

Mitigating wind energy impacts on wildlife: approaches for multiple taxa

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Abstract: Mitigating impacts of wind energy development on wildlife is important for conservation and public acceptance of this energy source. We provide an overview of approaches to mitigate impacts of onshore wind energy development on wildlife, following steps in the mitigation hierarchy, including avoidance, minimization, and compensatory mitigation. Planning and avoiding predicted high-risk areas is fundamental to reduce impacts on birds and bats. Contrary to avoidance, once facilities are built, options to minimize impacts need to be tailored to species at the specific site, and can be limited especially for bats. Curtailing wind turbine operations is the only approach proven effective at reducing bat mortality. While curtailment may in part also be effective for birds, micro-siting and repowering also are likely to reduce mortality. Compensation should be considered only as part of the mitigation hierarchy when unforeseen or unavoidable impacts remain. Offsite habitat-based compensatory measures may provide the best offsets for incidental bird and bat mortality. While the conceptual framework and predictive modelling for compensatory measures are well-established, empirical evidence demonstrating effectiveness and achievement of no-net loss for wildlife populations is lacking. Similarly, few studies have evaluated effectiveness of minimization measures and other forms of mitigation. Evaluating effectiveness of pre-construction wildlife assessments and habitat modeling in predicting wildlife mortality at wind facilities remains a research need. Additionally, lack of population data for many species of wildlife hinders knowledge of population-level impacts and effectiveness of mitigation measures. Policy revisions and regulation may be necessary, especially when wildlife agencies have little or no authority in decision-making or no protection for wildlife beyond voluntary measures.

Key words: bats, birds, compensatory mitigation, curtailment, cut-in speed, deterrents, human–wildlife conflict, mitigation hierarchy, off-sets, wind turbines

ONSHORE WIND ENERGY development continues to expand worldwide, in part due to recent technological advances, cost-competitiveness with conventional energy sources, and significant tax incentives (Toman et al. 2008). However, shifting production from fossil fuels to renewables that are gathered more diffusely from a broader spatial area involves tradeoffs (Kiesecker et al. 2011b) and different planning approaches (Köppel et al. 2014). Impacts of wind energy development on wildlife can be direct (e.g., collision fatality) or indirect (e.g., functional habitat loss, barriers to movement; Arnett et al. 2007). Often overlooked are impacts from habitat loss and, perhaps more importantly, behavioral modifications of animals that seek to avoid larger areas of habitat due to disturbance. Behavioral modifications due to disturbance may include fleeing, activity shifts, or changed habitat utilization (usually termed avoidance or displacement (Frid and Dill 2002, May 2015).

It is, therefore, crucial to understand species-specific behavioral characteristics that enhance vulnerability to collisions with wind turbines (Dahl et al. 2013, May et al. 2013). Avoidance of habitat may be short-term (i.e., during only the construction phase; Pearce-Higgins et al. 2012) or long-term, depending on the species and extent and level of disturbance activities after construction (Arnett et al. 2007). Impacts of wind energy further compound population declines for many species of wildlife from other anthropogenic-induced or natural sources of mortality and habitat loss. As more wind energy facilities are developed, site-specific and cumulative impacts on wildlife can be expected.

Birds and bats are especially vulnerable to mortality due to wind-turbines, because both are volatile taxa. Probability of collision with rotor blades depends on a species' aerodynamic capabilities. High mortality of birds (Ferrer et al. 2012, Smallwood 2013, Smallwood and Thelander 2008, Loss et al. 2013) and bats

(Arnett et al. 2008, Baerwald and Barclay 2009, Rydell et al. 2010, Camina 2012) at wind facilities have been documented worldwide. Indeed, recent estimates of annual and cumulative bird (Loss et al. 2013) and bat mortality at wind energy facilities (Arnett and Baerwald 2013, Smallwood 2013, Arnett et al. 2015) raise concern about population-level impacts, especially for

bats and long-lived bird species, given their life history traits and reproductive capabilities (Carrete et al. 2009, Barclay and Harder 2003). However, the context of wind turbine fatalities remains poorly understood in part because little population data exist for many species of birds and most species of bats (O'Shea et al. 2003). This gap hinders knowledge of population-level impacts and effectiveness of mitigation measures. Still, given the magnitude and extent of wind turbine-related mortality and habitat impacts, conservation implications are important for many species, and impacts should be mitigated.

Mitigation typically follows what is now a well-established hierarchy described by numerous authors (Kiesecker et al. 2010, 2011a, Jakle 2012, Hayes 2014, May 2016). This hierarchy typically involves avoidance of high-risk sites during planning of wind-turbine facilities, followed by minimization measures during operations, and compensating for unforeseen or unavoidable impacts through compensatory measures (often called biological offsets; Kiesecker et al. 2010, 2011a; Cole and Dahl 2013). Implementing the mitigation hierarchy should occur throughout the life cycle of a wind facility to ensure that impacts can be mitigated to achieve no net loss (May 2016). Efficacy of mitigation measures may, however, be highly site- and species-specific. Additionally, some steps in the mitigation hierarchy may not be achievable for all species of wildlife impacted by wind facilities. Given that

Table 1. Options for multiple-species and multiple-taxa approaches for mitigating wind-turbine induced mortality in birds and bats.

Mitigation measure	Birds	Bats	Specification
Avoid	+	±	At larger regional scales
Repowering	+	–	Larger and fewer turbines
Turbine location	+	–	Fine-scale micro-siting
Curtailement	±	+	Cut-in speed and/or temporal shut-down
Acoustic deterrence	±	±	Not compatible across taxa
Visual approaches	±	±	Not compatible across taxa
Other minimization measures	–	–	
Offsite compensation (in-kind)	+	+	Habitat-for-habitat
Offsite compensation (out-of-kind)	+	+	Nature-based solutions

≥1 species may be impacted by development of a wind facility, there is a need to elucidate those mitigation options that may allow for multiple-species and multiple-taxa approaches

Here, we provide a broad overview of approaches to mitigate impacts on wildlife of onshore wind energy development by following steps in the mitigation hierarchy. We focus our discussion and synthesis of key research findings on avoidance, minimization, and offsite compensatory measures. Comparing mitigation measures for birds and bats, which are the most affected species groups at wind facilities, allows for assessing options and limitations for multiple-taxa approaches. The expected efficacy of various mitigation measures were evaluated based on experimental studies, as well as inferences based on species-, site-, and turbine-specific risk factors (cf. Marques et al. 2014, May et al. 2015). Central criteria for evaluating mitigation measures include efficacy along the stressor-exposure-response gradient used in ecological risk assessments (Environmental Protection Agency 1998) and potential for ensuring effectiveness over time (Rankin et al. 2009). In addition to this, we assess species-specificity of the proposed measures to allow implementation for multiple-species and multiple-taxa (Table 1). We also discuss knowledge gaps and future research needs to evaluate efficacy of mitigation efforts for wildlife during wind energy planning and development. This overview is not intended to encompass all available literature, and it builds

upon more thorough reviews of mitigation that are useful resources for biologists and managers (Marques et al. 2014, May et al. 2015, Peste et al. 2015, May 2016). Also, Bright et al. (2008), Kiesecker et al. (2010, 2011*a, b*), Fargione et al. (2012), and Köppel et al. (2014) present approaches for landscape-scale planning and mitigation, including biological offsets, to compensate for impacts on wildlife.

Avoiding high-risk sites

The most fundamental step of mitigation begins during planning before construction of a wind facility begins when environmental issues and species-specific impacts are identified. Decision-making regarding planning and consenting wind energy projects are usually based on (Strategic) Environmental Impact Assessments (SEA and EIA) where avoidance issues are to be addressed (May 2016). Avoidance of existing sensitive areas for wildlife often is determined through consultation with local wildlife agencies and stakeholders (e.g., important bird areas, crucial winter range; U.S. Fish and Wildlife Service 2011). However, given that guidelines are voluntary, it is likely that not all developers follow this process, which could lead to poor siting in some places. Wyoming's strategy for conserving greater sage-grouse (*Centrocercus urophasianus*), for example, states that wind energy development is not recommended in core areas, which are mapped and available to developers (State of Wyoming 2011). Bright et al. (2008) mapped priority and statutory special protection areas in Scotland to aid developers in avoiding high-risk sites.

Numerous researchers have published approaches to modeling rare, unique, sensitive, or otherwise high-risk habitats. Kiesecker et al. (2011*a*) examined patterns of wind energy potential in terrestrial landscapes already disturbed by human activities (e.g., agriculture, oil and gas development) and estimated that there are 3,500 gigawatts of potential wind energy on lands in the United States that already are disturbed. Additionally, they noted that a disturbance-focused development strategy would avert development of 2.3 million ha of undisturbed lands while generating the same amount of energy. Kiesecker et al. (2011*a*) suggested that wind subsidies targeted at favoring low-

impact developments and creating avoidance and mitigation requirements that raise costs for projects impacting sensitive lands could improve public value for wildlife conservation and wind energy. Obermeyer et al. (2011) found that approximately 10.3 million ha in Kansas (nearly half of the state) potentially could be used to provide 478 gigawatts of installed capacity while still meeting conservation goals. They also reported that approximately 2.7 million ha of the 10.3 million ha would require no compensatory mitigation and could produce up to 125 gigawatts of installed capacity. These and other modeling efforts (Fargione et al. 2012) clearly demonstrate that wind energy can be developed in ways that avoid sensitive areas and important habitats, thus, reducing habitat loss and fragmentation. However, wildlife mortality due to collisions with wind turbines may not be fully avoided, especially for bats, which are known to be potentially attracted to wind turbines (Horn et al. 2008, Cryan et al. 2014).

Regional patterns of bird collision risk, while not negating the need for species-specific and local-scale assessments, may inform broad-scale and multiple-species decisions about siting wind facilities (Loss et al. 2013). Models of bird migration (Liechti et al. 2013, Pocewicz et al. 2013), abundance and aggregations (Carrete et al. 2012*a*, but see de Lucas et al. 2008), and habitat use or flight patterns (Katzner et al. 2012) have been used to generate species-use distributions, and merged with wind development potential to create risk probability maps to determine high-risk areas to potentially avoid. During initial planning phases (U.S. Fish and Wildlife Service 2011, Strickland et al. 2011), developers are encouraged to use these and other available tools and information to identify these areas and plan for avoidance. Mandatory measures would ensure greater compliance and effectiveness.

Using habitat-based models to estimate probabilities of risk of collisions with turbines by bats could aid in predicting and avoiding areas of high use and assumed risk of conflict with wind facilities. In Italy, Roscioni et al. (2013) used species distribution models and found that 41% of the region offers suitable foraging habitat for 2 species of bats (Leisler's bat [*Nyctalus leisleri*] and the common pipistrelle

[*Pipistrellus pipistrellus*]) that are vulnerable to collision with wind turbines. They noted that these same areas encompass >50% of existing or planned wind farms. Roscioni et al. (2014) further investigated habitat connectivity as a surrogate for assessing risks of wind facilities to bat migration and commuting in Italy and determined that most corridors used by bats were concentrated in an area where planned and existing (72 and 54%, respectively) wind facilities could interfere with connectivity in the region. In Portugal, fatality risk models indicated that wind facilities located in humid areas with mild temperatures and within 600 m of steep slopes had greatest probabilities of wildlife mortality (Santos et al. 2013). Unfortunately, most models have not been verified by linking mortality data from wind facilities, and this is a critical next step if such habitat-based risk models are to be valuable in predicting and avoiding high-risk sites for bats.

Locating wind farms at sites with least environmental impact is a multiple-criteria exercise that requires balancing of economic, technological, societal, and environmental demands within a spatial context (Aydin et al. 2010, Gorsevski et al. 2013, Tsoutsos et al. 2015; van Haaren and Fthenakis 2011). Although sensitivity maps may help identify sites that potentially are sensitive for birds or bats, these need to be offset against other demands, such as wind resources, connectivity to the electricity grid, and visibility in the landscape (May 2016). Multiple-criteria decision-making tools, incorporating mapping of important bird and bat habitat, however, enable multiple-taxa avoidance of sites that are environmentally sensitive.

Minimizing mortality at operating facilities

Risk of bird collision is usually estimated during pre-construction surveys and monitoring programs (Marques et al. 2014), although data are rarely made available (Arnett et al. 2007). However, the predictive relationship between pre-construction assessments and mortality can be weak (Ferrer et al. 2012). Mitigating wind-turbine mortality for birds is particularly complicated because the nature and magnitude of collision, disturbance, and barrier effects are influenced by species-specific sensory

capabilities, aerodynamics, and other factors (Marques et al. 2014, May et al. 2015). The extent of a birds' response toward wind turbines may also vary spatially and temporally, influenced by behavioral patterns, wind and topography, and condition of the turbine (Marques et al. 2014). Pre-construction studies that document bat activity using acoustic detectors to infer risk of bat mortality through collision with turbines failed to link with post-construction data gathered from searches for bird carcasses (Kunz et al. 2007a, Hein et al. 2013, Arnett et al. 2015). One possible explanation is that bats are attracted to turbines (Kunz et al. 2007b, Horn et al. 2008, Cryan et al. 2014), and once constructed, sites may be used differently by at least some species relative to the pre-construction period. If true, pre-construction assessments indicating low use could falsely assume low risk to bats (i.e., a Type II hypothesis error).

Repowering

Replacing several small turbines with fewer and larger turbines (i.e., repowering) has been hypothesized to minimize collision risk to birds, particularly raptors (Smallwood and Karas 2009, Dahl et al. 2015). At a repowered wind facility in California, Smallwood and Karas (2009) found that mortality at larger turbines was 54% less for all raptors and 64% for all birds compared to small, old-generation turbines. They concluded that, because new-generation turbines can generate nearly 3 times the energy per megawatt of rated capacity compared to old turbines, repowering could reduce mean annual bird mortality significantly, while more than doubling annual wind-energy generation. Dahl et al. (2015) predicted a reduction of 29 to 68% in collision risk when repowering the Smøla, Norway, wind farm (68 2-megawatt turbines) to 50 3-megawatt and 30 5-megawatt turbines. However, other studies demonstrate little (Krijgsveld et al. 2009), or even opposite effects (de Lucas et al. 2008), on bird mortality. Also, Loss et al. (2013) noted that bird mortality increased with increasing hub height. While almost nothing has been reported on repowering and bats, Smallwood and Karas (2009) noted that repowering wind facilities may result in greater bat mortality. Indeed, taller turbines may result in greater mortality for bats (Barclay et al. 2007).

Turbine location

Placement of turbines (i.e., micro-siting) in a landscape could minimize collision risk for some species of birds. May (2016) reported that micro-siting has been proposed along ridges for soaring raptors (Barrios and Rodriguez 2004, de Lucas et al. 2012b, Katzner et al. 2012, Smallwood and Thelander 2008), near wetlands and in agricultural areas (Mammen et al. 2011). Efficacy of micro-siting of single turbines to minimize bird impacts is likely site-specific (May 2016) and is largely based on untested predictive models as opposed to retroactively moving problem turbines and assessing mortality (Figure 1). Actual effectiveness of micro-siting is not fully understood. Still, landscape features enhancing potential risk for birds should be included when designing turbine placement at a facility, including orographic and areas with thermal updrafts for soaring and migratory birds (May 2016). Facilities also can consider openness between turbine rows and create flight corridors or divide the facility into separate clusters to minimize bird mortality (May 2016). The possible attraction of bats to turbines (Kunz et al. 2007b, Horn et al. 2008, Cryan et al. 2014) limits efficacy of micro-siting turbines to reduce bat mortality.

Curtailing operations

Temporary shutdown of wind facilities during high-risk periods for birds has been proposed (Marques et al. 2014, May et al. 2015), but not broadly implemented and tested. De Lucas et al. (2012a) tested a program to selectively stop turbines when Griffon vultures (*Gyps fulvus*) were observed near them, mortality rate for this species subsequently was reduced by 50%. They concluded selective curtailment at turbines with the greatest mortality rates can help mitigate impacts with a minimal effect on energy production. Real-time detection via radar or video, coupled with high-risk weather conditions, and associated curtailment has been proposed and implemented at some wind energy facilities (May 2016); however, findings have never been published and effectiveness remains questionable. For large, soaring birds, adjusting the cut-in speed (i.e., the least wind speed at which turbines generate power to the utility system) to 5 to 8 m/s at specific turbines



Figure 1. A wind turbine shown in a “feathered” position during a curtailment experiment designed to reduce bat fatalities at a wind facility in south-central Pennsylvania. (Photo courtesy of Edward Arnett)

and within limited time windows, will reduce collision risk at lesser wind speeds (Barrios and Rodriguez 2004, Smallwood et al. 2009). However, this may be a realistic option only when loss of energy output is limited.

A substantial percentage of bat mortality occurs during relatively low-wind conditions in late summer or fall (Arnett et al. 2008, Rydell et al. 2010). Because nonspinning turbine blades and monopoles do not kill bats (Horn et al. 2008, Cryan et al. 2014), it has been hypothesized that curtailing turbine operations when bats are at greater risk could minimize fatalities (Kunz et al. 2007b, Arnett et al. 2008). Raising turbine cut-in speed above the manufacturer’s recommendation (usually 3.5 to 4.0 m/s on modern turbines) renders turbines non-operational until the greater cut-in speed is reached and turbines then begin to spin and produce power (Arnett et al. 2011). Thus, raising turbine cut-in speed during low-wind periods should reduce bat kills.

In the United States and Canada, most curtailment studies report at least a 50% reduction in bat fatalities when turbine cut-

in speed was increased by >1.5 m/s above the manufacturer's recommended cut-in speed, with up to a 93% reduction in bat fatalities in 1 study (Arnett et al. 2013a). In Canada, Baerwald et al. (2009) demonstrated equally beneficial reductions (~60% fewer fatalities) with a low-speed idling approach, where blades were pitched 45° and generator speed required to start energy production was lessened. Even though turbines are not producing electricity while freewheeling below their normal cut-in speed, blades may still rotate at high speeds, which are lethal to bats (Arnett et al. 2013a). Young et al. (2011) discovered that feathering turbine blades (pitched 90° and parallel to the wind) at or below the manufacturer's cut-in speed resulted in $\geq 72\%$ fewer bats killed when turbines produced no electricity into the power grid. This is significant, because many types of turbines spin at speeds below their manufacturer's cut-in speed and likely kill bats when no electricity is being produced (Arnett et al. 2013a).

More recently, condition- and situation-dependent algorithms have been developed for wind turbine operating systems to reduce bat mortality. These algorithms consider several parameters, including wind speed, ambient temperature, season and time of day, as well as recorded levels of bat activity for defining a set of operation rules dictating when turbines will curtail (O. Behr, Friedrich-Alexander-University Erlangen-Nuremberg, unpublished data). Similar algorithms also may be applied to birds. Although curtailment requirements for birds may be greater than for bats with respect to wind speed thresholds, condition- and situation-dependent algorithms may provide a promising methodology for multiple-taxa curtailment. Also, bat-related curtailment may contribute to reduced bird fatalities at lesser wind speeds.

Acoustic approaches

Auditory methods to deter birds have been attempted, but there are few published studies on their effectiveness. Auditory harassment, whereby high-intensity sounds are emitted when birds are present, is deemed to have limited efficacy due to birds' potential habituation (May et al. 2015). Acoustic deterrent devices projecting broadband ultrasound have

been developed and investigated recently as an approach to reducing bat fatalities at wind facilities. Arnett et al. (2013b) tested a deterrent emitting broadband ultrasound in the 20 to 110 kHz range and found that, after accounting for inherent variation among sample turbines, bat mortality was reduced up to 64% at turbines with deterrent devices relative to control turbines. However, variation in reduced mortality was greater than that demonstrated for curtailment, and the device tested by Arnett et al. (2013b) suffered moisture damage during the study, rendering it unsuitable for broad deployment. Effectiveness of ultrasonic deterrents to reduce bat mortality also is limited by distance and area that ultrasound can be broadcast, as ultrasound attenuates quickly and is influenced by humidity (Jakevičius et al. 2010). Arnett et al. (2013b) cautioned that ultrasonic deterrents are not yet ready for operational deployment at wind facilities, but warrant further experimentation and modifications. Due to the dissimilar auditory capabilities of birds and bats, multiple-taxa solutions based on acoustics are not an option.

Visual approaches

Marques et al. (2014) and May et al. (2015) reviewed several approaches to alerting birds to the presence of turbines by painting 1 blade (Figure 2) to increase their detection by birds (W. Hodos, National Renewable Energy Lab, unpublished data) or using ultraviolet-reflective paint on rotor blades for UV-sensitive species (D. Young, Western Ecosystems Technology, unpublished data). Adjusting the turbine lighting regime also has been proposed to mitigate nocturnal bird mortality; pulsating lights or other wavelengths (blue or green lights; Poot et al. 2008) may reduce fatalities (Johnson et al. 2007). Long et al. (2010) investigated relative attraction of insects to specific turbine colors to determine if turbine paint color influences insect numbers at wind facilities. They found that, at ground-level, common turbine colors (white and light grey) attracted significantly more insects than other colors tested. However, tests at hub height and at operating wind facilities to determine effectiveness in minimizing bat mortality have not been conducted, thus negating this approach as a viable solution at present.



Figure 2. Painting of rotor blades to enhance visibility to birds and reduce avian collisions is being tested in situ at the Smøla wind farm, Norway. (Photo courtesy of Roel May)

Because bats are attracted to street lights due to increased insect presence (Fenton 2003), adjusting lighting regimes at wind facilities may reduce attraction, particularly to white lights used at buildings and electrical substations. So far, however, no effects of minimal turbine lighting on attraction and fatalities has been documented (Johnson et al. 2003, Johnson et al. 2004), and red aviation lights on turbines do not appear to increase bat mortality (Arnett et al. 2008, Bennett and Hale 2014).

Other minimization approaches

Other visual approaches, including placement of markings (e.g., scarecrows, raptor models) on the ground, replaying bio-acoustic sounds, such as distress calls, deterrence through olfaction, and approaches to making turbine surroundings less attractive (e.g., removing prey base) inside the wind facility have been extensively reviewed by Marques et al. (2014), May (2015), and May et al. (2015). In Scotland, Nicholls and Racey (2009) hypothesized that bats may be deterred by electromagnetic signals from small, portable radar units; they found that bat activity and foraging effort per unit time were reduced significantly when radar antenna produced a unidirectional signal maximizing exposure of foraging bats to the radar beam. Effectiveness of radar as a potential deterrent has not been tested at an operating wind facility to date, and it remains unknown if bat mortality could be significantly reduced by these means. All of these proposed, but largely untested, approaches are, however, likely to be species-specific.

Offsite compensatory mitigation

Compensatory mitigation is usually rare for wind developments, primarily because there is little regulatory structure requiring compensation for wind turbine–wildlife impacts (Jakle 2012). Compensatory mitigation, described as biodiversity offsets by some (Kiesecker et al. 2010, 2011a), are intended to ensure that unforeseen or unavoidable impacts of development are moderated by achieving a net neutral or positive outcome. May (2016) reviewed mitigation measures for birds and categorized compensatory efforts into 4 broad categories: on-site (in or adjacent to the wind farm); off-site; in-kind (targeting similar effects); and out-of-kind. Compensatory mitigation measures may include, but are not limited to: (1) habitat expansion, creation or restoration (including breeding, roosting and wintering sites); (2) exotic or invasive species removal; (3) supplementary feeding or prey fostering; and (4) predator control (Marques et al. 2014, Peste et al. 2015). Compensatory measures for a given species and situation should be selected based on limiting factors affecting the target species population in each area (Marques et al. 2014).

Several key assumptions surrounding compensatory measures, notably that such offsets actually mitigate mortality at least equal to that experienced at a project site. Additionally, it assumes that habitat acquisition, creation, or restoration will replace habitat impacted by the project so as to result in no net-loss to bird or bat populations (Gardner et al. 2013). Another key assumption is that all

habitats or conditional uses of habitat (e.g., for breeding and rearing of young) can be offset. Importantly, while the conceptual framework and predictive modelling for compensatory measures has been well-established, there are challenges for achieving no net-loss (Cole 2011, Gardner et al. 2013). Empirical evidence demonstrating effectiveness and achievement of no-net loss for wildlife populations is generally lacking. Moreover, effectiveness of voluntary guidelines (e.g., USFWS 2011) and need for mandatory measures to mitigate wildlife impacts should continually be evaluated. Also, given projected increases in multiple sources of energy development, including biomass, wind, and oil and gas development, future conflicts surrounding land-use, mitigation, and conservation strategies should be anticipated more holistically (Arnett et al. 2007, May 2016). Habitat mitigation options may be compromised by development of other energy sources seeking similar mitigation options. Therefore, when evaluating compensatory measures to mitigate impacts at wind energy facilities, broader assessments and forecasts of cumulative impacts of all possible land uses will be necessary to ensure that conservation strategies among industries, agencies, and private landowners are effective (Arnett et al. 2007, Cole 2011).

While compensatory mitigation is a plausible option to address habitat impacts for many species of wildlife, it is unknown if such measures can mitigate wildlife mortality of a wide variety of migratory bird or bat taxa. Offsite, compensatory approaches to mitigate wildlife fatalities at wind facilities have been contemplated, but never used or tested for effectiveness. Potential conservation measures for bats could include preservation and provision of roosts, creation of open water, and forest management and protection beneficial to bats (Peste et al. 2015). For birds, providing roosting sites and perches and supplemental feeding stations and by reducing other causes of mortality have been proposed (Marques et al. 2014, May 2016). A fundamental problem with offsite compensation for wind turbine-related mortality is that there is no empirical basis for determining how much of any given conservation measure, or combination of measures, is needed to offset mortality and

over what temporal scale. Habitat-based compensation to offset mortality to deter population-level effects seems impossible for species experiencing high cumulative mortality or long-lived, rare and declining bird and bat species (Carrete et al. 2009, Arnett and Baerwald 2013). It is unlikely that habitat offsets could realistically compensate for high mortality in such species, and offsets also would have to continue through space and time to compensate for continued mortality at existing facilities and for new facilities. This approach seems prohibitively expensive and, thus, unlikely to be successful.

For some species of bats, offsite compensatory mitigation measures could provide long-term conservation benefits, such as cave-gating, which is known to reduce disturbance at hibernacula and to potentially increase populations (Crimmins et al. 2014). Unfortunately, presence of white-nosed syndrome in cave-hibernating bats in the United States and Canada (Frick et al. 2010) likely limits effectiveness of cave conservation measures at least in areas where this disease is prevalent or likely to occur. Cole and Dahl (2013) assessed how retrofitting power line pylons on the island could reduce electrocution of the species to compensate for wind-turbine-induced mortality of white-tailed eagles (*Haliaeetus albicilla*) at the Smøla, Norway wind facility. They found that retrofitting 25 to 40% of the most dangerous junction pylons could offset fatalities at the wind facility. As a last resort, offsite and out-of-kind compensation approaches, such as conservation banking and in-lieu fees (Jakle 2012) or nature-based solutions also may be considered to reduce climate change impacts directly (e.g., carbon sequestration stores, floodplain restoration).

Conclusions and future research needs

Direct and indirect impacts on wildlife at wind facilities are a global issue, and avoiding or mitigating these impacts are important to conservation and public acceptance of wind-energy development. Following the mitigation hierarchy through the life cycle of a wind energy project can provide a framework consistent with sustainable development (Kiesecker et al. 2010). There are numerous approaches to avoid,

minimize, or mitigate impacts via compensatory measures available to wind energy developers (Jakle 2012, Marques et al. 2015, May et al. 2015, Peste et al. 2015, May 2016). Several guidance documents (Kunz et al. 2007a, Rodrigues et al. 2008, Strickland et al. 2011) also complement a rich scientific literature and should be used by developers and permitting agencies when determining facility locations, siting of turbines, conducting monitoring and research, and mitigating impacts. Implementation of methods and compliance with guidelines should be assessed by regulatory agencies to ensure that mitigation is being conducted and is effective.

In this review, we assessed options for multiple-species and multiple-taxa mitigation of impacts from wind facilities on birds and bats. Avoidance of high-risk sites for development, curtailment during operation, and compensation are deemed most promising in addressing potential impacts across taxa (Table 1). While several mitigation approaches have been implemented at wind turbine facilities, there remains a dearth of empirical evidence to support the effectiveness of most of them and how many facilities employ mitigation measures. Moreover, data often are never made publically available by developers, which impedes scientific progress and creates distrust. Evaluating effectiveness of pre-construction wildlife assessments and habitat modeling in predicting future mortality at wind facilities remain valid research efforts for all species of wildlife. Predicting and avoiding high-risk areas for bats have proven difficult in most situations and are complicated by the fact that bats are attracted to wind turbines (Horn et al. 2008, Cryan et al. 2014). Empirically verifying behavioral or habitat-based risk models will be an important next step to determine accuracy and precision of model-based predictions of wildlife mortality or other impacts of wind turbines. Also, alternative mitigation approaches to operational adjustment (e.g., raising cut-in speed), such as acoustic deterrents, should be proven to be equally or more effective at reducing mortality before being accepted as viable approaches.

Curtailling wind turbine operations is one of the only mitigation approaches proven effective at reducing wildlife mortality (Baerwald et al.

2009, Arnett et al. 2011, de Lucas et al. 2012), but actual effectiveness remains unknown. Population data are lacking for many species of wildlife, including those at greatest risk from wind turbines (O’Shea et al. 2003, Carrete et al. 2009). This not only impedes our understanding of actual impacts on wildlife caused by collision with turbines, but also limits understanding effectiveness of mitigation efforts. For example, is a 50% reduction in bat fatalities from raising turbine cut-in speed adequate to mitigate population-level impacts, or is it simply delaying inevitable population losses? Lack of population data also makes it difficult to set thresholds for mitigation (Arnett et al. 2013c). Population data are not likely to be available for most species of wildlife in the near future and, thus, wind operators and regulators should practice the precautionary principle (Carrete et al. 2012b) avoiding high-risk sites and implementing minimization measures at sites where mortality is predicted or found to be high, even without population data.

Several policy, regulatory, and communication challenges have been identified that may impede protection of wildlife and developing wind energy responsibly (Arnett 2012). Unless there is a government-based nexus, most siting, monitoring, and mitigation efforts by wind energy developers and operating companies are voluntary, usually without regard for cumulative effects (Arnett 2012). Stronger coordination among agencies and stakeholders is essential, and policy revisions and regulation may be necessary in most parts of the world. Decision-making should be grounded in the best available science. If we are to successfully develop wind energy that protects wildlife consistent policy, accountability, effective mitigation strategies, requirements, and incentives for all companies are fundamental (Arnett 2012). The up-take of the entire mitigation hierarchy throughout the life cycle of a wind-energy facility contributes to the no-net-loss goal of least possible environmental costs per kWh from wind energy (May 2016).

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