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Review

Considerations for upscaling individual effects of wind energy development towards population-level impacts on wildlife

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ABSTRACT

The expansion of wind energy poses challenges to policy- and decision-makers to address conflicts with wildlife. Conflicts are associated with impacts of existing and planned projects on wildlife, and associated difficulties of prediction where impacts are subject to considerable uncertainty. Many post-construction studies have demonstrated adverse effects on individuals of various bird and bat species. These effects may come in the form of collision-induced mortality or behavioral or physiological changes reducing the fitness of individuals exposed to wind energy facilities. Upscaling these individual effects to population impacts provides information on the true value of interest from a conservation point of view. This paper identifies methodological issues associated when moving from individual effects to population impacts in the context of wind energy. Distinct methodological approaches to predict population impacts are described using published case studies. The various choices of study design and metrics available to detect significant changes at the population level are further assessed based on these. Ways to derive impact thresholds relevant for decision-making are discussed in detail. Robust monitoring schemes and sophisticated modelling techniques may inevitably be unable to describe the whole complexity of wind and wildlife interactions and the natural variability of animal populations. Still, they will provide an improved understanding of the response of wildlife to wind energy and better-informed policies to support risk-based decision-making. Policies that support the use of adaptive management will promote assessments at the population level. Providing information to adequately balance the development of wind energy with the persistence of wildlife populations.

1. Introduction

A drive to reduce emissions of greenhouse gases to mitigate anthropogenic climate change has boosted the innovation, development and application of renewable energy sources such as wind. All power generation, however, has environmental costs (Intergovernmental Panel on Climate Change, 2011). Achieving acceptable environmental and social costs per kWh from wind energy therefore depends on the ability to address environmental and societal challenges. On the environmental side, populations of birds, bats, marine mammals and fish have the potential to be affected by the development of wind energy (Gill, 2005; Inger et al., 2009; Katzner et al., 2013; Schuster et al., 2015). Although this has so far not received much attention, terrestrial mammals may also be affected (Agnew et al., 2016; Skarin et al., 2015). The fast rate of wind-energy development presents the challenge of verifying the magnitude of impacts on wildlife and, if necessary, constructing ways of mitigating these (Langston and Pullan, 2003; May et al., 2015). Negative effects on wildlife are generally perceived as a major conflict issue for wind-power development (Drewitt and Langston, 2006; Stewart et al., 2007).

In this respect, it is important to distinguish between the effects wind-power plants have on individuals and how these ultimately impact populations. Effects here relate to any change in the survival probability of an individual due to disturbance, barrier effects and direct injury or mortality. Impacts occur when the vital rates (reproduction, mortality, survival) for the population these individuals are part of are changed. Recent research has provided insight into the potential impacts of wind-power plants at the population level for various species (see Supplementary Information). However, it often remains difficult to assess population-level impacts due to the spatial scale and long-term monitoring data required for such studies. Currently, licensing of renewable energy developments is therefore routinely based on predicted

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effects to individuals of sensitive species, e.g. use of collision-risk modelling and proximity to breeding sites. In some cases, local individual effects are extrapolated over large spatial scales as a proxy for potential population impacts (e.g. Brabant et al., 2015).

From a conservation point of view, it is crucial to assess the potential impact the development of a wind-power plant will have on the population at large. This, however, requires a good understanding of the definitions and requirements for appropriately predicting population-level impacts. Setting appropriate decision thresholds for regulation of the impacts of wind energy, and associated mitigation, are being suitably managed (Brownlie et al., 2013). The research question derived from this preamble, is how population impacts caused by wind energy development should be assessed. The objective of this review therefore is to provide an overview over how populations are to be defined, impacts measured and predicted, and how impact thresholds can be set and applied for decision making. Although the total load of all anthropogenic impacts in both space and time in the end determine the long-term fate of a population, this review focuses specifically on impacts due to wind energy development. The review was executed as part of the International Energy Agency's Task 34 called Assessing Environmental Effects of Wind Energy.

The review was based on an extensive desk research and literature review, where relevant literature was obtained through searches on Google Scholar, ISI Web of Science and the Tethys Knowledge Base (https://tethys.pnnl.gov/knowledge-base-wind-energy). Relevant search terms included: wind energy OR wind power, wind farm OR wind-power plant, onshore, offshore, population, demography, impact, effect, bird, bat, marine mammal.

2. Theoretical foundations for population-level consequences

The construction and operation of wind-power plants may affect individuals of a species through collision mortality, changes in behavior due to disturbance (e.g. moving rotor blades, noise, electromagnetic fields) and barrier effects, and habitat modifications leading to displacement. The nature and magnitude of those effects are highly site- and species-specific (Drewitt and Langston, 2006). The magnitude of such effects depends on the sensitivity of a species for disturbance and the effects this has on an individual's energy balance and consequently its fitness. Time and energy expenditure may increase due to stress-related physiological responses, increased movement activity, and ultimately injury and death of either the individual or its dependent young. Increased energy expenditure due to barrier effects may lead to reduced fitness (Masden et al., 2010, 2009). Displacement from breeding or foraging habitat and changes in foraging efficiency may also influence an individual's energy uptake and ability to reproduce successfully. Recently, a study by Agnew et al. (2016) indicated physiological stress in badgers (*Meles meles*) nearby wind turbines.

Depending on the magnitude-of-effect these mainly behavioral effects have on the fitness of an individual coupled with the number of affected individuals, ultimately leads to reduced survival, reduced reproduction and increased mortality at the population level (King et al., 2015). Dependent on the demographic characteristics and spatial requirements of a species, these effects may result in significant population level impacts. Long-lived species with slow reproduction and high annual survival rates are particularly vulnerable to increased mortality (Dahl, 2014). The reduced breeding success due to displacement effects (e.g. abandonment of breeding sites) and/or loss of parents (through collisions or injury) may in turn affect population dynamics (e.g. Carrete et al., 2009; Dahl et al., 2012). It may however not always be clear whether the presence of wind turbines has significant population consequences (Dahl, 2014; de Lucas et al., 2008; Hunt et al., 1998; Madders and Whitfield, 2006), as this depends on the rate of direct mortality, the fitness costs of disturbance and on the availability of alternative habitat (Gill et al., 2001).

Within meta-populations, migration of individuals from good-quality source habitat to lower-quality sink habitats may stabilize the demographic dynamics of a population (Dias, 1996). Wind-power plants located in good-quality habitat may change such sources into sinks (Dahl et al., 2012; Kirol et al., 2015). Sudden environmental change may uncouple the cues that individuals use to assess habitat quality (yielding lower fitness) from the true quality of the environment (Robertson and Hutto, 2006). This has been dubbed the ecological trap theory (Battin, 2004; Patten and Kelly, 2010; Robertson and Hutto, 2006). Ecological traps may occur when animals are falsely attracted to habitats with consequences of reduced fitness, survival and reproduction (Battin, 2004). Wind energy relevant examples include fish and their predators attracted to artificial reefs (Reubens et al., 2013; Scheidat et al., 2011) and bats misinterpreting turbines as trees (Cryan et al., 2014). Conversely, perceptual traps may occur when high-quality habitats are avoided when perceived to be less attractive (Patten and Kelly, 2010). Dependent on the sensitivity a species to disturbance and the vulnerability to mortality (Adams et al., 2016; Furness et al., 2013; Robinson Willmott et al., 2013), behavioral decisions (e.g. avoidance or attraction) may lead to functional habitat loss affecting fitness in individuals (May 2015). However, the magnitude of behavioral responses to disturbance does not necessarily reflect population-level consequences as such are dependent on the availability of alternative habitat and site fidelity (Gill et al., 2001). An example of this can be seen for the white-tailed eagle (*Haliaeetus albicilla*) at the Smøla wind-power plant where low levels of behavioral responses (Dahl et al., 2013; May et al., 2013), affect mortality and breeding (Dahl et al., 2012; May et al., 2010, 2011) but not population persistence (Dahl, 2014).

Sensitivity to wind-power plants may be related to age, sex or size classes, and specific life stages (e.g. migration, territorial/floater), as well as being potentially density-dependent. Consequently, the effects may not be homogeneous across a population but effect certain groups disproportionally affecting population dynamics in unexpected ways (Vindenes et al., 2008). The way in which the dynamics of a population are impacted by wind energy development also depends on the life-history strategy of the species of concern. While high-reproductive and often short-lived species (*r*-selection) are mainly affected through changes in fecundity, long-lived species often with lower reproductive rates (*K*-selection) are more sensitive to changes in survival (Sæther and Bakke, 2000). Fluctuations in the size of recruitment-driven populations are more strongly influenced by environmental stochasticity than survival-restricted populations (Sæther et al., 2004). Consequently, mortality for *K*-selection species will more likely be additive while *r*-selection species may compensate for collision mortality with a reduction in mortality from other causes or increased reproduction (Peron, 2013). Assessing additive effects may therefore prove to be more problematic in *r*-selection species. The extent of additive versus compensatory density-dependent responses to collision mortality is however not yet well understood, and difficult to study (Diffendorfer et al., 2015; Horswill et al., 2017; Peron, 2013).

3. Moving from individual effects to population-level impacts

Environmental assessment has been developed to ensure that the potential environmental consequences of plans and projects are taken into account before the project is licensed. Within the framework of these assessments, the planning and siting of renewable energy projects are guided by the precautionary principle in an attempt to carefully address wildlife challenges (Köppel et al., 2014). However, because uncertainty will likely remain, population assessment frameworks may be more suited to adaptive management approaches. Adaptive management approaches embrace the inherent scientific uncertainty and require tolerance thresholds of change and adoption of practices that build consensus through reducing scientific uncertainty to enable improved decision-making (Köppel et al., 2014). Clearly defining acceptable levels of population impacts and necessary mitigation to achieve the goal at the level of individual projects will be critical in assessing