# Future Research Directions to Reconcile Wind Turbine–Wildlife Interactions

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**Abstract** Concurrent with the development of wind energy, research activity on wind energy generation and wildlife has evolved significantly during the last decade. This chapter presents an overview of remaining key knowledge gaps, consequent future research directions and their significance for management and planning for wind energy generation. The impacts of wind farms on wildlife are generally site-, species- and season-specific and related management strategies and practices may differ considerably between countries. These differences acknowledge the need to consider potential wildlife impacts for each wind farm project. Still, the ecological mechanisms guiding species' responses and potential

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J. Köppel (ed.), *Wind Energy and Wildlife Interactions*,
DOI 10.1007/978-3-319-51272-3_15

vulnerability to wind farms can be expected to be fundamental in nature. A more cohesive understanding of the causes, patterns, mechanisms, and consequences of animal movement decisions will thereby facilitate successful mitigation of impacts. This requires planning approaches that implement the mitigation hierarchy effectively to reduce risks to species of concern. At larger geographical scales, population-level and cumulative impacts of multiple wind farms (and other anthropogenic activity) need to be addressed. This requires longitudinal and multiple-site studies to identify species-specific traits that influence risk of mortality, notably from collision with wind turbines, disturbance or barrier effects. In addition, appropriate pre- and post-construction monitoring techniques must be utilized. Predictive modelling to forecast risk, while tackling spatio-temporal variability, can guide the mitigation of wildlife impacts at wind farms.

**Keywords** Future research directions · Impacts of wind farms · Wildlife · Animal movement decisions · Mitigation hierarchy

## Introduction

Reducing emissions of greenhouse gases to prevent anthropogenic climate change has boosted the innovation, development and application of renewable energy sources such as wind. At the same time, environmental and social issues will affect wind energy development opportunities (IPCC 2011). As wind energy development increases and larger wind farms are considered, existing concerns become more acute and new concerns may arise. Depending on the planned level of development, a need to reconcile renewable energy targets and biodiversity conservation will emerge, to ensure the lowest possible environmental costs per kWh (cf. van Kuik et al. 2016). This in turn requires comprehensive insight into potential effects of wind farms on wildlife such as disturbance, habitat loss and mortality, impacts on a population level (cf. Boehlert and Gill 2010), and innovative measures to mitigate these impacts. Forthwith we use the term "wind turbine–wildlife interactions", to capture all interactions wildlife species may have with wind turbines, associated infrastructure and human activity within the wind farm area throughout its entire life cycle.

Since the early 2000s, the number of peer-reviewed publications on wind energy generation and wildlife impacts has increased more than tenfold (Fig. 1). Especially after the first Conference on Wind energy and Wildlife impacts in 2011 there was a threefold increase in the number of publications. For example, while studies on behavioural responses of wildlife to wind farms increased from around 2005, mitigation studies started to become more common from 2010 onwards. A similar trend was also seen in the programs of the consecutive Conferences on Wind energy and Wildlife impacts. Reviews synthesizing the current knowledge have furthered our understanding of the behavioural and ecological mechanisms guiding

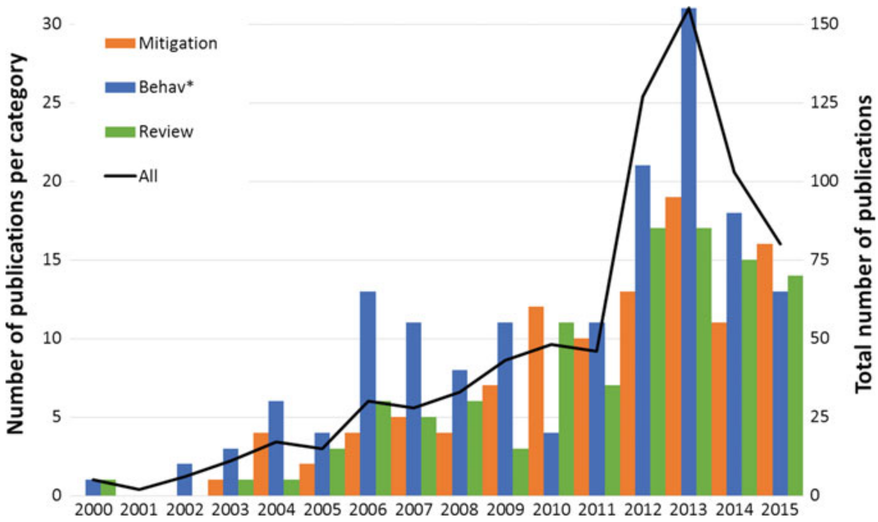


**Fig. 1** Number of peer-reviewed publications recorded in the wind-wildlife impacts literature database (https://wild.nrel.gov/) maintained by National Renewable Energy Laboratory (NREL) within the period 2000–2015 (*black line*; *right* y-axis). *Stacked columns* indicate the number of publications within specific categories (*left* y-axis): publications focusing on mitigation (*orange*) or behaviour (*blue*), and review publications (*green*) (Color figure online)

species' responses and potential vulnerability to wind farms (Cryan and Barclay 2009; Inger et al. 2009; Marques et al. 2014; May 2015; Schuster et al. 2015). The enormous increase in publications on wind turbine–wildlife interactions during the last decade necessitates an evaluation of the current knowledge on these topics, especially with regard to underexposed topics. This chapter presents an overview of key knowledge gaps, consequent future research directions (see also Gill 2005; Kunz et al. 2007; Wang et al. 2015) and their significance for management and planning for wind energy generation.

## *Setting the Stage: Planning for Wind Energy Development*

Improved understanding of the implications of wind energy for the environment and adequate implementation of mitigation efforts, require transdisciplinary approaches that are embedded in complex decision-making processes. The discussion of social acceptance in wind energy development as well as the trade-offs between ecosystems services (e.g. climate change mitigation vs. biodiversity benefits) have become paramount research challenges. The boundaries between science and policy in wind energy and wildlife research need to be considered more systematically, as science-policy transitions might prove further decisive to future research.

## Green Versus Green Ethics

The rapid rate of wind energy development throughout the world has simultaneously led to stronger opinions from both opponents and proponents of wind energy development (IPCC 2011; Wolsink 2012). This requires considering arguments of 'green versus green' environmentalism, where proponents promote the benefits of wind energy development in reducing $CO_2$ emissions to mitigate climate change, and opponents point to the costs involved for biodiversity and ecosystem services through land-/seascape changes (Warren et al. 2005). The problem here not only lies in a simplistic misjudging of the biodiversity issue as NIMBYism (Not-In-My-Back-Yard), but may also be related to various forms of resistance and institutional settings (Cowell et al. 2011; Wolsink 2012; Huesca-Pérez et al. 2016). Differences between beneficiaries and those bearing the costs may thereby cause challenges for planning. This is due to uneven spatial distribution of equity, inter-generational dimensions (decisions made today affecting future generations) and scientific uncertainty of impacts (Gardiner 2011).

In addition, when decision-making is valued within an ethical framework of economic rationality (Cowell et al. 2011), short-term economic benefits and local societal costs often take precedence over environmental considerations (Kopnina 2013). Environmental impacts may then be perceived as a technological problem or economic cost that can be avoided, minimized, mitigated or compensated to reach no net loss (Wolsink 2012). On the one hand, given the benefits of wind energy development for climate change mitigation in the longer term, a case might be made for a certain level of acceptable environmental impact. On the other hand, given the benefits of efficiently implementing the mitigation hierarchy during wind farm development and the resulting long-term benefits for biodiversity, a case might be made for stronger restrictions in the planning of future wind energy projects. To address these spatio-temporal ethical challenges further research is required to support political decision-making processes and planning strategies.

## Transdisciplinary Decision-Making

Top-down siting and consenting processes, coupled with mistrust among stakeholders and institutional settings, impede the ability to appropriately site wind farms in locations with acceptable impacts (Warren et al. 2005). The clue in reconciling arguments for and against wind energy development lies therefore in scaling decision-making processes and strategic planning to intermediate spatial and temporal scales. By assessing potential impacts (environmental or societal) of a specific project at a regional spatial scale transcending its life cycle, i.e. above the local and immediate opponent scale but below the national/global and diffuse proponent scale. Both the proponent and opponents must then upscale or down-scale their arguments to fit the planning level (i.e. 'think global, act local…but plan regional', cf. Warren et al. 2005). This requires that strategic environmental assessments are prioritized to assess all alternative strategies, are taken up in the decision-making process, and are tied to Environmental Impact Assessment (EIA) practice (Jay 2010; Geißler 2013; Geißler et al. 2013; Phylip-Jones and Fischer 2014).

Several authors have also stressed the need for collaborative and transdisciplinary strategic planning processes and transparent decision-making (Warren et al. 2005; Cowell et al. 2011; Wolsink 2012; Petrova 2016). The issues related to wind energy development and wildlife impacts have been and will continue to be addressed by policy-makers, regulatory agencies, industry, non-governmental organizations, and the scientific community. Perspectives of these groups on such issues vary, as do motivations, power, consistency and levels of engagement. The role of scientists in the science–policy–practice interface is to provide evidence-based and policy-relevant information upon which transparent decisions can be based. To improve this transdisciplinary interface, further research is required to evaluate approaches that may enhance participation and transparency in decision-making processes.

## *Planning and Management Approaches and Regulations*

Planning and management of wind energy projects vary considerably among countries, and have evolved over the years. While early wind energy projects were constructed without clear strategic planning requirements, the monitoring and mitigation guidelines in permitting processes have recently become more commonplace. Implications for relevant regulations in relation to wind and wildlife issues also advance as more knowledge and experience is gained. These implications include, for example, problems associated with take permits, application of the precautionary principle, and transboundary effects (Voigt et al. 2012; Köppel et al. 2014). Comparative research will be needed to assess how various planning and management strategies are able to address human–wildlife conflicts relating to wind energy development. Such an evaluation should identify key planning components that moderate conflict levels, reduce uncertainty, and avoid delays in consenting processes. Investigations could be directed toward the consequences of regulations and guidelines that were prepared with more or less adaptive approaches (Köppel et al. 2014). Yet, the practicability and effectiveness of such adaptive approaches remain to be tested.

A relatively new opportunity for addressing offshore wind energy projects and their impacts on wildlife in particular is available through marine spatial planning (MSP). An adaptive approach can also be adopted for marine planning where it has the potential to reduce the loss of ecosystem services, help address or avoid conflict, and create economies of scale and efficiencies in enforcement and management (Portman 2015). MSP is a process that aims to rationalize the use of marine space and identify the compatibility between activities. This facilitates the identification of conflicts and synergies between uses. Such an approach incorporated in an MSP process could contribute to the integration of offshore wind energy projects and other co-uses while minimizing impacts to wildlife (Portman 2011).

## The Mitigation Hierarchy

Reconciling wind energy development with conservation of the environment necessitates that mitigation measures are implemented to attempt to eliminate negative impacts caused throughout the life cycle of a wind farm. Implementation of effective and practical measures to mitigate impacts is paramount in order to achieve climate-change mitigation goals whilst protecting biodiversity (Madsen et al. 2006; Marques et al. 2014; May et al. 2015; Peste et al. 2015; Arnett and May 2016). Mitigation simultaneously decreases the general level of conflicts with wildlife and enables development at sites previously considered to pose too great a risk. The (proposed) mitigation of environmental impacts is a key stage within EIA process, where developers are to mitigate impacts following the so-called 'mitigation hierarchy'.

The prioritized steps of the mitigation hierarchy are tiered to the consecutive decision gates required for wind farm development. This tiered approach ensures that mitigation decisions are taken prior to the appropriate development phase when they are to be implemented. The hierarchy is as follows. (1) Impacts should foremost be avoided when planning prior to siting. (2) Unavoidable impacts should minimized during the design phase prior to construction. (3) Measures to further reduce impacts should be implemented during construction prior to operation. (4) Any residual impacts should thereafter be compensated during operation. (5) At the end-of-life of a wind farm, the area should be restored as part of decommissioning (May 2016).

## Avoid: Consensus-Based Siting Approaches for Improved EIAs

Spatial planning that informs all involved parties on the wildlife species likely to be affected by wind energy projects is essential for avoiding these impacts through careful siting (e.g. Garthe and Hüppop 2004). Pre-construction sensitivity maps for locational guidance (e.g. Bright et al. 2008; Bradbury et al. 2014) can provide important input to multiple-criteria assessments for siting of wind farms (e.g. Tsoutsos et al. 2015). Geographic Information Systems (GIS) are valuable tools for this purpose, enabling different data layers to be overlaid with any proposed wind farm boundary, as part of the risk assessment. This requires up-to-date knowledge on the distribution and ecology of potentially affected species at appropriate geographic scales (Hammond et al. 2013). Pre-construction surveys, designed to collect data to record occurrence of sensitive species and predict impacts, are an essential part of the EIA procedure. Such surveys should be made available to enable access to cost-effective, incremental and updated information on the distribution of sensitive species and their habitats across wind energy projects. For migratory and highly-mobile species that shift their distributions to adapt to changes in prey availability or season (e.g. Baerwald and Barclay 2009; Hammond et al. 2013), there exists a need to increase our understanding on what drives their distribution to predict these shifts. For species that are mostly affected during the construction phase, such as Harbour porpoises (Madsen et al. 2006) or red grouse (Pearce-Higgins et al. 2012), prediction of high-density habitats and high-sensitivity time periods, such as breeding and nursing periods, will be crucial.

Another important issue with regard to the avoidance-effectiveness of spatial planning is data availability across spatial scales. Most surveys are done at the individual project level, but compilation of such fine-scale information on the occurrence and spatio-temporal distribution of relevant species is limited due to a lack of standardization and spatial coverage. Regional spatial planning can therefore only utilize available regional or countrywide occurrence data resulting in a higher degree of uncertainty (e.g. no-data vs. absence of occurrence). Future research should develop a systematic approach for the respective data requirements at the different spatial scales to enhance the effectiveness of sensitivity mapping (cf. van Kuik et al. 2016). This will help to avoid the licensing of wind energy projects in important areas for species of conservation concern (e.g. Bright et al. 2008).

## *Minimize: Project-Level Siting and Micro-Siting Tools*

During the pre-construction design phase for licensed wind energy projects, but also when repowering, potential impacts can be minimized by adjusting the ecological footprint of wind farms or single wind turbines. Measures to minimise impacts through adjustments in turbine configuration, wind farm design and micro-siting are aimed at decreasing the potential hazard or exposure of the turbines to wildlife (May et al. 2015). Vertical axis wind turbines have recently been promoted as being environmentally-friendly (Islam et al. 2013), however the scientific evidence for this technology is still lacking (Santangeli and Katzner 2015). Utilizing fewer and larger turbines that are placed farther apart may contribute to reducing collision risk (Smallwood et al. 2009; Dahl et al. 2015), yet empirical data also suggests disproportionally higher fatalities rates for bats at larger wind turbines (Barclay et al. 2007).

Micro-siting of turbines within the landscape during the pre-construction design phase can optimize wind capture whilst simultaneously taking into account areas of high bird concentration or sites with increased collision risk (e.g. Bohrer et al. 2013). Although predictive tools have been developed to provide insights into possible impacts of different wind farm designs (e.g. Masden et al. 2012), it remains unclear to what extent micro-siting practice has actually resulted in adjusted design of wind farms. This requires that both wind engineers learn how siting decisions relate to collision impacts, and environmental scientists understand the impacts of siting on wind energy generation. There is great opportunity for siting to simultaneously optimize wind energy generation and mitigate wildlife impacts. To validate predicted risk zones in operational wind farms, comparative research is required to investigate how turbine configurations and wind farm designs are affecting wildlife. By employing e.g. meta-analyses, actual risk caused by disturbance potential, barrier effects and collision risk can be evaluated against siting options. This would require access to data from commissioned monitoring and technical data on energy yield of wind turbines at consented sites. Finally, development of guidelines for environment-friendly construction as well as limiting construction and maintenance activity in sensitive periods may contribute to reduced disturbance potential.

## *Reduce: In Situ-Innovative Techniques*

The efficacy of post-construction measures to reduce impacts varies across taxa and geographic region (Madsen et al. 2006; Marques et al. 2014; May et al. 2015; Arnett and May 2016). Many impact reduction measures have been proposed, but only few have been tested and found to be effective (e.g. cut-in speeds for bats: Baerwald et al. 2009; Arnett et al. 2011). To test the effectiveness of onsite impact-reduction measures satisfactorily, tests should be consistent with experimental design principles. The five most important principles include clear articulation of the hypothesis associated with the impact reduction strategy, use of controls, replication and interspersion of treatments, and implementation at appropriate temporal and spatial scales. In addition, sample sizes of experimental units need to be decided in order to obtain a suitable effect size. Acoustic deterrence of marine mammals during pile-driving have so far shown varying results (Madsen et al. 2006). Further research needs to focus on ways to reduce the emitted noise from construction activities (e.g. bubble curtains, mode of operation).

Acoustic and visual deterrence, with or without detection systems, has also been proposed for birds and bats, although their efficacy, and level of habituation, has yet to be tested in situ. Similarly, more in situ testing is needed on wind-turbine design modifications (e.g. blade painting or safety illumination schemes). Curtailment has been shown to be effective in reducing bat fatalities (e.g. Arnett et al. 2011), but limited evidence exists in support of curtailment as a strategy to reduce bird fatalities (de Lucas et al. 2012). However, temporary shutdown of turbines has potential as long as effective algorithms can be developed to restrict shutdown to specific events of near-collisions (May et al. 2015). One research track that has received less attention so far is ecological management strategies to reduce wildlife impacts. On-site and/or off-site habitat management may dissuade wildlife to be attracted to the wind turbines and/or lure them away towards improved habitat refuges outside the wind farm site.

## *Compensate: Offsetting Methodology, Options and Tools*

Compensation is still in its infancy with regard to offsetting residual impacts during a wind farm's life cycle. It requires good knowledge of the magnitude of population-level impacts and of the extent that the previous steps of the mitigation hierarchy have lessened the impact. There is also a pressing need to understand which compensation strategies may benefit wildlife species most, if at all, and which scaling methodology may be most appropriate to use (May 2016). However, also more fundamental questions need to be addressed, related to like-for-like compensation and scaling issues. Dependent on the nature of the impact (e.g. fatalities versus displacement), off-site habitat enhancement or out-of-kind compensation options may or may not be able to offset impacts. This will depend on the direct and indirect benefits the measure has on the species' demography.

Compensation may be further hampered by scaling issues when sufficient action can only be obtained over large geographical areas. Creation of artificial reefs, de facto refuges from fishing, and re-establishment of the undisturbed seabed in offshore wind farms (Wilson and Elliott 2009) could be considered compensation for potential impacts, however, only of a temporal nature. The spatial origin of the impact will also be a prerequisite for effective compensation as affected animals may originate from large geographic areas (Hüppop et al. 2006; Voigt et al. 2012; Hammond et al. 2013). As a last resort, research programmes should consider the potentials and drawbacks of compensation measures in areas other than the wind farm site, taking into account the like-for-like habitat paradigm.

## *Restore: Best-Practice from Planning to Decommissioning*

At the end of the life of a wind farm decommissioning should ensure that the original status of a wind farm area is restored. Although best-practice guidance exists (Welstead et al. 2013), the long-term ecological restoration of the wind farm area is not regarded as an issue during planning. Life cycle assessment and environmental legislation do require consideration of decommissioning so this will require further research. More operational knowledge will be required on the long-term efficacy of restoration with regard to wind farms, including but not limited to removal of infrastructure, hydrology, vegetation re-establishment and ecosystem recovery (May 2016). What will also be an important facet is how shifting baselines affect restoration options as the surrounding landscape may have undergone more or less permanent changes during the 25-year operational phase of a wind farm. In the offshore environment, decommissioning of e.g. oil and gas platforms pre-suppose that the natural processes of the dynamic environment enable recovery (Schroeder and Love 2004), however how comparable these findings are is unknown. The consequences of artificial reef creation and recovery of the 'natural state' of the seabed due to reduced fishing within offshore wind farms for long-term ecological functioning of such artificially altered ecosystems provide a future research area (Inger et al. 2009; Wilson and Elliott 2009). Restoration will likely become more topical in the coming decade as more and more wind farms will reach their end-of-life and require decommissioning.

## *Species-Specific Responses to Wind Farms*

Wildlife responses to wind turbines are highly variable and often very species-specific (Drewitt and Langston 2006). This variability arises from a range of behavioural, ecological and environmental risk factors (Box 1). There still remain significant gaps in our understanding on the relative importance of these risk factors and the underlying mechanisms that trigger responses (May 2015). Priorities for EIA, monitoring and research tend to focus on endangered species and species of conservation concern; however, these may not always be the most tractable species to study. The main effects arising from the construction and operation of wind farms on wildlife are additional mortality due to (sub)lethal injury, disturbance and displacement, as well as loss of habitat (Schuster et al. 2015). The empirical basis for understanding these effects, their species-specific responses, and the likelihood of impacts, is variable in both quality and quantity.

**Box 1** *Cross-taxa ecological and environmental risk factors*

- life-history traits
- manoeuvrability, physiology
- behavioural patterns, movement behaviour
- seasonality and utilisation of space
- habitat preferences and connectivity
- topographic terrain/substrate
- weather conditions
- wind farm operation characteristics
- background anthropogenic effects

## *Understanding Movement Behaviour, Habitat Preferences and Connectivity*

An improved understanding of the movement ecology of species in conflict with wind turbines are of eminent need, for mobile and migratory species but also for stationary species that may not be able to relocate. Important aspects of movement ecology include movement behaviour, habitat preferences and utilization, and connectivity with respect to potential interactions with wind farms. Although there have been in-depth studies of some species of concern, there remain key gaps in understanding. Inter-annual, seasonal and diurnal cycles notably require long-term studies to reveal temporal variability in ecology and behaviour. Furthermore, the effect that availability of alternative habitat and refuges may have on movement behavioural responses at wind farms are important to explore. Multiple-scale studies, connecting fine-scale movement behaviour to habitat associations, landscape connectivity and ultimately its consequences for populations are essential.

Research is also required on the proximate and ultimate causes of movement behaviour, focusing on how and why specific areas are utilized. From this perspective, obtaining increased insight into the morphological (e.g. wing morphology), physiological and cognitive mechanisms underlying movement decisions will be crucial (Nathan et al. 2008). How wind-turbine turbulence affects birds and bats with different aerodynamic and cognitive capabilities also requires further research. Greater understanding of wildlife behaviour and perception of wind farms (Martin 2012; Tougaard et al. 2015) will improve objective assessments of risk and assist with developing mitigation measures. To advance our knowledge base, a combination of in-depth and long-term studies is required on model species, theoretical reviews as well as meta-analyses. Together this will improve the prospects of discerning what aspects of a species' ecology and behaviour increase interactions with wind farms, leading to potential impacts, and may inform effective mitigation measures (May et al. 2015).

## *Understanding Avoidance/Attraction Mechanisms*

Wildlife may respond to wind turbine-induced effects through fleeing, activity shifts or changed habitat utilization (either increased or decreased); usually termed avoidance/attraction. An increasing number of empirical studies have improved our understanding of avoidance, although significant knowledge gaps remain. Formalizing the different forms of avoidance facilitates the design of avoidance studies and ensures that all associated predictions are considered à priori. This in turn helps to minimize modelling bias in predictive risk models and enhances the potential for comparison across sites (May 2015). The effects of human-made aerial structures on birds and bats are not yet well understood (Drewitt and Langston 2008; Cryan et al. 2014; Walters et al. 2014) and subsea changes that occur are only just starting to be understood (Lindeboom et al. 2015). Studies teasing apart the relative impacts derived from wind turbine structures versus other features, such as vehicle/vessel movements associated with maintenance activities and powerlines or subsea cables, are therefore required. Disturbance of wildlife can occur at any stage during the lifetime of a wind energy project, indicating the need for pre-construction, during construction and post-construction studies (Pearce-Higgins et al. 2012). Displacement causes functional habitat loss, which may be total or partial, temporary or long-term. Whether or not displacement has population consequences will depend on a combination of the availability of alternative habitat, duration and magnitude of displacement, and the consequences for survival and productivity, all of which justify further study (Gill et al. 2001; May 2015). These aspects have so far not been addressed in studies related to the extent of displacement (May 2015).

Conversely, species may habituate (e.g. Madsen and Boertmann 2008) or even be attracted to wind turbines. Some species will actively associate with the wind-turbine structure and foundations and include them as alternative habitats to move between (for examples see: Schuster et al. 2015). Why and under which circumstances habituation or attraction may occur should be the focus of longitudinal studies. Whether wind farms may create novel communities (e.g. artificial reefs, foraging habitat) or encourage redistribution is important for both the species forming these assemblages and for predators that aggregate there. Information about the causes and consequences of barrier effects is sparse, but can be related to avoidance of structures, noise or electromagnetic fields from subsea electrical cables leading to increased energy expenditure and loss of connectivity (Masden et al. 2010b; Gill et al. 2012).

## *Effects of Noise*

The construction of offshore wind farms, and in particular the noise generated during pile-driving, has been identified as adversely affecting the behaviour of marine mammals and fish, including displacement (Gill et al. 2012; Tougaard et al. 2015). Other hypothesized effects of sound introduced into the water require further research, including masking of communications, increased stress levels leading to reduced fitness and the occurrence of temporary or permanent threshold shifts in hearing. Operational noise levels are very unlikely to lead to injury to cetaceans or seals and there is no indication that they will lead to avoidance behaviour. Impact studies have demonstrated that the effects of sound on marine mammals range from negative impact, no change to an increase in abundance according to location (Scheidat et al. 2011), although the sound source and characteristic of sound may be similar. From this perspective, it will be important to get a better understanding on low-frequency noise-propagation conditions (e.g. water depth, seabed substrate, currents) and other anthropogenic noise-source properties (Madsen et al. 2006). Also, there is a great lack of understanding how these effects on individuals translate to a potential population impact. In planning future wind farms, this is a vital point to investigate, as it stresses the fact that results from one wind farm are not necessarily transferable to other wind farms located in different physical environments. The noise impact of construction and/or operation activities for other species such as birds (stress, displacement) or fish (barotrauma, behavioural changes) seems less evident (Kight and Swaddle 2011; Francis and Barber 2013).

## *Monitoring Risk for Planning and Management*

Regulatory permitting processes typically involve, as part of an EIA, an assessment of the risks the development pose to wildlife. Although such risk assessments are often based on the limited information available pre-construction, they form the basis for consenting decisions comprising the entire life cycle of a wind farm. Recognizing and properly addressing the variability and uncertainty in risk assessments will contribute to evidence-based decision-making processes. This requires novel research designs and techniques, advancements on the strengths and weaknesses of predictive modelling, and tackling the spatio-temporal challenges in risk assessments.

## *Design and Techniques for Targeted Impact Monitoring*

As can be deduced from the manifold of research themes, scientific investigation is needed using the appropriate metrics and methodology to answer clearly formulated hypotheses. Relevant metrics include fatality rates, area utilization, behavioural patterns, increased energy budgets, breeding success and survival (including density dependent effects). An often-overlooked candidate metric is social interactions in the vicinity to wind turbines. In particular, there remains a need for multiple-site longitudinal studies tailored to targeted individual species, which should apply well-designed Before-After-Control-Impact (BACI) or gradient methods. This allows for differentiation of short-term and long-term effects and to investigate the extent to which habituation may occur (Stewart et al. 2007). Assessing population-level consequences and effects on migratory species especially require long-term studies at larger geographic scales (e.g. countrywide, migratory flyways). Appropriate measuring of impacts caused by wind turbines is critical for comparing impacts among projects, wind-turbine attributes and sites, and mitigation strategies. This requires standardization of field and analytical methods. Future research must be directed towards reducing uncertainty in the type, magnitude and duration of effects, and their population consequences. In addition, research is needed on the strengths and weaknesses of various techniques such as observational, telemetry, radar, acoustics, video and thermal imaging for obtaining useful data with regard to accuracy, precision, consistency, completeness as well as species-specificity (Exo et al. 2003).

Animal-borne tracking devices, such as GPS tags, will become increasingly important for understanding behavioural responses to wind turbines and consequent collision risk/avoidance, including providing measurements of flight height and flight speed (e.g. Cleasby et al. 2015; Thaxter et al. 2015). Most evidence for collisions with wind turbines comes from onshore studies of birds and bats. Information is notably limited at offshore wind farms. There are pronounced technical challenges to overcome in order to obtain empirical data on collisions at offshore wind turbines, requiring innovative fatality detection technology. These technologies include the use of high-resolution animal tracking, drones with pre-defined flight patterns and high-resolution video cameras, and accelerometers in rotor blades to detect impacts. Research is also needed to evaluate and standardize monitoring procedures, including effects of study duration on patterns in occurrence, fatality rates, search interval, search radius, carcass removal and detection trials (Bernardino et al. 2013). Standardized fatality rate estimates are most valuable for comparative purposes (Loss et al. 2013; Smallwood 2013) to understand site or wind turbine attributes that contribute most to fatality rates and to direct mitigation measures.

## *Predictive Modelling and Forecasting Risk*

Although it will be crucial to increase our knowledge base on the ecology of wind turbine–wildlife interactions, consenting decisions are based on current knowledge and pre-construction data coupled with predicted effects on species of concern. To enable consenting authorities to make evidence-based decisions, pre-construction monitoring needs to be well-designed in order to limit variability across projects as much as possible, as well as to attain the required power-of-analyses. Statistical testing should preferably give insight into both the magnitude and the likelihood of the estimated effects. Predictive modelling should explicitly be clear on assumptions of the chosen model as well as on the uncertainty relating to both data quality and model outcomes (Masden and Cook 2016).

Predictive models come in various forms and functions, such as collision risk models, habitat-based movement modelling, population modelling and individual-based models. Dependent on the model of choice, specific data is required to understand the impact metric. As yet there is only limited insight into how the forecasting of risk should be performed, including spatial and temporal scales, and especially how science can inform policy makers to set risk thresholds. Development of individual-based models simulating species-specific movement behaviour and responses to wind turbines are appealing due to their universal applicability. However, data scarcity for parameterization and being computationally intensive are still challenges. Probability-based techniques have been under-used in the past, with a reliance on deterministic approaches to measure the effect and describe the impact. Whilst statistically robust, these deterministic approaches do not inform an objective assessment of the inherent uncertainties and associated risks (Schaub and Kéry 2012).

## *Tackling Spatio-Temporal Uncertainty in Risk Assessments*

Fundamental to risk assessment is to understand the likelihood of a certain event to occur. Hence, for assessing risks to wildlife it is essential to take into account that the majority of species move around either on a daily or seasonal basis.

Furthermore, their behaviour coupled with species-specific traits may bring them into encounter with wind turbines. Current knowledge on where and when the animals are is variable depending on the taxa of interest. Hence, this variable knowledge brings uncertainty to any risk assessment. Failing to include the dynamics of species-specific responses to wind turbines leads to assumptions that may be unrealistic (May 2015). Individual responses lead to individual vulnerabilities and unless a large proportion of animals responds in a similar way to the hazard, it is difficult to extrapolate responses of individual animals to biologically meaningful impacts (Boehlert and Gill 2010). Hence, the variability and uncertainty in risk assessment becomes more apparent.

Each hazard to the species of interest should be properly characterized and this must include the spatial and temporal characteristics and the probability of exposure, to ensure that the risks are properly evaluated and that assessment of uncertainties is undertaken. Risk assessments traditionally are based on single point estimates of the risk (i.e. deterministic), judged against some threshold (that is often difficult to define), as if the likelihood of occurrence of the risk is precisely known. However, the uncertainty in animals' spatial and temporal occurrence means that, although science-based, policy thresholds may become inappropriate (Johnson 2013). Whilst this adds to the complexity of the analysis, a simple chain of cause and effect to an 'average animal' is not sufficient. Obviously, uncertainty in the risk assessments may be reduced through appropriate study designs ensuring ample sample size, replicates and study duration. Probabilistic approaches attempt to address this by setting parameters in predicted risk assessments based on a range of risk probabilities and thus take into account variability and uncertainty.

Although science can empirically predict the likelihood and magnitude of change, societal acceptance determines the final threshold value(s). However, thresholds need not be binary, but could also include levels of acceptance using e.g. traffic light approaches incorporating inherent variability (e.g. confidence quantiles). Logically, perception of risk and the associated uncertainty rises with complexity that then leads to us being risk-averse according to the pre-cautionary principle. However, renewable energy is a useful contributory tool for a low-carbon future with the aim of reducing adverse environmental effects of climate change. Hence, we should seek to improve our understanding of spatio-temporal variability of wind turbine–wildlife interactions and treat the associated uncertainty as an optimization challenge to balance wind energy development with wildlife conservation.

## *Upscaling Impacts*

With a piecemeal development where each wind farm may in itself present little conflict, multiple wind farms may in sum, however, seriously impact individual species or ecosystems over larger geographical areas. The increasing deployment of wind energy onshore and offshore poses ever more challenges to spatial and environmental planning systems, necessitating appropriately addressing cumulative and transboundary impacts. Here, environmental impacts will also need to be considered throughout a wind farm's life cycle to help attain no net loss.

## *Assessing Demographic and Cumulative Impacts*

From a conservation point of view, population-level impacts of anthropogenic activity, such as wind energy development, are most relevant for long-term species persistence. However, this is not reflected in current legislative frameworks. One of the main challenges of future research will be to determine more precisely how individual animals react to wind farms, and whether or not this will have any population level effects or impacts for different species (e.g. Diffendorfer et al. 2015). The distinction between effects and impacts is an important one. Effects on individuals or groups of individuals are observed, or predicted, based on knowledge about a species' ecology and behaviour. Effects may or may not, lead to impacts on populations, acting on survival rate and/or breeding productivity (Boehlert and Gill 2010). The magnitude of population-level impacts may depend on a species' life-history strategies (e.g. longevity, recruitment rate, age structure) coupled with their ecology. Assessing population-level impacts may however prove to be challenging, particularly in cryptic and wide-ranging or migratory species. Additionally, population studies are difficult to perform in long-lived species because the longevity of focal species may require long-term commitment of researchers and funding agencies.

Further, relatively little is known about density-dependent effects on life-history traits that might counterbalance increased additional mortality by wind turbines. In practice, it may be complicated to tease apart impacts of a specific wind farm from other anthropogenic activity within the region or other regions in migrating species, or from regime shifts e.g. due to climate change. Such cumulative effects are debated, but implementation is hampered by lack of a clear definition as well as methods suitable to assess these. Integrating key pressures on populations and the contribution likely to be attributable to wind energy generation in population models may enable assessment of the cumulative impacts of multiple wind farms at different spatial scales (Heinis et al. 2015). Individual- and agent-based simulation models may prove to be best suited to addressing such cross-sector and transboundary effects on populations (Masden et al. 2010a; Schaub 2012; Nabe-Nielsen et al. 2014).

## *Ecosystem and Life-Cycle Impacts of Wind Farms*

Research has so far primarily focused on effects on the behaviour, distribution and abundance of single species associated with single wind farms. Nevertheless, although the basic problems still remain seasonal and site-specific, some species' populations may be negatively impacted through disturbance or mortality (Schuster et al. 2015) while other populations may be relatively unaffected, or even benefit through the provision of novel habitat or refuges (Inger et al. 2009; Lindeboom et al. 2011). From an ecosystem perspective, however, species interact within communities and across trophic levels; impacts on one species may therefore in turn indirectly affect other species, ultimately affecting ecosystem function. While biodiversity loss and its consequences to ecosystem function are important in their own right, renewable energy systems may also degrade ecosystem services (Hastik et al. 2015; Papathanasopoulou et al. 2015). Given the complexity of ecosystems with interacting species within their environment, it is evident that there is a significant conflict potential if site-selection processes are not carried out carefully and holistically (Gill 2005; Stewart et al. 2007). Assessments of the total ecosystem load across species, and implementing this into an ecosystem service-logic, presents new research challenges. Ecosystem modelling exercises could enhance our understanding of long-term consequences of renewable energy for ecosystem processes on different trophic levels and at larger spatial and temporal scales (e.g. Burkhard et al. 2011).

Impacts, either for single species or for the ecosystem as a whole, will need to be addressed and mitigated throughout the life-cycle of a wind farm to contribute to the no net loss goal of lowest possible environmental costs per kWh from wind energy projects (cf. Gardner et al. 2013; May 2016). Determining what no net loss entails will be critical in assessing how wind energy generation can be reconciled with nature conservation laws, directives and policy (Cole 2011). This requires research assessing environmental impacts through all life cycle stages (construction, operation and decommissioning, possibly repowering) of a wind farm, considering impacts on human wellbeing, ecosystem quality and natural resources. However, life cycle impact assessments (LCIA) still lack the inclusion of impacts on biodiversity or land impacts (Arvesen and Hertwich 2012; Michelsen and Lindner 2015). Improved LCIA can highlight the main environmental impacts and identify trade-offs between different wind energy development options with regard to siting and modes of operation to attain no net loss.

## *Towards Consolidation*

Despite the wealth of scientific information available, this paper has emphasized future research directions in relation to wind turbine–wildlife interactions. The defined sensitivity of animal species often relates to their conservation status and expert judgement of the species at risk (Furness et al. 2013). Inevitably, this leaves behind other sensitive species that may have traits that make them susceptible in the future over longer time scales or greater spatial extent. This will require formal meta-analyses to obtain a better understanding of which traits enhance a species' susceptibility to wind energy development. Understanding why species-specific responses occur, require also approaches inherent to species' ecology. Longitudinal and multiple-site studies, which apply common methods and incorporating Before-After-Control-Impact (BACI) approaches, will offer greatest insights. Such studies will render important information for decisions on whether measures can be taken to reduce or mitigate any predicted population-level impacts.

In view of the fast rate of wind energy development and political goals for further development, cumulative impacts will become more urgent. The challenge to science is not only to identify and measure the extent of cumulative impacts on vulnerable species and ecosystems but also to provide solutions to handle and mitigate these impacts. With increasing cumulative impacts, the pressure for implementing effective mitigation measures is growing in importance. Consequently, a key research priority should centre on the development, monitoring and continuous improvement of mitigation measures to counteract impacts of cumulative wind energy development on wildlife. Finally, all involved stakeholders in wind energy development must shift their stance in effectively sharing previous, current, or upcoming data and results, as knowledge sharing within transdisciplinary co-learning will be pertinent to avoid persistence of science-policy-practice gaps. This challenge to reconcile wind turbine–wildlife interactions has the opportunity to be substantially addressed in future research directions.

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