk species
3. Increases investment in the development and evaluation of technologies that reduce bat activity in the rotor-swept zone of wind turbines
4. Supports the development of algorithms that increase the efficiency of curtailment by optimizing fatality reductions and power losses
5. Conducts basic research on habitat use and factors that may limit populations of at-risk species to aid in the identification of potential options for restoration or protection of high-quality bat habitat

We will also provide scientific support to work with existing policy and regulations that create incentives for increasing the rate at which research is conducted and incorporated into policy.

Further, collectively we will have to decide how much uncertainty we will be willing to accept about the risk to bats as we try to limit the greater risks of global extinctions from rapid climate change. The commitment of wind-wildlife stakeholders to bats and wind energy will enable us to successfully achieve wind energy goals while minimizing impacts to bats *in the longer term*. The great threat of a rapidly warming climate means that achieving emission reduction goals with the help of wind energy must happen now. Research to inform an integrated mitigation strategy may not eliminate the uncertainty regarding risk to bat species at the pace and scale of wind energy development needed to limit global warming. Thus, the stakeholder community faces the challenge of accepting some risk of population-level impacts to some bat species over *the short-term* to meet emission reduction goals.

To address this challenge, we propose to convene a structured conversation (Gregory et al. 2012) with wind-wildlife stakeholders to achieve a shared understanding of the pace and scale of renewable energy siting needed to help limit the wildlife impacts of climate change as we minimize impacts to bats. Achieving these goals will require an in-depth understanding of what’s important (values), and evaluation of the outcomes of alternatives (consequences). AWWI intends to continue its work with our partners in the wind industry, the conservation and scientific communities, and state and federal agencies in addressing the challenge of bats and wind energy.

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Tables

Table 1. Survey of bat numbers at hibernacula pre- and post-white nose (WNS) syndrome from 42 sites in five states (NY, PA, VT, VA, and WV) with WNS for at least two years (Turner et al. 2011).

Species	Pre-WNS	Post-WNS	% change
Little brown bat	348,277	30,260	-91%
Indiana bat	55,028	15,650	-72%
Northern long-eared bat	1,706	31	-98%
Eastern small-footed bat	1,393	1,142	-12%
Tri-colored bat	3,107	783	-75%
Big brown bat	2,919	1,713	-41%

Table 2. Number and percentage of bat fatality incidents from all post-construction monitoring studies contained in the American Wind Wildlife Information Center (AWWIC) and conducted between 2006 and 2016. Frequency is the number of studies containing fatality incidents of the species; the maximum number of studies is 190. Wing loading of each species is included if available as published in Norberg and Rayner (1987).

Species	# Incidents	% Incidents	Frequency	Wing Loading (g/m^2)[5]
Hoary bat	4033	31.85%	180	16.5
Eastern red bat	3042	24.03%	95	14.0
Silver-haired bat	2044	16.14%	135	8.2
Mexican free-tailed bat	1263	9.98%	51	11.5
Little brown myotis	647	5.11%	60	7.5
Big brown bat	636	5.02%	81	9.4
Tri-colored bat	217	1.71%	24	5.6
Evening bat	211	1.67%	15	10.7
Northern yellow bat	22	0.17%	3	-
Western red bat	16	0.13%	8	-
Southern yellow bat	14	0.11%	4	-
Seminole bat	9	0.07%	6	-

[5] Wing loading is a measurement relating the mass of a bat to its wing area; Source: Norberg, U.M. and Rayner, J.M.V. 1987. Ecological morphology and flight in bats (Mammalia; Chiroptera): wing adaptations, flight performance, foraging strategy and echolocation. Philosophical Transactions of the royal society of London B 316: 335-427.

Big free-tailed bat	8	0.06%	5	-
Western yellow bat	7	0.06%	3	-
Canyon bat	6	0.05%	4	6.9
Northern long-eared myotis	6	0.05%	5	6.8[6]
Pocketed free-tailed bat	5	0.04%	3	-
Indiana myotis	4	0.03%	4	6.5
Cave myotis	3	0.02%	3	6.3
Greater bonneted bat	3	0.02%	1	25.1
California myotis	2	0.02%	2	4.8
Long-legged myotis	1	0.01%	1	8.3
Unidentified bat	462	3.65%	93	-
Total	12661	100.00%	190	

[6] Used the value for *Myotis keenii*, which recently included northern long-eared bat.

Table 3. Number of species and number of bat fatality incidents reported in 190 post-construction fatality monitoring studies between 2006 and 2016 contained in the American Wind Wildlife Information Center (AWWIC) sorted by USFWS Region. Species number by Region was determined by overlap analysis of species' range data layers downloaded from the USGS Gap Program and the IUCN Red List (USGS 2018).

USFWS Region	# Projects in AWWIC	Median Fatality Estimate	# AWWIC Incidents	# Species in AWWIC	# Species in Region
Midwest	28	6.2	4775	10	16
Mountain Prairie	19	2.4	906	9	26
Northeast	33	3.5	3987	9	14
Pacific	24	0.7	525	4	17
Pacific Southwest	19	1.4	848	12	25
Southeast	-	-	-	-	21
Southwest	18	3.3	1620	14	43
United States	141	2.7	12,661	22	47

Table 4. Results from publicly available studies in the U.S. and Canada of curtailment effectiveness in reducing bat collision fatalities [adapted from USFWS (2016) and Arnett et al. (2013)]. Studies in the table are listed by lowest to highest treatment cut-in speed.

Study Location	Normal Cut-in Speed (m/s)	Treatment Cut-in Speed (m/s)	Mean % Reduction in Bat Fatalities	Mean % Reduction in Mortality Per Cut-in Speed	Source
Fowler Ridge, IN 2011	3.5	3.5*	36	36	Good et al. 2012
Mount Storm, WV 2010	4.0	4.0*	47		Arnett et al. 2013
Mount Storm, WV 2011	4.0	4.0*	9^	38	Arnett et al. 2013
Summerview, AB	4.0	4.0*	58		Baerwald et al. 2009
Fowler Ridge, IN 2011	3.5	4.5	57		Good et al. 2012
Anonymous Project (AN01), USFWS Region 3	3.5	4.5	47	57	Arnett et al. 2013
Raleigh Wind, ON	3.5	4.5	77		Normandeau. 2015
Wolf Island, ON 2011	4.0	4.5	48#		Arnett et al. 2013
Anonymous Project (AN02), USFWS Region 8	3.0	5.0	33		Arnett et al. 2013
Cassleman, PA 2008	3.5	5.0	82		Arnett et al. 2010
Casselman, PA 2009	3.5	5.0	72	57	Arnett et al. 2010
Criterion Wind, MD 2012	4.0	5.0	62		Arnett et al. 2013
Fowler Ridge, IN 2010	3.5	5.0	50		Good et al. 2011

Pinnacle, WV 2012	3.0	5.0	47		Hein et al. 2013
Pinnacle, WV 2013	3.0	5.0	54		Hein et al. 2014
Summerview, AB 2009	3.5	5.5	60	66	Baerwald et al. 2009
Fowler Ridge, IN 2011	4.0	5.5	73		Good et al. 2013
Anonymous Project (AN01), USFWS Region 3	3.5	5.5	72		Arnett et al. 2013
Wolf Island, ON 2011	4.0	5.5	60#		Arnett et al. 2013
Sheffield, VT	4.0	6.0	62	62	Martin et al. 2017
Casselman, PA 2008	3.5	6.5	82	77	Arnett et al. 2010
Casselman, PA 2009	3.5	6.5	72		Arnett et al. 2010
Fowler Ridge, IN 2010	3.5	6.5	78		Good et al. 2010
Pinnacle, WV 2013	3.0	6.5	76		Hein et al. 2014
Beech Ridge, WV 2012	3.5	6.9	81+	81	Arnett et al. 2013

*Turbine blades in this treatment group were feathered (turned parallel to the wind direction) below the manufacturer's cut-in speed of 3.5 m/s or 4.0 m/s.

^ Fatalities of treatment turbines were not significantly different from control turbines.

+ Treatment was applied to all turbines; lower end of range corresponds to comparison to projects in northeastern U.S. The higher reduction was based on comparison to two other West Virginia projects.

#Results were based on a small sample of carcasses and should be treated with caution.

Table 5. Bat deterrent strategies/technologies under development

Vendor and Deterrent	Technology	Status
General Electric – UAD[7]	Nozzles mounted on tower and nacelle release air creating high-frequency sounds	Effectiveness tested at a single site over multiple years and configurations; 25-42% reduction in fatalities of some species
NRG Systems – UAD	Nacelle-mounted, piezo-electric transmitters emitting at different ultrasonic frequencies	Currently undergoing testing at multiples sites; results indicate effectiveness for some species, up to 50% reduction
Frontier Wind – UAD	Blade-mounted ultrasonic transmitters; intended to increase coverage of the rotor swept zone	Testing at wind facility; no fatality reduction data available
University of Massachusetts – UAD	Blade-mounted, producing ultrasonic whistles as blades rotate	In proof-of-concept stage; prototypes under development
USGS – Visual deterrent	Low intensity ultra-violet light; reduce long-distance attraction to turbines	In proof-of-concept stage; shows some effectiveness in reducing activity of Hawaiian hoary bat
Texas Christian University – Textured turbine towers	Texturing turbine tower surface to reduce bat activity in turbine vicinity	Preliminary field testing of textured turbines to evaluate effect on bat activity

[7] UAD = ultrasonic acoustic deterrent

Figures

Figure 1. Bat diversity in the U.S. Color and intensity represent the estimated number of bat species based on GIS analysis of range maps and species distribution models downloaded from https://gis1.usgs.gov/csas/gap/viewer/species/Map.aspx. Diversity increases from lowest (light blue) to highest (dark blue). Green circles are locations of wind turbines as contained in the U.S. Wind Turbine Database (https://eerscmap.usgs.gov/uswtdb/viewer/#3/39.51/-96.74 accessed June 2018).

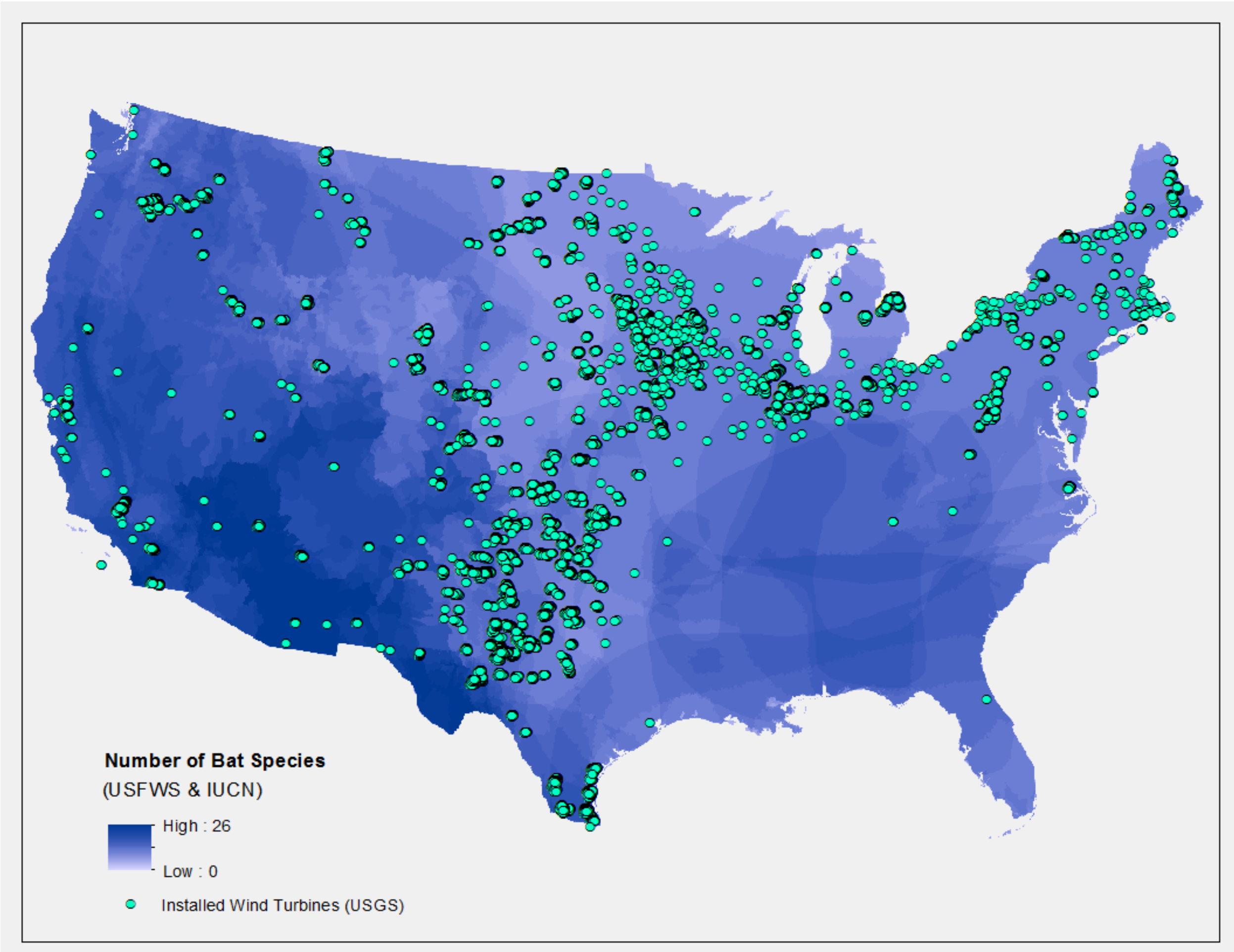


Figure 2. Adjusted bat fatality estimates by USFWS Region from 202 post-construction studies conducted between 2006 and 2016 and contained in the American Wind Wildlife Information Center (AWWIC). Box plot of bat fatality estimates displays median and quartile values with outliers indicated by open circles and mean value indicated by "x." Numbers in parentheses are number of projects within each USFWS Region.

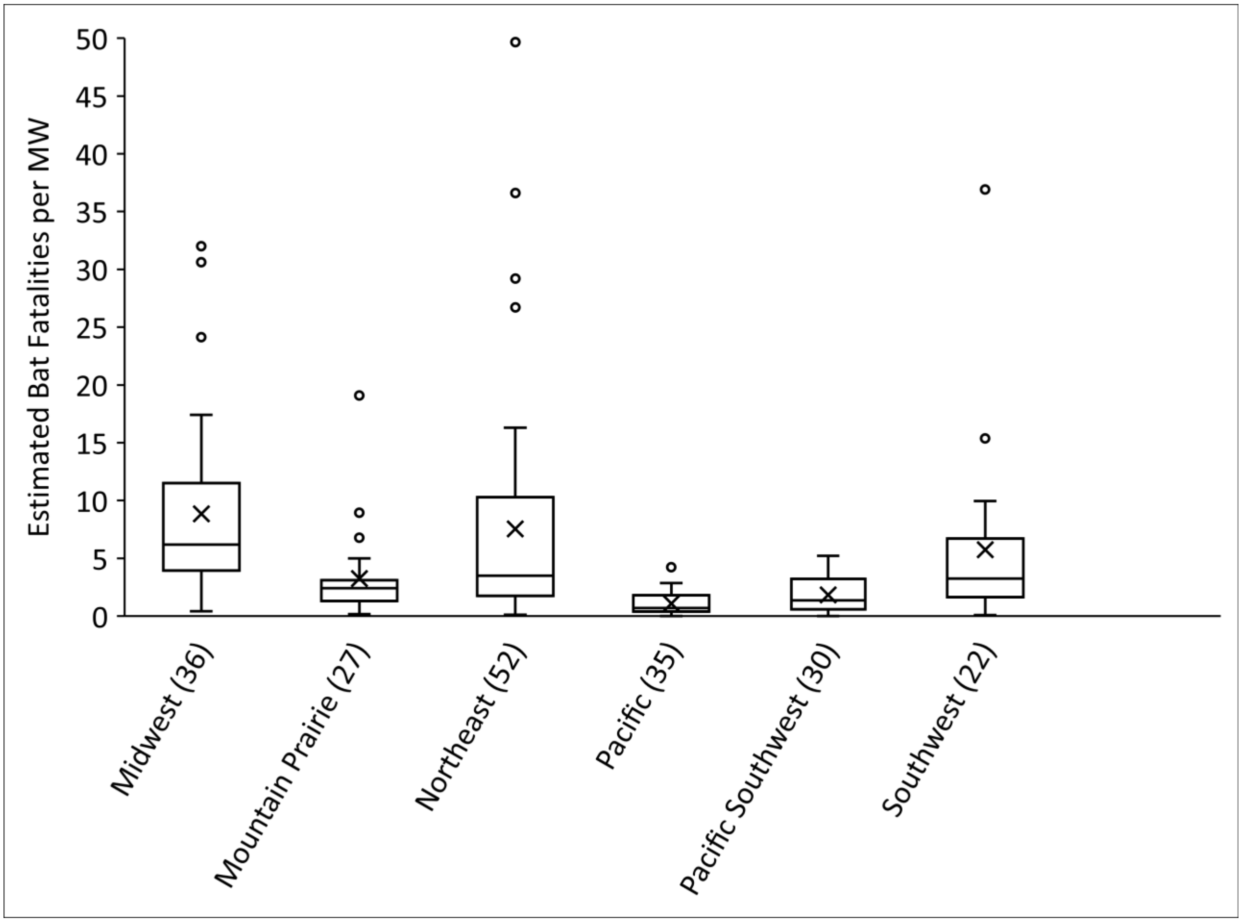
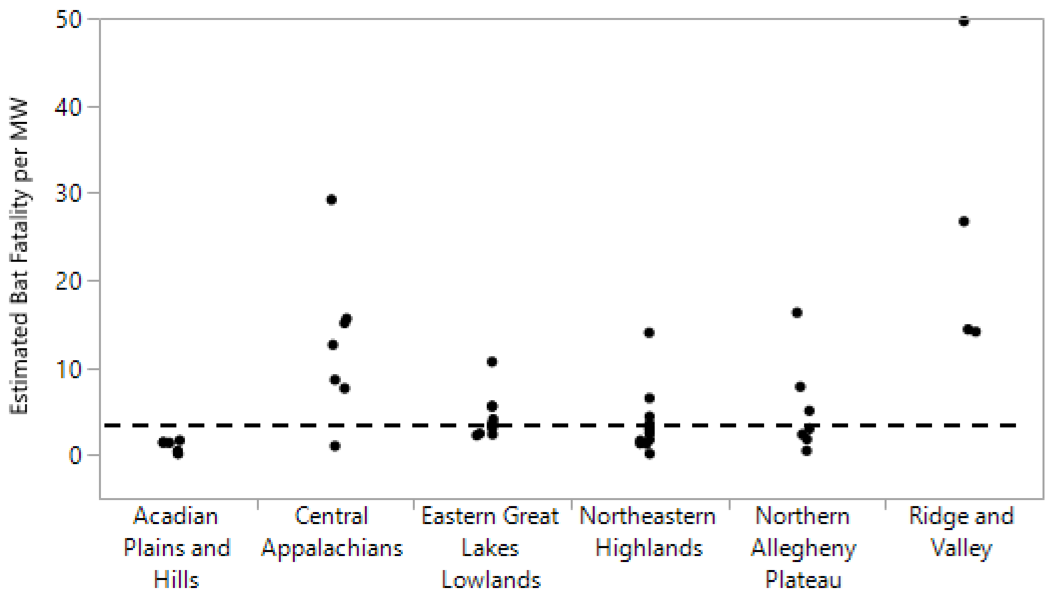
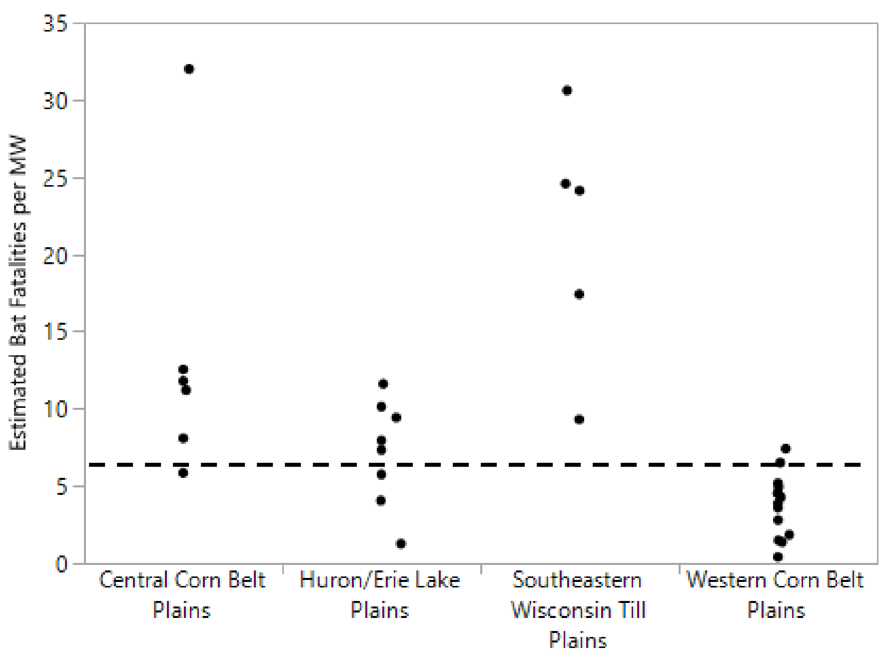


Figure 3. Adjusted bat fatality estimates for two USFWS Regions with high within-region variability. Fatality rates are sorted by EPA Level III Ecoregion within a) the Northeast (N=52) and b) Midwest USFWS Regions (N=36) for post-construction studies conducted after 2006 and contained in the American Wind Wildlife Information Center (AWWIC). Dashed line represents median bat fatality rate for the two Regions.

a)



b)



Appendices

Appendix A. Bat species/subspecies known to occur in the U.S. and Canada: range, litter size, body mass, wing loading, abundance estimate in U.S., and percent fatality incidents contained in the American Wind Wildlife Information Center (AWWIC). For the latter, blank means no incidents are recorded in AWWIC. Species/subspecies in red font are listed as federally endangered by USFWS; brown font species are federally threatened. Rows with pink highlighting are known to have White-nose syndrome; blue highlighted rows are species in which the fungus, *Pseudogymnoascus destructans*, has been detected, but no disease has been found. Sources of information include Walker, "Mammals of the World"; Harvey, Altenbach, and Best, "Bats of the United States and Canada"; and Norberg and Rayner (1987). Nomenclature follows Harvey, Altenbach, and Best.

Fatality Incidents	Common Name	Family/Genus/Species	North American Range	Litter Size	Body Mass (g)	Wing Loading	Abundance Estimate
		PHYLLOSTOMIDAE					
	Mexican long-tongued bat	*Choeronycteris mexicana*	SW U.S.	1	17.5	13.7	Rare in the U.S.
	Mexican long-nosed bat	*Leptonycteris nivalis*	S TX	1	24	-	Endangered in U.S.
	Lesser long-nosed bat	*L. yerbabuenae*	S AZ and SW NM	1	20	10.6	**Note: this species was delisted in April 2018**
	California leaf-nosed bat	*Macrotus californicus*	SW U.S.	1	12.5	10.2	Special concern in U.S.
	Jamaican fruit-eating bat	*Artibeus jamaciensis*	Florida Keys	1	43	16.6	Rare in U.S.; elsewhere common
		MORMOOPIDAE					
	Peters's ghost-faced bat	*Mormoops megalophylla*	S AZ & S TX	1	16	11.2	Common winter resident in TX
		MOLOSSIDAE					
	Florida bonneted bat	***E. floridanus***	**S FL**	**1**	**42.5**	**-**	**Endangered; <10,000**
0.02%	Greater bonneted bat	*E. perotis*	SW U.S.	1	65	25.1	Subspecies *E. p. californicus*, special concern
	Underwood's bonneted bat	*Eumops underwoodi*	S AZ	1	55	-	Special concern in U.S.

	Pallas' mastiff bat	*Molossus molossus*	Florida Keys	1	14	16	Rare in U.S.; common elsewhere
0.04%	Pocketed free-tailed bat	*Nyctinomops femorosaccus*	SW U.S.	1	12	-	Uncommon in the U.S.
0.06%	Big-free-tailed bat	*N. macrotis*	SE KS, SW U.S.	1	27.5	-	Special concern in U.S.
10.0%	Mexican free-tailed bat	*Tadarida brasiliensis*	S U.S.	1	13	11.5	Estimated 100+ million in U.S.
		VESPERTILIONIDAE					
	Southwestern bat	*Myotis auriculus*	SW U.S.	1	6.5	-	Common throughout its range
	Southeastern bat	*M. austroriparius*	SE U.S.	2	6.5	-	Once common; recent declines
0.02%	California bat	*M. californicus*	W NA (SE Alaska and south)	1	4	4.8	Common throughout its range
	Western small-footed bat	*M. ciliolabrum*	SW Canada to W OK	1	5	-	Special concern
0.01%	Long-eared bat	*M. evotis*	SW Canada, W U.S.	1	6.5	6.1	Special concern
	Gray bat	***M. grisescens***	**E KS & OK to W VA and NW FL**	**1**	**9.5**	**-**	**1.5 million in 1980's; increasing trend**
	Keen's bat	*M. keenii*	SE AK, W BC and WA	1	5	6.8	Special concern; relatively uncommon
0.01%	Eastern small-footed bat	*M. leibii*	SE Canada to E OK and GA	1	3.5	6.7	Special concern; uncommon
5.1%	Little brown bat	*M. lucifugus*	AK, Canada, U.S. throughout	1	10.5	7.5	Once most common; WNS decline
	Dark-nosed small-footed bat	*M. melanorhinus*	S BC and W U.S.	-	4.5	-	Special concern
	Arizona bat	*M. occultus*	S CA, AZ, NM, CO	-	8	7.3	Special concern
0.05%	**Northern long-eared bat**	***M. septentrionalis***	**Manitoba & E U.S.**	**-**	**7.5**	**-**	**Once common; major WNS decline**
0.03%	**Indiana bat**	***M. sodalist***	**E U.S.**	**1**	**7.5**	**6.5**	**Once ~400K; WNS declines**
	Fringed bat	*M. thysanodes*	W NA (s. BC and south)	1	6	6.2	Special concern

0.02%	Cave bat	*M. velifer*	SW U.S.	1	13.5	6.3	Special concern
0.01%	Long-legged bat	*M. Volans*	W NA	1	7.5	8.3	Special concern
	Yuma bat	*M. yumanensis*	W NA (BC and south)	1	5	7.8	Special concern; locally common
	Pallid bat	*Antrozous pallidus*	S BC & MT and south	1-2	27.5	8.1	Common throughout its range; sometimes placed in own family
16.1%	Silver-haired bat	*Lasionycteris noctivagans*	SE AK, S Canada, conterminous U.S.	2	9.5	8.2	Relatively uncommon in its range
1.7%	Tri-colored bat	*Perimyotis subflavus*	E NA (MN to Nova Scotia and south)	2	7	5.6	Once common; may be declining - WNS
0.05%	Canyon bat	*Parastrellus hesperus*	W North America	-	4.5	6.9	Relatively common in its range
5.0%	Big brown bat	*Eptesicus fuscus*	S Canada and south	1-2	17.5	9.4	Common throughout its range
1.7%	Evening bat	*Nycticeius humeralis*	S Ontario, E U.S.	2	10.5	10.7	Common southern bat; uncommon elsewhere
0.2%	Northern yellow bat	*Lasiurus intermedius*	Atlantic and Gulf coasts	1-4	22.5	-	Relatively common in its range
0.1%	Southern yellow bat	*L. ega*	S TX	-	12.5	-	Rare in the U.S.; common in S. America
0.1%	Western yellow bat	*L. xanthinus*	S CA, AZ, NM	-	12.5		Possibly expanding range
31.9%	Hoary bat	*L. cinereus*	North-central & S Canada, conterminous U.S.	1-4	27.5	16.5	Relatively common in U.S.; ***L.c.semotus***, endangered in Hawaii
0.07%	Seminole bat	*L. seminolus*	PA, SE U.S.	2-4	11.5	-	Common throughout its range
24.0%	Eastern red bat	*L. borealis*	Alberta & Nova Scotia and south	2-5	12	14.0	Common throughout its range
0.1%	Western red bat	*L. blossevillii*	S BC to Utah and south	-	12.5	-	Common throughout its range
	Rafinesque's big-eared bat	*Corynorhinus rafinesquii*	IN, SE U.S.	1	11	5.9	Uncommon in the U.S., special concern

Townsend's big-eared bat	*C. townsendii*	W North America	-	11	7.2	Western subspecies special concern
Ozark big-eared bat	***C. townsendii ingens***	**W U.S. Ozarks**	**-**		**-**	**Endangered; 1900-2400 (est.)**
Virginia big-eared bat	***C. townsendii virginianus***	**Central Appalachians**	**-**		**-**	**Endangered**
Allen's big-eared bat	*Idionycteris phyllotis*	SW U.S.	1	12	6.6	Generally rare, but locally common
Spotted bat	*Euderma maculatum*	S BC, W U. S.	1	18	-	Considered one of rarest bats in North America