



Review

Impact of wind power plants on mammalian and avian wildlife species in shrub- and woodlands

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ABSTRACT

Wind energy, being one source of renewable energy, is one of the fastest increasing sectors worldwide, but it can have negative impacts on wildlife. Wind power plants have been mainly built in open landscapes in the past, but are recently increasingly planned and constructed in shrub- and woodlands. However, while there is a growing body of literature analyzing and discussing the impacts of wind power plants on wildlife in open landscapes, little has been done to date on that issue in shrub- and woodland environments. Therefore, we explored the effects of wind power plants in shrub- and woodland areas on woodland-dwelling wildlife species in the continents Europe and North America. Our systematic literature review was based on peer-reviewed journal articles. Out of 825 peer-reviewed articles, we synthesized detailed information from 27 articles. Reviewing scientific literature indicated that there is still very limited knowledge on effects of wind power plants on shrub- and woodland-dwelling wildlife species. Literature yielded evidence that construction, operation and maintenance of wind facilities affect mortality and behavior of mammals and birds as well as habitat suitability. However, the extent to which wind power plants affect shrub- and woodland-dwelling wildlife species highly depends on species-specific habitat requirements and distance thresholds, thereby indicating the urgent need of further studies, which reach beyond the scale of a single case study. Systematical assessments and monitoring based on a before-after control-impact design over several years are urgently required to fill knowledge gaps and better support concrete planning decisions in practical contexts.

1. Introduction

Global warming and related consequences have procured a number of international political agreements, which all aim at an increasing production of renewable energy including wind energy, photovoltaics or other techniques (UNFCCC, 2015). Of these, wind energy is the fastest increasing sector worldwide (Renewable Energy Network, 2018). Wind power is usually evaluated as renewable “green” energy, primarily due to low ecological impacts in terms of environmental pollution or water usage (Saidur et al., 2011). However, there are increasing concerns about potential effects of wind power plants on human welfare (e.g. Merlin et al., 2013) or on wild-living animals (e.g. Kuvlesky et al., 2007; Drewitt and Langston, 2008). Hereinafter we refer to WPP as one or several wind towers, including wind turbines and associated infrastructure related to the turbines, e.g. roads, transmission lines, meteorological towers.

A series of studies have shown adverse effects of WPP on diverse animal taxa worldwide, including insects (Long et al., 2011; Elzay et al.,

2017), birds (Drewitt and Langston, 2006; De Lucas and Perrow, 2017; Hötter, 2017), bats (Rydell et al., 2010b; Barclay et al., 2017) as well as non-volant terrestrial (Rabin et al., 2006; Helden et al., 2017) and marine mammals (Koschinski et al., 2003). Wind energy development in natural landscapes commonly entails several potential effects: The most obvious effect is mortality of animals, colliding with rotor blades or turbine towers or suffering from barotraumas. Large numbers of annual fatalities of flying vertebrates are well documented (bats: Baerwald et al., 2008; Hayes, 2013; Smallwood, 2013; Thompson et al., 2017; birds: Sovacool, 2009; Loss et al., 2013; Smallwood, 2013; Zimmerling et al., 2013; Erickson et al., 2014). It is estimated, that 888,000 bat and 573,000 bird fatalities on wind energy facilities occur per year in the United States (Smallwood, 2013). Less evident, but as well important might be effects of WPP on behavioral decisions of wildlife species ranging from seasonal migration patterns or dispersal between (small) populations to behavioral responses in terms of changed anti-predator behavior (Rabin et al., 2006), territorial behavior (Zwart et al., 2016) or habitat use (Hötter, 2017). Such responses of wildlife species might

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occur during the construction phase of WPP, where increased levels of noise emission, vibration and human presence arise, or during the operating phase of WPP with increased noise emission, shadowing, flickering of warning lights and enhanced human presence compared to similar areas without WPP construction.

Aiming at an increasing contribution of renewable energy to gross primary energy production, remote sites in shrub- and woodland areas or on mountain ridges are currently more in focus for WPP construction than before. In Germany, WPP have been less frequently built in forested areas in the past (Wind, 2017), yielding only 5% of all WPP at the end of 2016 (see also Bunzel et al., 2019). However, almost 82% of these woodland WPP have been installed between 2010 and 2016, indicating a rapid development in these landscapes more recently (Wind, 2017). In addition, countries largely covered by forests offer high potential for onshore wind energy within this type of land cover (e.g. in Northern Europe: Finland, Sweden, Norway; EEA, 2009). WPP in mountain regions with particular high proportions of forests (e.g. Alps) are still also less common (EEA, 2009), although mountain ridges, peaks or high altitude passes offer high potential for wind energy production (Hastik et al., 2015).

WPP construction in such remote areas might yield specific effects on wildlife, that diverge from those in open landscapes or lowlands, as the change of landscape features might be more pronounced there. Such changes include the construction or expansion of forest roads for an obligatory year-round maintenance of WPP, which means a permanent opening up of forest canopies and which provides additional access both for humans (e.g. in terms of secondary use of roads for recreation activities) and for predators. As one example, Sirén et al. (2017) have shown, that montane habitats, usually being inaccessible for American red foxes (*Vulpes fulva*) and coyotes (*Canis latrans*) in winter due to snow cover, became increasingly accessible for these two canid species due to road construction for WPP maintenance. Such changes in habitat selection might entail further effects, such as increased competition for food sources with other predators and increased predation pressure on in situ prey species (Sirén et al., 2017).

As shown by Thomas et al. (2014), opening up of forest canopies might change species assemblages as the abundance of species occupying more open-structured, early successional zones might rise at the expense of forest-interior species. Bats, which depend on native forests with a high structural complexity (e.g. old trees with cavities providing roosts for bats or birds) seem to be particularly vulnerable (Peste et al., 2015). Nonetheless, mono-culture plantations may provide habitat patches for foraging or breeding of wildlife species as well (birds: Volpato et al., 2010; bats: Law et al., 2016) and have thus to be equally considered, when addressing potential effects of WPP on shrub- and woodland-dwelling wildlife. Some studies provide evidence, that large numbers of annual bat fatalities occur at WPP that have been installed along forested hills and ridges (Kunz et al., 2007; Arnett et al., 2008; Rydell et al., 2010a). In contrast, Thompson et al. (2017) found no indication that forest cover is related to bat mortality. It has been hypothesized that wind power plants are less disruptive in forests than on open landscapes, as shrub- and woodlands are naturally characterized by medium-sized to tall structures (Smith and Dwyer, 2016), but this assumption still has to be proven.

Empiric data on effects of WPP on wildlife is mainly derived from studies in open habitats (Smallwood and Karas, 2009; Loesch et al., 2013; Raynor et al., 2017; Smith et al., 2020) or lowland sites, where WPP have been built more frequently in the past and which provided adequate opportunities for studies. In contrast, related knowledge on effects of WPP on wildlife in shrub- and woodland and wooded, high-altitude environments is comparatively scarce (Hastik et al., 2015). In the past, research strongly focused on the effects of WPP on volant species (e.g. birds, bats), while studies addressing non-volant terrestrial mammals (Lovich and Ennen, 2013) are still rare. Thus, while extensive reviews on effects of WPP on wildlife species in open landscapes are available (Drewitt and Langston, 2006; Smallwood, 2013; Marques

et al., 2014; Smith and Dwyer, 2016), a comprehensive review of studies on effects of wind power plants on shrub- and woodland-dwelling wildlife was missing until now. The objective of the given review is thus to compile scientific knowledge on documented effects of WPP on shrub- and woodland-dwelling mammalian and avian wildlife species with particular focus on boreal and temperate ecosystems - ranging along a successional gradient from shrublands to forests, hereafter termed "shrub- and woodlands" - and to derive resulting conservation needs or management options. The questions being addressed in this systematic review were: Which effects do WPP have on habitat selection, species abundance and biodiversity of shrub- and woodland-dwelling wildlife species? Do effects of WPP in shrub- and woodlands decrease with increasing distances and do species-specific distance thresholds exist? In addition, we derive recommendations in terms of future study design, conservation needs and mitigation measures.

2. Materials and methods

2.1. Systematic literature search

Our review was based on peer-reviewed literature, collected in two renowned scientific electronic databases, i.e. the Web of Science Core Collection (URL: www.webofknowledge.com) and Scopus (URL: www.scopus.com). We followed the guidelines of Pullin and Stewart (2006) and the Collaboration for Environmental Evidence (2013) for conducting a systematic literature review. A flow diagram for the systematic review is available in the online Appendix (Fig. A1).

We structured a wide range of Boolean search terms within seven sets (see Table 1), which focused on our general aim to compile documented and published effects of WPP in shrub- and woodland habitats on wildlife. The first two sets of search terms (wind energy (1), woodland habitat (2)) were combined with the wildlife (3), direct effects (4) and indirect effects set (5), respectively. In addition, terms relevant for wind energy developments (1) were each combined with the bird (6) and mammal sets (7), which included a predefined selection of animal species, that have a known preference for shrub- and woodland habitats or regularly occur there. We included studies on reindeer, which were semi-domesticated, since the behavior of domesticated and herded reindeer very much resembles with wild reindeer and caribou (Skarin and Åhman, 2014). The sets of search terms were synchronously applied to the search fields title, abstract and keywords within the two scientific databases.

Table 1
Sets of Boolean search terms ("OR") used for the systematic literature search. The first two sets were combined ("AND") with the sets 3–7, respectively.

Nr.	Set	Search terms
1	wind energy	"wind energ*", "wind farm*", "wind power", "wind turbine**"
2	woodland habitat	forest*, tree*, wood*
3	wildlife	animal*, avian*, bat*, bird*, insect*, invertebrate*, mammal*, raptor, wild*
4	direct effects	collision*, disturb*, migrati*, mortalit*, population*, "risk assessment"
5	indirect effects	constructi*, fragment*, "habitat loss", infrastruct*, road*
6	birds	accipiter, "black grouse", "black stork", buzzard, capercaillie, caprimulgus, ciconia, columba, corvidae, "Cuculus canorus", cuculidae, dendrocoptos, "Garrulus glandarius", goshawk, grouse, grus, jay, lyrrurus, nightjar, "Nucifraga caryocatactes", nutcracker, owl, scolopax, sparrowhawk, strigidae, tetrao, woodcock, woodpecker, "wood pigeon"
7	mammals	alces, badger, bear, bovidae, canidae, canis, cervidae, chamois, deer, elk, felidae, lynx, marten, martes, mustelidae, moose, rangifer, reindeer, rodent, rodentia, rupicapra, suidae, sus, ursus, ursidae, "wild boar", wolf (not "grey wolf optimi**"),

The full list of search term combinations and related search results were comprehensively documented for transparency (see online Appendix, Table A1). References, including title, abstracts and keywords were imported into the reference management software Endnote and duplicate records were automatically discarded. Afterwards, we screened articles for relevance in a two-staged process: 1) Article titles and abstracts were read and obviously non-relevant articles were removed (e.g. studies focusing on technical aspects of wind blade construction). 2) Full-texts of articles, passing the first stage, were accessed to determine those articles that focus on the effects of wind power plants on mammal and bird species.

2.2. Study inclusion criteria

An article was considered relevant when an animal species was mentioned in relation to wind power developments located in shrub- and woodland environments. Furthermore, the articles had to determine the effects of wind power plants on bird and mammal species, specify their response and include new data. Details on procedures related to reviews or meta-analyses are presented below.

As shrub- and woodland communities and related structures vary distinctly on a global scale and are highly specific within geographical regions (Sjoegren, 1989), we confined our review to temperate and boreal ecosystems, ranging along a successional gradient from shrublands to forests, located on the continents Europe and North America. Thus, Mediterranean regions and mountain ridges above treeline frequently covered by bushes or dwarf shrubs were also included.

We exclusively considered studies for our systematic literature review, which provided detailed information on the location of WPP. Thus, study site sections of reviewed articles had to offer either detailed descriptions of habitat parameters or to provide specific information on individual wind power plants (GPS data, facility names). By providing GPS locations or distinctive facility names, we could verify locations of turbines using the software Google Earth Pro (Version 7.1.8.3036), indicating that (at least part of the studied) wind turbines were located within shrub- and woodlands. In case that articles did not provide detailed information on wind power plant locations, we discarded them from further analyses. The fate of each article was recorded (see online Appendix, References A1). The bibliographies of review publications or meta-analyses were checked for new relevant sources and articles cited within these reviews were included in our analyses following the above described two-stage process (see online Appendix, Reference A2).

2.3. Data extraction and organization

We extracted the following facts from all included relevant articles: the name and location of the WPP (latitude and longitude of the center, state, country), the habitat type surrounding wind turbines (e.g. forest), the number of turbines and turbine types used, the study period (initial year of operation, the start and end of sampling period), the study design (before/during/after construction, control-impact site), the type of data collected (e.g. survey type: carcass search, point counts etc.) and the response of shrub- and woodland-dwelling wildlife species. It is important to recognize, that one article can contain more than one study, e.g. by addressing several different taxonomic groups of wildlife species, different types of responses, or by applying different study methods. Maps were created using ArcGIS® software by Esri (www.esri.com).

3. Results

3.1. Scope and quality of reviewed studies

The systematic literature search yielded 825 peer-reviewed articles and additional 103 peer-reviewed articles from screening reviews/meta-analyses, of which 326 passed the first stage of our two-staged process (full-text read, online Appendix, References A3). 27 of the full-texts

fulfilled our criteria and were relevant in terms of our research question (see Table 2). The majority of studies was conducted on a single ($n = 12$, 44%) or on two wind power plant sites ($n = 7$, 26%) (see Table 2). The study sites described within the 27 articles were located within 9 European countries, 6 states of the USA and 2 provinces in Canada, but exact GPS coordinates of wind power plants located in shrub- and woodlands were only available for 11 and 15 WPP sites in North America and Europe, respectively (see Fig. 1). Almost 40% of WPP ($n = 10$) were located along mountain ridges, within forests or dense shrubland.

Most studies included data from 1 to 4 years ($n = 18$, 67%), only 9 studies covered 5 to 11 years (see Table 2). Studies comparing the effect of WPP before and after the construction of wind turbines and between areas with development and reference sites (BACI study design) lasted between 3 and 9 years (Mean = 5.8, SE = 1.0, $n = 6$). Almost 40% ($n = 10$) of the reviewed studies assessed the effect of WPP on woodland-dwelling wildlife after WPP were constructed, while 4 studies compared effects of WPP with control sites (CI study design) or focused on the effects before, during and after WPP construction (BDA, $n = 3$), respectively. The remaining 4 studies compared differences before and after ($n = 2$), before and during ($n = 1$) and during and after WPP construction ($n = 1$) (see Table 2). Studying effects of WPP on habitat use and on the activity of mammals was based on telemetry, acoustic surveys, video monitoring and on track counts during winter (see Table 2). In contrast, counting birds at point-count stations or along line transects and recording of indirect signs on systematic grids provided data on bird abundance, biodiversity and habitat use (see Table 2). Collision surveys (with and without dogs) were conducted to study mortality of flying vertebrates (birds, bats) on wind power plants.

We included only articles published in scientific journals (peer-reviewed), recognizing that additional data would be available in unpublished reports, grey literature or within electronic databases. We were unable to get access to full-texts of additional 11 articles, because articles were not available online and corresponding authors did not respond (see online Appendix, References A3). Thus, we are aware that limitations on data availability may affect the interpretation of results.

3.2. Documented responses of shrub- and woodland-dwelling wildlife species to WPP

Slightly more than half of the studies focused on the effects of wind power plants in forests on mammal species ($n = 14$, 52%), 11 articles investigated effects on bird species (41%) and the remaining 2 studied the effects of wind power plants on both, shrub- and woodland-dwelling mammalian and avian wildlife species (7%, see Table 2). Distinguishing articles and studies is important, because one article might contain more than one study (see also Collaboration for Environmental Evidence, 2013). Since the total number of studies conducted is higher than the number of articles included in this review ($n = 27$, see also Table 2), articles might be repeatedly mentioned in the following subsections.

Of the 27 articles being related to shrub- and woodlands, which finally entered this review, two studies were documenting collision mortality of bird species (Barrios and Rodríguez, 2004; De Lucas et al., 2008), four focused on avian flight behavior (Barrios and Rodríguez, 2004; De Lucas et al., 2005; De Lucas et al., 2008; Johnston et al., 2014), another four were documenting mortality of bats (Apoznański et al., 2018; Arnett et al., 2011; Horn et al., 2008; Pylant et al., 2016) and one of these studies was also addressing mitigation measures to reduce bat collision (Arnett et al., 2011). Documented bat species suffering from barotrauma, trapped in blade-tip vortices or directly colliding with rotating blades were e.g. soprano pipistrelle (*Pipistrellus pygmaeus*, Apoznański et al., 2018), hoary bat (*Lasiurus cinereus*) and eastern red bat (*Lasiurus borealis*, Pylant et al., 2016). Birds colliding with turbine blades and found dead below WPP belonged to the orders e.g. Accipitriformes, Falconiformes, Strigiformes, Ciconiiformes and Cuculiformes (Barrios and Rodríguez, 2004; De Lucas et al., 2008) (Table 2).

Table 2

All articles included in the systematic review (n = 27), and the resulting number of species-specific case studies (n = 44). Some journal articles contained more than one study.

Class	Species order	Species English name	Species scientific name	No. study sites	Country	Dominant habitat types	No. study years	Study design	Survey type	Type data collection	Effect	Reference
Aves	Acc	golden eagle	<i>Aquila chrysaetos</i>	1	Canada	forest, mountainous	3	BA	Point Counts	Flight behavior	Negative	Johnston et al., 2014
Aves	Acc, Fal and several others (e.g. Cic, Cuc, Pas, Str)	several	<i>several</i>	2	Spain	forest, dense shrubland, pastures, mountainous	2	A	Collision Surveys	Mortality	Negative	Barrios and Rodríguez, 2004
Aves	Acc, Fal and several others (e.g. Cic, Cuc, Pas, Str)	several	<i>several</i>	2	Spain	forest, dense shrubland, pastures, mountainous	2	A	Collision Surveys	Mortality (throughout seasons)	Contrary	Barrios and Rodríguez, 2004
Aves	Acc, Fal and several others (e.g. Cic, Cuc, Pas, Str)	several	<i>several</i>	2	Spain	forest, dense shrubland, pastures, mountainous	2	A	Point Counts	Flight behavior (throughout seasons)	Contrary	Barrios and Rodríguez, 2004
Aves	Acc, Cic, Fal, Str	several	<i>several</i>	2	Spain	forest, dense shrubland, pastures, mountainous	11	A	Collision Surveys	Mortality	Negative	De Lucas et al., 2008
Aves	Acc, Cic, Fal, Str	several	<i>several</i>	2	Spain	forest, dense shrubland, pastures, mountainous	11	A	Collision Surveys	Mortality (throughout seasons)	Contrary	De Lucas et al., 2008
Aves	Acc, Cic, Fal, Str	several	<i>several</i>	2	Spain	forest, dense shrubland, pastures, mountainous	11	A	Point Counts	Flight behavior (throughout seasons)	Contrary	De Lucas et al., 2008
Aves	Cha	woodcock	<i>Scolopax rusticola</i>	1	Germany	forest	3	BACI	Point Counts	Abundance	Negative	Dorka et al., 2014
Aves	Gal	black grouse	<i>Lyrurus tetrix</i>	3	Austria	forest, alpine meadow, mountainous	9	BA	Point Counts	Abundance	Negative	Zeiler and Grünschachner-Berger, 2009
Aves	Gal	cantabrian capercaillie	<i>Tetrao urogallus cantabricus</i>	1	Spain	forest	5	BACI	Line Transects	Presence/Absence, Sign-density	Negative	González et al., 2016
Aves	Gal	capercaillie	<i>Tetrao urogallus</i>	6	Austria, Germany, Sweden	forest	7	BACI	Point Counts	Presence/Absence, Sign-density	Negative	Coppes et al., 2020b
Aves	Gal	common pheasant	<i>Phasianus colchicus</i>	3	Poland	forest, agriculture	3	ACI	Line Transects	Abundance	Positive	Łopucki et al., 2017
Aves	Pas	bicknell's trush	<i>Catharus bicknelli</i>	2	Canada	forest, mountainous	4	BDA	Point Counts	Presence/Absence	Contrary	Lemaître and Lamarre, 2020
Aves	Pas	bicknell's trush	<i>Catharus bicknelli</i>	2	Canada	forest, mountainous	4	BDA	Point Counts	Presence/Absence with mitigation measure	No effect	Lemaître and Lamarre, 2020
Aves	Pas and several others (e.g. Acc, Apo, Col, Cor, Fal, Gal, Pic, Str, Sul)	several	<i>several</i>	1	Italy	forest	1	DCI	Point Counts	Biodiversity	No effect	Battisti et al., 2016
Aves	Pas and several others (e.g. Acc, Ans, Cha, Col, Cuc, Fal, Gal, Pel)	several	<i>several</i>	12	Ireland	forest, clearfell, grassland, scrub, peatland, human altered	2	ACI	Point Counts	Abundance	Negative	Fernández-Bellon et al., 2019
Aves	Pas and several others (e.g. Acc, Apo, Cha, Col, Fal, Pic)	several	<i>several</i>	1	Spain	bushes, small wood	3	BACI	Line Transects	Abundance	No effect	De Lucas et al., 2005

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Table 2 (continued)

Class	Species order	Species English name	Species scientific name	No. study sites	Country	Dominant habitat types	No. study years	Study design	Survey type	Type data collection	Effect	Reference
Aves	Pas and several others (e.g. Acc, Apo, Cha, Col, Fal, Pic)	several	<i>several</i>	1	Spain	bushes, small wood	3	BACI	Line Transects	Flight behavior	Contrary	De Lucas et al., 2005
Aves	Col, Cuc, Pas	several	<i>several</i>	1	Italy	forest	8	BACI	Point Counts	Abundance	Contrary	García et al., 2015
Mammalia	Chi	hoary bat, eastern red bat	<i>Lasiurus cinereus</i> , <i>Lasiurus borealis</i>	6	USA	forest	4	A	Collision Surveys	Mortality	Negative	Pylant et al., 2016
Mammalia	Chi	several	<i>several</i>	2	USA	forest, open grassland	2	A	Collision Surveys	Mortality	Negative	Arnett et al., 2011
Mammalia	Chi	several	<i>several</i>	2	USA	forest, open grassland	2	A	Collision Surveys	Mortality with curtailment	Contrary	Arnett et al., 2011
Mammalia	Chi	several	<i>several</i>	29	France	agriculture, forest	1	A	Acoustic Surveys	Activity	Negative	Barré et al., 2018
Mammalia	Chi	several	<i>several</i>	1	USA	agriculture, shrub-woodland	6	A	Acoustic Surveys	Activity	Positive	Foo et al., 2017
Mammalia	Chi	several	<i>several</i>	1	USA	agriculture, shrub-woodland	6	A	Prey Surveys	Food availability	Positive	Foo et al., 2017
Mammalia	Chi	several	<i>several</i>	1	USA	forest, mountainous	1	A	Video Monitoring	Mortality	Negative	Horn et al., 2008
Mammalia	Chi	several	<i>several</i>	1	USA	forest, mountainous	1	A	Video Monitoring	Activity	Positive	Horn et al., 2008
Mammalia	Chi	several	<i>several</i>	1	USA	forest	2	A	Acoustic Surveys	Activity (throughout seasons and different weather conditions)	Contrary	Reynolds, 2006
Mammalia	Chi	western barbastelle	<i>Barbastella barbastellus</i>	1	Sweden	forest	3	A	Acoustic Surveys	Activity	Negative	Apoznański et al., 2018
Mammalia	Chi	western barbastelle	<i>Barbastella barbastellus</i>	1	Sweden	forest	3	A	Telemetry Studies	Activity (during foraging)	–	Apoznański et al., 2018
Mammalia	Chi	western barbastelle	<i>Barbastella barbastellus</i>	1	Sweden	forest	3	A	Bat Roosts	Habitat use	Negative	Apoznański et al., 2018
Mammalia	Chi	western barbastelle	<i>Barbastella barbastellus</i>	1	Sweden	forest	3	A	Collision Surveys	Mortality	Contrary	Apoznański et al., 2018
Mammalia	Art	reindeer	<i>Rangifer tarandus tarandus</i>	2	Sweden	forest	6	BDA	Point Counts	Presence/Absence	Negative	Skarin and Alam, 2017
Mammalia	Art	reindeer	<i>Rangifer tarandus tarandus</i>	2	Sweden	forest	4	BD	Telemetry Studies	Habitat use	Negative	Skarin et al., 2015
Mammalia	Art	reindeer	<i>Rangifer tarandus tarandus</i>	2	Sweden	forest	6	BDA	Telemetry Studies	Habitat use	Negative	Skarin et al., 2018
Mammalia	Art	reindeer	<i>Rangifer tarandus</i>	1	Norway	shrubland, grassland	9	BACI	Area Search	Abundance	No effect	Tsegaye et al., 2017
Mammalia	Art	reindeer	<i>Rangifer tarandus</i>	1	Norway	shrubland, grassland	9	BACI	Telemetry Studies	Habitat use (throughout seasons and between two wind power plant zones)	Contrary	Tsegaye et al., 2017
Mammalia	Art, Car, Lag	European roe deer, European hare, European red fox	<i>Capreolus capreolus</i> , <i>Lepus europaeus</i> , <i>Vulpes vulpes</i>	3	Poland	forest, agriculture	3	ACI	Line Transects	Abundance	Contrary	Łopucki et al., 2017
Mammalia	Car	american marten	<i>Martes americana</i>	1	USA	forest, mountainous	2	DA	Telemetry Studies	Habitat use	Negative	Sirén et al., 2016

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Table 2 (continued)

Class	Species order	Species English name	Species scientific name	No. study sites	Country	Dominant habitat types	No. study years	Study design	Survey type	Type data collection	Effect	Reference
Mammalia	Car	american marten, American red fox, coyote	<i>Martes americana</i> , <i>Vulpes fulva</i> , <i>Canis latrans</i>	3	USA	forest, partly mountainous	2	A	Line Transects	Habitat use	Contrary	Sirén et al., 2017
Mammalia	Eul, Rod	several	several	3	Poland	forest, agriculture	1	ACI	Line Transects	Abundance	No effect	Łopucki and Mróz, 2016
Mammalia	Eul, Rod	several	several	3	Poland	forest, agriculture	1	ACI	Line Transects	Biodiversity	No effect	Łopucki and Mróz, 2016
Mammalia	Rod, Sor	several	several	1	Spain	bushes, small wood	3	BACI	Line Transects	Abundance	No effect	De Lucas et al., 2005

Species order abbreviation: Acc = Accipitriformes, Ans = Anseriformes, Apo = Apodiformes, Art = Artiodactyla, Car = Carnivora, Cha = Chariidriiformes, Chi = Chiroptera, Cic = Ciconiiformes, Col = Columbiformes, Cor = Coraciiformes, Cuc = Cuculiformes, Eul = Eulipotyphla, Fal = Falconiformes, Gal = Galliformes, Lag = Lagomorphia, Pas = Passeriformes, Pel = Pelicaniformes, Pic = Piciformes, Rod = Rodentia, Sor = Soricomorpha, Str = Strigiformes, Sul = Suliformes.

Species trivial name: several = more than three species were included in studies.

Study design: A = After, B = Before, D = During, CI = Control impact.

Effect: Negative = negative effects observed (e.g. increased mortality, avoidance or reduced activity close to windfarms), Positive = positive effects observed (e.g. higher activity or food availability close to wind power plants), Contrary = positive and negative effects observed, No effect = no effect observed.

Nine studies focused on the effect of WPP on habitat selection, habitat use and abundance of bird species (De Lucas et al., 2005; Zeiler and Grünschachner-Berger, 2009; Dorka et al., 2014; Garcia et al., 2015; González et al., 2016; Łopucki et al., 2017; Fernández-Bellon et al., 2019; Coppes et al., 2020b; Lemaître and Lamarre, 2020) and within one of these studies effectiveness of mitigation measures was also tested (Lemaître and Lamarre, 2020). While five of these studies indicated clear negative effects of WPP on bird abundance and habitat use (e.g. woodcock (*Scolopax rusticola*) Dorka et al., 2014, western capercaillie (*Tetrao urogallus*) Coppes et al., 2020b, Cantabrian capercaillie (*Tetrao urogallus cantabricus*) González et al., 2016, black grouse (*Lyrurus tetrix*) Zeiler and Grünschachner-Berger, 2009; and several species of the order Passeriformes Fernández-Bellon et al., 2019), contrary results regarding temporal responses of birds were detected within two studies (e.g. Bicknell's thrush (*Catharus bicknelli*) Lemaître and Lamarre, 2020, and several other species of the orders Passeriformes, Garcia et al., 2015). A positive reaction to WPP proximity (common pheasant (*Phasianus colchicus*), Łopucki et al., 2017) and no differences in breeding bird abundances before, during and after windfarm installation were found in one study (e.g. order Passeriformes, De Lucas et al., 2005), respectively.

Four articles were related to habitat use and activity of bat species (Horn et al., 2008; Foo et al., 2017; Apoznański et al., 2018; Barré et al., 2018). Two of these studies showed that activity of bats was reduced in proximity to WPP (Apoznanski et al., 2018; Barré et al., 2018), while the other two studies showed that bats actively foraged near operating turbines (Horn et al., 2008; Foo et al., 2017). No effect of WPP on small mammal abundance (e.g. species of the order Rodentia, Soricomorpha and Eulipotyphla) was detected in two studies (De Lucas et al., 2005; Łopucki and Mróz, 2016). Three studies on carnivores showed that WPP can affect habitat use and abundance (Sirén et al., 2016; Łopucki et al., 2017; Sirén et al., 2017). However, while European red fox (*Vulpes vulpes*) abundance was not affected by WPP (Łopucki et al., 2017), habitat use of American red fox extended to new habitats due to availability of WPP infrastructure (roads) in mountainous regions (Sirén et al., 2017).

One study determined biodiversity of bird (Battisti et al., 2016) and small mammal (Łopucki and Mróz, 2016) species, respectively, but no differences (mean number of species; species composition, diversity and evenness) were found between WPP and control sites. Two studies determined distance thresholds to WPP in birds (Fernández-Bellon et al., 2019; Coppes et al., 2020b) and another two studies focused on mammals (Skarin et al., 2015; Barré et al., 2018). Effects of WPP on bird abundance were detectable within 100 m (forest bird species, Fernández-Bellon et al., 2019) and 650 m (western capercaillie (*Tetrao urogallus*), Coppes et al., 2020b). Bat activity (Barré et al., 2018) and reindeer (*Rangifer tarandus*) movement and habitat use (Skarin et al., 2015) were affected within 1 km (bats); and 3 to 5 km (reindeer) from WPP.

Temporal variation in the number of bird collisions was found in two studies (Barrios and Rodríguez, 2004; De Lucas et al., 2008). In total, greater number of dead birds of the orders Accipitriformes, Strigiformes, Falconiformes and Ciconiiformes were found in winter (De Lucas et al., 2008), but high numbers of juvenile common kestrel (*Falco tinnunculus*) collisions were detected in summer (Barrios and Rodríguez, 2004). Along with concentrated griffin vulture (*Gyps fulvus*) deaths in winter, a high frequency of passes in risk zones (< 250 m) of WPP was detected for this species especially in autumn and winter (Barrios and Rodríguez, 2004). In contrast, golden eagles (*Aquila chrysaetos*) seemed to adapt their flight behavior to WPP and decreased ridge-top crosses within risk zone (< 150 m) after WPP construction (Johnston et al., 2014). In addition, flight height of non-nesting birds was higher in a WPP area during construction phase than in control sites (De Lucas et al., 2005).

Activity of bat species within WPP sites was investigated throughout nights and in different seasons within one study (Reynolds, 2006). In addition, four studies showed that habitat use of mammals of the order

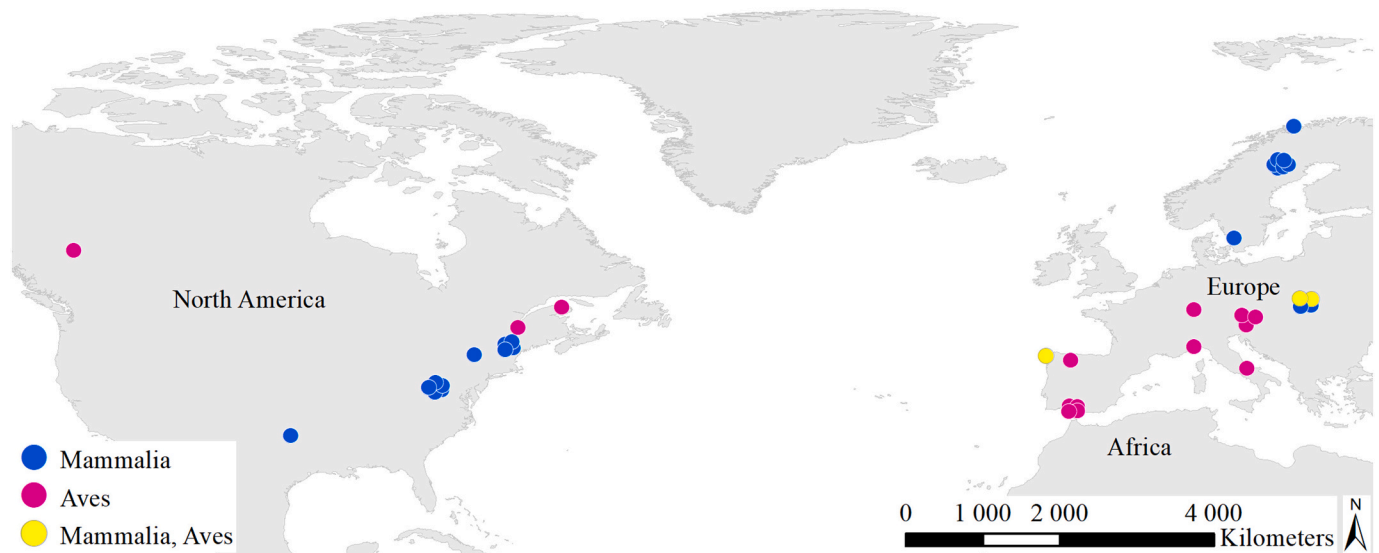


Fig. 1. Exact location of wind power plants situated in shrub- and woodlands. Studies focused either on the effect of wind power plants on mammals, on birds, or on species of both classes (World Continents, Data source: ArcWorld Supplement, Data location: ESRI Data and Maps\world\continent.sdc).

Artiodactyla (e.g. European roe deer (*Capreolus capreolus*) Lopucki et al., 2017 and reindeer Skarin et al., 2015, Skarin and Alam, 2017, Skarin et al., 2018)) was affected by WPP construction and operation, while one study detected no differences in reindeer density before, during and after WPP construction (Tsegaye et al., 2017).

4. Discussion

4.1. Mortality on wind turbines

The susceptibility of volant wildlife species to collide with wind turbines is highly species-specific and linked to morphological and behavioral traits of the species (Smallwood et al., 2009; Marques et al., 2014). Together with behavioral plasticity of species, responses might distinctly change in space and with time. While some volant species seem to adapt flight behavior to avoid collisions, other species might even be attracted by wind turbines, therefore facing increased risks of mortality. Thus, general conclusions on risks for species assemblages are hardly possible, even within one species or one taxonomic group: For example, foraging activity of bats above the canopy of closed mature stands might put them at risk to collide with wind turbines located within woodlands (Müller et al., 2013). While no western barbastelle (*Barbastella barbastellus*) fatalities have been found under WPP in a Swedish study, mortality of three other bat species (common noctule (*Nyctalus noctula*), soprano pipistrelle, northern bat (*Eptesicus nilssonii*)) was documented (Apoznański et al., 2018). Thus, although moving vertically along towers (Budenz et al., 2017), tracked via acoustic, almost no echolocation calls were detected above the forest canopy (> 50 m) for the western barbastelle, indicating potentially lower risk of direct collision with rotor blades (Budenz et al., 2017) than for other bat species, which show high mortality rates at turbine blades (e.g. hoary bat, Johnson et al., 2004; eastern red bat, Pylant et al., 2016). However, telemetry data provided additional information on habitat characteristics of feeding sites, used by western barbastelles in the Swedish study (Apoznański et al., 2018). While feeding sites of barbastelles were mainly located within mature deciduous woodland, WPP were located within conifer plantations (Apoznański et al., 2018). Therefore, it can be assumed that even western barbastelle face a risk of colliding with wind turbines, if WPP will be located within foraging habitats in broadleaf forests. Apart, the activity of several bat species highly depends on forest management and increases after clear fell harvesting in intensively managed non-native coniferous forests, raising concerns that activity

and subsequent collision risk could also increase after small-scale felling required for WPP installations in forests (Kirkpatrick et al., 2017). Birds also face a proven risk to collide with WPP in forested landscapes. While high-flying bird species (e.g. birds of prey) usually collide with rotor blades (De Lucas and Perrow, 2017), where blade sweeps exceed forest canopy heights (e.g. short-toed snake eagle (*Circaetus gallicus*), De Lucas et al., 2008), low-flying species (e.g. black grouse (*Lyrurus tetrix*)) have been found to collide with wind turbine towers (Zeiler and Grün-schachner-Berger, 2009; Coppes et al., 2020a). Collisions of griffin vultures seem to be associated with weather conditions and seasons, because lower temperatures (scarce thermals) in autumn and winter are insufficient to lift vultures above turbine blades (Barrios and Rodríguez, 2004). In contrast, high kestrel mortality in summer might be related to aggregations of juvenile kestrels foraging close to wind power plants (Barrios and Rodríguez, 2004).

Species-specific flight behavior might also be altered in landscapes comprising WPP. For example, the presence of densely-spaced wind turbines along mountain ridges affects the flight behavior of migratory golden eagles (Johnston et al., 2014): While golden eagles further use wind power plant sites during migration without distinct displacement compared to “before construction” situations, flight behavior changes post construction. Thereby, the number of crosses at rotor-swept height decreases indicating that golden eagles might be able to detect wind turbines and to adapt their flight behavior during migration. In contrast to low collision risks during migration, extensive use of wind power plant sites during breeding periods (associated with aerial display behavior and hunting flights) might increase collision risks at wind turbines (Johnston et al., 2014). Annual shutdown during single seasons or curtailments during specific weather conditions might therefore be ineffective to reduce bird fatalities (Smallwood and Bell, 2020). However, preliminary studies suggest that automated shutdowns of wind turbines using cameras installed on the wind turbine can be an effective measure to reduce collisions of birds of prey (McClure et al., 2018).

To estimate mortality on WPP, the number of dead animals found underneath the wind turbines is recorded. However, detection of collision victims is highly depending on several factors like scavenger densities, carcass size, terrain features (DeVault et al., 1994; Arnett, 2006; Smallwood, 2007; Smallwood et al., 2010; Paula et al., 2014). While human searchers can more easily detect large carcasses (e.g. of the size of black kites (*Milvus migrans*) or larger; Barrios and Rodríguez, 2004), they more frequently fail when searching for smaller animals (Barrionto et al., 2018). A recent study showed that especially carcasses from small

species (e.g. songbirds, bats) are often overlooked by humans; in contrast, trained detection dogs can do a much better job in finding even small carcasses (Barrientos et al., 2018; Smallwood et al., 2020). A large proportion of collision victims might not be recorded in previous studies; thus, robust mortality data that are reliable and empirically derived are needed (Jones and Pejchar, 2013). Within some studies, preliminary experiments are performed to estimate searcher efficiency and carcass removal rates and to finally overcome limitations of imperfect carcass detection in shrub- and woodlands by accounting for detectability when calculating total fatality rates (e.g. Barrios and Rodríguez, 2004; Apoznański et al., 2018). Others focus on larger species (e.g. black kite, De Lucas et al., 2008), or conduct searches only in habitats with high visibility (Arnett et al., 2011).

4.2. Land transformation in shrub- and woodland habitats can affect habitat suitability

Constructing WPP is inevitably accompanied by land transformation, since selected areas have to be cleared to build turbine pads, but also to set up required infrastructure (e.g. roads, transmission lines, meteorological towers, operation buildings) related to WPP (Jones et al., 2015). Both the surface area needed and the level of land transformation required for building WPP are strongly associated with land cover and topography and therefore highly site-specific (Diffendorfer and Compton, 2014; Jones et al., 2015). The extent of land transformed is low if facilities will be built on already tilled or agricultural landscapes. Within these landscapes road networks already exist. In contrast, high levels of land transformation are required to establish new WPP in forests or shrublands, as trees must be removed around turbine pads and along roads. Even more complex road networks are typically required, when turbines are placed along mountain ridges (Diffendorfer and Compton, 2014). As a consequence, shrub- and woodland habitat features are altered, but the extent to which these habitat modifications affect shrub- and woodland-dwelling wildlife species depends on species-specific habitat requirements and distance thresholds. Land transformations might be both relevant for highly mobile species occupying varying habitats throughout the year (breeding, foraging, wintering), but also for less mobile habitat specialists. This modification of habitat features might both induce attractiveness for shrub- and woodland-dwelling species and avoidance of other species.

4.3. Habitat use, abundance and biodiversity are affected by wind power plants under construction and during operation

Apart from habitat loss due to the construction of WPP and related infrastructure, fragmentation might be caused by disturbances arising from construction work and the subsequent maintenance of operational turbines. Correspondingly, telemetry data of American martens (*Martens americana*) showed that high-elevation ridgelines nearby a WPP site are not used during the construction phase (Sirén et al., 2016). Disturbances due to heavy machinery and blasting might affect high-elevation habitat use (Sirén et al., 2016).

Studies in Scandinavia addressed movement behavior and habitat selection of reindeer before and during construction of WPP (Sweden: Skarin et al., 2015), and after wind turbines became operational (Sweden: Skarin and Alam, 2017; Skarin et al., 2018; Norway: Tsegaye et al., 2017). Distances between reindeer calving sites and operational WPP sites increase (Skarin et al., 2018). Sound and sight of wind turbines might disturb females during the sensitive period of parturition (Skarin et al., 2018). While the studies in Sweden showed that movement corridors are less used once construction of WPP has started (Skarin et al., 2015) and habitats are less used during the operational phase compared to the preconstruction phase (Skarin and Alam, 2017), no significant differences in reindeer densities were found in Norway before, during and after wind power plant construction (Tsegaye et al., 2017). However, results should be carefully interpreted as the study of Tsegaye et al.

(2017) was conducted on an island in Norway, where coastlines limit reindeer space use.

Analyzing the number of snow tracks along a distance gradient to an operational WPP in Poland showed that habitat use of terrestrial animals in adjacent open landscapes is altered, but responses were again highly species-specific (Lopucki et al., 2017). In contrast to roe deer and European hare (*Lepus europeus*) which reduced the frequency of use near WPP, a positive response was found in common pheasants. Acoustic factors could have affected movement behavior of the two herbivorous mammals, because close proximity to operational wind turbines may impair roe deer's and European hare's ability to hear approaching predators. Reduced avian predator pressure (due to high mortality at turbine blades) might be one reason that common pheasants are found and might even be drawn to WPP, as turbine pads provide suitable habitats during winters by offering patches with sparse snow cover and grit availability (Lopucki et al., 2017).

Habitat modifications can alter habitat suitability and habitat use which might be reflected on the long-term by changes in species abundance or species assemblages (diversity). A study in Austrian WPP sites, situated along mountain ridges, showed that the number of displaying black grouse cocks changed after WPP construction, while turbine construction itself obviously had no effect on cocks' displaying behavior (Zeiler and Grünsachner-Berger, 2009). Despite heavy construction work, males might lek in close vicinity to WPP sites. One year after wind power plant construction, still no effect on male black grouse at lek sites was evident. However, the number of displaying males at lek sites decreased significantly within subsequent four years after WPP construction (Zeiler and Grünsachner-Berger, 2009). Disentangling causes for declining numbers of black grouse is difficult. While WPP might have direct effects on black grouse by disturbing displaying behavior, increasing tourism in mountainous regions can also cause significant disturbances to animals (Zeiler and Grünsachner-Berger, 2009). In contrast, habitat use and abundance of Cantabrian capercaillie in northern Spain is affected by disturbances along maintenance tracks during WPP construction (González et al., 2016). There, the number of droppings collected on WPP sites decreased with starting WPP construction activities, while remained stable and did not significantly differ before and after WPP construction on control sites (González et al., 2016). Similar results were found for effects of WPP constructions on Eurasian woodcock within a BACI study (Dorka et al., 2014): In contrast to a constant number of displaying woodcocks on reference sites, less woodcocks displayed on the wind power plant site after the construction of WPP. Thereby, disturbances during and after wind power plant construction might be the main cause of reduced display activities (Dorka et al., 2014; Schmal, 2015; Straub et al., 2015).

A study in Italy brought no evidence for WPP-related effects of land transformations on breeding bird assemblages in a highly heterogeneous oak mosaic landscape (Battisti et al., 2016). Neither mean number, nor abundance of breeding bird species differed close to wind turbines or in control areas. The extent of land transformation (10% habitat perforation) related to WPP construction might have not been high enough to affect species assemblage and guilds of common breeding birds (Battisti et al., 2016). A Spanish BACI study on bird species composition and density also did not yield clear indications how WPP construction in shrubland affects avian diversity and abundance (De Lucas et al., 2005): Relative abundances of nesting birds neither differed throughout three study periods (before, during and after construction), nor on the WPP site vs. the control site among study years. However, abundances of birds nesting on the wind power plant site were lower compared to control sites during WPP construction (De Lucas et al., 2005). High variation in species-specific responses of birds to WPP also became obvious when comparing national population trends of breeding passerines with data collected at a wind power plant site in Italy (García et al., 2015). While a decreasing trend was found for some species throughout the construction phase, populations recovered in the years after construction and show overall similar trends as national population

trends. Thus, it seems like WPP construction might disturb nesting birds, but increasing population trends afterwards (during operation years) indicate that wind power plant sites do not necessarily hamper conservation of breeding passerine populations (Garcia et al., 2015).

4.4. Distance thresholds and habituation

Distance to wind turbines might drive species' habitat use, since negative effects of wind power plants might vanish with increasing distance. Forests clearings and reduced canopy cover at wind power plant sites are linked to decreasing densities of forest birds, with negative effects being significant within distances of 100 m from turbines (Fernández-Bellon et al., 2019). Similar results are reported in a more recent study, investigating the effect of wind turbines on a woodland-dwelling grouse species (Coppes et al., 2020b). Indirect signs of Western capercaillie presence, collected on six study sites across Europe (Sweden, Germany, Austria) indicated, that on a regional scale, overall observation densities of capercaillie do not differ between wind power plant and control sites and over time. However, the study showed that the probability of presence of capercaillie is negatively affected by wind turbines on a local scale. Habitat selection of areas close to wind turbines was negatively affected by turbine predictors (proximity, shadow flickering, noise), which are detectable within approx. 650 m distance to wind turbines (Coppes et al., 2020b).

Negative impacts of habitat modifications on sensitive species might be large, particularly when wind turbines are situated within specialists' habitats. A study in northwest France showed reduced bat activity within 1000 m distances to wind turbines (Barré et al., 2018). Since almost 90% of wind turbines in this region are located in close vicinity (< 200 m) to wooded edges (forests or hedgerows), bat species with high dependence on woodland habitats (e.g. *Myotis* spp.) might be severely affected by habitat loss due to wind turbine avoidance (Barré et al., 2018). In contrast, movement and habitat use of reindeer seemed to be altered across greater distances to WPP: step length increased and stopover habitat use decreased within 5 km and 3 km during WPP development, accordingly (Skarin et al., 2015). However, the extent of avoidance has always to be evaluated in terms of e.g. a species' home range, territory behavior, habitat availability and quality.

Over time, species can also adapt to modified environments, by reducing their avoidance behavior and becoming habituated to WPP (Madsen and Boertmann, 2008). Obviously unchanged behavior of wildlife species must not be interpreted as absence of responses to WPP construction. Being exposed to actual or perceived threats, animals might respond more apparently or more concealed, ultimately adjusting to environmental changes (Cockrem, 2007). One concealed response, being frequently explored in studies, is stress which might be captured in terms of changes in glucocorticoid (cortisol or corticosterone) levels (Möstl and Palme, 2002; Sheriff et al., 2011). High hair cortisol levels indicated that badgers (*Meles meles*) are physiologically stressed when living in close vicinity (< 1 km) to wind power plants (Agnew et al., 2016). Badgers seem not to become habituated to wind turbines, as cortisol levels measured one and four years after WPP start-up date did not differ significantly. It is assumed that noise produced by wind turbines causes the increase in stress level (Agnew et al., 2016). A more recent study on roe deer also showed that cortisol concentrations seem to be positively related to wind power plant size (Klich et al., 2020).

4.5. Responses to noise and visual effects

A systematic review of 49 studies brought evidence that the impact of infrastructure on birds and mammals is more pronounced in open landscapes compared to forested areas (Benitez-Lopez et al., 2010). Differences between these two habitat types might be related to a reduced visibility of infrastructure in dense vegetation (Benitez-Lopez et al., 2010). Nevertheless, shrub- and woodland-dwelling wildlife species show behavioral responses to acoustic effects of wind turbines in

shrubs- and woodlands during construction, operation and maintenance.

Noise being related to WPP and associated infrastructure is assumed to affect habitat use, territorial behavior and breeding success of animals. Habitat quality for forest passerines seems to be negatively affected by anthropogenic noise (Bayne et al., 2008). Passerine density in areas near noise-generating facilities is lower than density in areas near noiseless energy facilities (Bayne et al., 2008). A study in North America focused on the effects of WPP construction on the occurrence of the Bicknell's thrush (Lemaître and Lamarre, 2020). Thereby, thrush abundance is significantly lower during WPP construction than eight years after construction. Noise during WPP construction together with the associated infrastructure might affect habitat use (Lemaître and Lamarre, 2020). However, noise generated by WPP can also affect bird behavior more directly. Wind turbine noise seems to mask territorial defense signals of European robins (*Erithacus rubecula*), since usage of low-frequency elements as response to simulated intrusion is reduced in presence of wind turbine noise (Zwart et al., 2016). It is assumed that noise can thereby hamper breeding success, if bird's energy requirements increase to deter competitors and defend territories (Zwart et al., 2016).

A short-term study in Poland addressed abundance and diversity of small mammals trapped close to wind turbines (Łopucki and Mróz, 2016). While the authors presumed that small mammals might avoid wind power plant sites due to negative effects of noise or vibration, no differences were found on the paired turbine-control sites. Neither the composition of small mammal communities (species diversity, species evenness), nor species abundance differed significantly between turbine and control sites in this study (Łopucki and Mróz, 2016). Consequently, more studies on related effects on both mammalian and avian wildlife species are urgently needed, better supporting concrete planning decisions in practical contexts (e.g. location of WPP, mitigations measures, permission processes).

4.6. Suggestions for future research

To accurately estimate impacts of WPP in shrub- and woodlands on wildlife, systematical and authoritative assessments are urgently needed. Reviewing studies on the impact of shrub- and woodland WPP on wildlife showed that within many studies (37%, $n = 10$), effects of WPP on wildlife are only studied after WPP construction. In contrast, studies comparing the effects of WPP before and after the construction of WPP and between areas with WPP development and reference sites (BACI study design) are rather rare ($n = 6$). Accurate estimates of effect sizes can be gained by using BACI study design, but the choice and selection of adequate control sites is of high importance (Christie et al., 2019). Location and time specific differences between study and control areas can bias results (Underwood, 1992). Thus, robust studies with BACI design can therefore only become a constitutive part of approval procedures and decisions processes in general, when habitat characteristics (e.g. vegetation, altitude) of sites are very similar to ensure comparability (Hurlbert, 1984).

Reviewing articles indicated, that effects of wind power plants on shrub- and woodland-dwelling wildlife species are highly site- and species-specific. Thus, there is an urgent need of further studies, which reach beyond the scale of a single case study, but comprise a medley of forest sites, forest types and species assemblages (both mammalian and avian) to allow for more general conclusions on potential impacts of WPP or related mitigation measures. Furthermore, species distribution models should be developed on a regional scale, e.g. particularly addressing wildlife species, which have been shown to respond sensitively to WPP, are of high conservation concern, or hold an umbrella function. This could help to assess potential overlaps between wildlife habitat occurrence and existing or planned WPP sites (Roscioni et al., 2013; Santos et al., 2013; Roscioni et al., 2014). In addition, spatially-explicit multi-criteria decision analysis to balance various technological, societal and environmental values in the landscape can support

decisions in regional spatial planning of renewable energy production (e.g. [Hanssen et al., 2018](#)). Thereby, spatial aspects like short-distance (e.g. foraging, dispersal) and long-distance movements (e.g. migration) of flying vertebrates ([Roscioni et al., 2014](#)) could be adequately addressed. However, such large-scale habitat selection analyses or species distribution models usually do not provide detailed information on the specific location of wind power plants and have thus to be supplemented with data of higher spatial resolution (i.e. fine-scaled habitat maps).

There are numerous studies focusing on collision fatalities on WPP throughout the world (see [Thaxter et al., 2017](#)), but many studies are limited in timeframe and/or spatial extent. Corrections to account for loss of carcasses from scavenging ([DeVault et al., 1994](#); [Smallwood et al., 2010](#); [Paula et al., 2014](#)) and detection bias ([Smallwood, 2007](#); [Barrantes et al., 2018](#)) should be applied when calculating fatality rates related to wind power facilities. However, number of fatalities at wind turbines is not necessarily related to species abundance (see [De Lucas et al., 2008](#)), as collision risk is also dependent on topography, weather, season and flight behavior ([Drewitt and Langston, 2006](#)) and varies throughout seasons (breeding, migration, wintering). This has to be considered when modelling collision risks to predict impacts of wind power plants on volant species ([Thaxter et al., 2017](#)).

4.7. Mitigation measures

To avoid negative effects of shrub- and woodland WPP on wildlife, appropriate measures can already be taken at an early (planning) stage. Siting of wind turbines inevitably overlaps with species' habitats, and rare and endangered species with long lifespans and low reproduction rates are facing a high risk of extinction, when wind power plants might cause demographic consequences. Mortality at wind power plants can be reduced by careful placing of wind turbines (see [Hanssen et al., 2020](#)).

To reduce the risk of collision several mitigation measures can be considered (e.g. curtailment, painting). Restricting the operation phases of wind turbines during low wind speed periods might lead to a strong reduction in the number of fatalities among bats, since the activity of bats is increased on warm, low-wind days ([Baerwald et al., 2009](#); [Arnett et al., 2011](#)). Curtailment of wind turbines during low speed periods in comparison to fully operational turbines decreases number of bat fatalities by an average of 72–82% ([Arnett et al., 2011](#)). Similar results can be found in open, agricultural landscapes, where altering operational parameters of wind turbines also leads to a significant reduction in bat fatalities ([Baerwald et al., 2009](#)). An additional temporary curtailment of WPP during the period of the strongest migratory movements might also have positive effects on the number of collisions of bats with rotor blades ([Northrup and Wittemyer, 2013](#); [Smallwood and Bell, 2020](#)). In contrast, curtailment of WPP solely to hours with low wind speeds may not have a strong impact on the number of collision victims among birds, because great differences in the susceptibility of bird species exist. Reducing bird fatalities on WPP requires high temporal flexibility in curtailment measures, as collision risk are highly dependent on seasons and weather conditions. Constant development of technology and software might allow for more accurate curtailment of WPP by using automated shutdown systems ([McClure et al., 2018](#)).

As many bird species are susceptible to collide with stationary turbine components ([Smallwood and Bell, 2020](#)), painting of lower parts of turbine towers ([Stokke et al., 2020](#)) and rotor blades (see [May et al., 2020](#)) could reduce number of bird collisions. Two first pilot studies were performed in open terrain with comparatively small sample sizes of painted WPP (10 turbines with marked turbine towers, [Stokke et al., 2020](#); 4 turbines with marked rotor blades, [May et al., 2020](#)); thus additional studies in wooded landscapes are required to get a broader insight into the effectiveness of painting part of WPPs in shrub- and woodlands. Bird mortality attributed to WPP also includes electrocution of large species with poor maneuverability at transmission lines or

collisions of birds with vehicles (see review of [Jones et al., 2015](#)). Additional mitigation measures to reduce the risk of collisions include the installation of power lines underground (see review of [Gasparatos et al., 2017](#)).

4.8. Implications for WPP construction in shrub- and woodlands

Construction of new WPP is related to land transformation, but highly dependent on land cover and topography ([Diffendorfer and Compton, 2014](#)). Impacts of WPP construction on landscape features and thus wildlife might be minimized, when siting WPP on developed land, as roads and transmission lines already exist there ([Diffendorfer et al., 2019](#)). Infrastructure, associated to wind power plants, is assumed to have an even larger potential impact on wildlife than the WPP themselves ([Kuvlesky et al., 2007](#)). As wind power plant development will expand to increasingly remote areas (e.g. mountain ridges, [Hastik et al., 2015](#); [Jones et al., 2015](#)), more miles of infrastructure (roads, transmission lines etc.) will be required. Before wind power plant construction, data on wildlife habitat distribution should be compiled or collected to estimate spatial overlap with both already existing and proposed WPP sites. These initial assessments can help to reduce the negative impacts of wind power plants, especially for endangered species facing risks from disturbance or collision mortality during breeding, migration or wintering ([Pearse et al., 2016](#)). A study in Canada showed, that after applying careful siting of wind turbines with respect to a species' occurrence no effects of wind power plants on shrub- and woodland-dwelling wildlife can be detected. Micro-siting of wind turbines was an effective strategy to reduce the impact of habitat loss and disturbance on Bicknell's thrush ([Lemaître and Lamarre, 2020](#)). Thus, the extent of habitat loss and fragmentation affecting wildlife species can be reduced by carefully placing turbines at appropriate sites, within already disturbed areas ([Jones and Pejchar, 2013](#)). In addition, constructions of WPP in critical regions or vulnerable areas should be avoided, since reduced connectivity among habitats and populations can reduce gene flow and metapopulation dynamics ([Frankham et al., 2010](#); [Balkenhol et al., 2016](#)). Maintenance of undeveloped land is of major importance, as these landscape sectors can provide refuge areas for several species. However, since species habitat requirements (roosting, breeding, foraging, migration) can change throughout the year, siting of wind power plants remains a challenging spatial planning task ([Northrup and Wittemyer, 2013](#)).

5. Conclusion

Reviewing scientific literature on effects of WPP on shrub- and woodland-dwelling wildlife species indicated that current knowledge is rather scarce and as well controversial. Published peer-reviewed literature yielded evidence that construction, operation and maintenance of wind facilities might affect mortality and behavior of mammals and birds as well as habitat suitability. However, different studies yielded either negative, positive or even no responses of wildlife species to WPP in shrub- and woodlands, and some studies did not generate clear patterns. Such controversial results might exist even within one wildlife species (e.g. reindeer), potentially deriving from largely varying study settings in terms of addressed habitats, study design, season, length of observations, sample sizes and more. Different response types within one species might also be related to demographic differences, to individual life histories or to behavioral switching. All these aspects might have considerable implications for the significance and informative value of studies and it might lead to a large remaining uncertainty about their generality – both for their significance for population biology and for conclusions on potential management and mitigation strategies. Highly site- and community-specific studies as well as results from short-term studies are beyond the most important constraints for inferring general patterns, which should urgently be overcome by future multi-annual, multi-site studies following a BACI design. Additional studies

in shrub- and woodlands are also required to get insight into the effectiveness of mitigation measures and micro-siting of WPPs. Thereby gained knowledge is required to support planning decisions in practical context.

Glossary

A	After
B	Before
D	During
CI	Control impact
BACI	before-after control-impact study design
WPP	wind power plants including wind turbines and associated infrastructure related to the turbines, e.g. roads, transmission lines, meteorological towers

The full electronic search strategy for the two databases (e.g. search term combinations, date searched, etc.; Table A1), a flow diagram for systematic reviews (Fig. A1), a list of all journal articles detected in the initial article search (825 journal articles, References A1), a list of additional journal articles detected after screening reviews/meta-analyses (103 journal articles, References A2) and a list of articles and additional articles from reviews/meta-analyses, passing the first stage of our two-stages process (326 journal articles, Reference A3) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

CRediT authorship contribution statement

Eva Maria Schöll: Conceptualization, Methodology, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Project administration, Funding acquisition, Ursula Nopp-Mayr: Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing, Supervision, Funding acquisition.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Agnew, R.C.N., Smith, V.J., Fowkes, R.C., 2016. Wind turbines cause chronic stress in badgers (*Meles meles*) in Great Britain. *J. Wildl. Dis.* 52, 459–467. <https://doi.org/10.7589/2015-09-231>.
- Apoznański, G., Sánchez-Navarro, S., Kokurewicz, T., Pettersson, S., Rydell, J., 2018. Barbastelle bats in a wind farm: are they at risk? *Eur. J. Wildl. Res.* 64, 43. <https://doi.org/10.1007/s10344-018-1202-1>.
- Arnett, E.B., 2006. A preliminary evaluation on the use of dogs to recover bat fatalities at wind energy facilities. *Wildl. Soc. Bull.* 34, 1440–1445. [https://doi.org/10.2193/0091-7648\(2006\)34\[1440:APEOTU\]2.0.CO;2](https://doi.org/10.2193/0091-7648(2006)34[1440:APEOTU]2.0.CO;2).
- Arnett, E.B., et al., 2008. Patterns of bat fatalities at wind energy facilities in North America. *J. Wildl. Manag.* 72, 61–78. <https://doi.org/10.2193/2007-221>.
- Arnett, E.B., Huso, M.M.P., Schirmacher, M.R., Hayes, J.P., 2011. Altering turbine speed reduces bat mortality at wind-energy facilities. *Front. Ecol. Environ.* 9, 209–214. <https://doi.org/10.1890/100103>.

- Baerwald, E.F., D'Amours, G.H., Klug, B.J., Barclay, R.M.R., 2008. Barotrauma is a significant cause of bat fatalities at wind turbines. *Curr. Biol.* 18, R695–R696. <https://doi.org/10.1016/j.cub.2008.06.029>.
- Baerwald, E.F., Edworthy, J., Holder, M., Barclay, R.M.R., 2009. A large-scale mitigation experiment to reduce bat fatalities at wind energy facilities. *J. Wildl. Manag.* 73, 1077–1081. <https://doi.org/10.2193/2008-233>.
- Balkenhol, N., Cushman, S., Storfer, A., Waits, L., 2016. *Landscape Genetics: Concepts, Methods, Applications*. John Wiley & Sons, Ltd, Chichester, UK.
- Barclay RMR, Baerwald EF, Rydell J. 2017. Bats in Perrow M, editor. *Wildlife and wind farms: conflicts and solutions*. Volume 1 onshore: Potential effects. Pelagic Publishing, Exeter, UK.
- Barré, K., Le Viol, I., Bas, Y., Julliard, R., Kerbiriou, C., 2018. Estimating habitat loss due to wind turbine avoidance by bats: implications for European siting guidance. *Biol. Conserv.* 226, 205–214. <https://doi.org/10.1016/j.biocon.2018.07.011>.
- Barrientos, R., Martins, R.C., Ascensão, F., D'Amico, M., Moreira, F., Borda-de-Água, L., 2018. A review of searcher efficiency and carcass persistence in infrastructure-driven mortality assessment studies. *Biol. Conserv.* 222, 146–153. <https://doi.org/10.1016/j.biocon.2018.04.014>.
- Barrios, L., Rodríguez, A., 2004. Behavioural and environmental correlates of soaring-bird mortality at on-shore wind turbines. *J. Appl. Ecol.* 41, 72–81. <https://doi.org/10.1111/j.1365-2664.2004.00876.x>.
- Battisti, C., Fortunati, L., Ferri, V., Dallari, D., Lucatello, G., 2016. Lack of evidence for short-term structural changes in bird assemblages breeding in Mediterranean mosaics moderately perforated by a wind farm. *Global Ecology and Conservation* 6, 299–307. <https://doi.org/10.1016/j.gecco.2016.03.012>.
- Bayne, E.M., Habib, L., Boutin, S., 2008. Impacts of chronic anthropogenic noise from energy-sector activity on abundance of songbirds in the boreal forest. *Conserv. Biol.* 22, 1186–1193. <https://doi.org/10.1111/j.1523-1739.2008.00973.x>.
- Benitez-Lopez, A., Alkemade, R., Verweij, P.A., 2010. The impacts of roads and other infrastructure on mammal and bird populations: a meta-analysis. *Biol. Conserv.* 143, 1307–1316. <https://doi.org/10.1016/j.biocon.2010.02.009>.
- Budenz, T., Gessner, B., Lüttmann, J., Molitor, F., Servatius, K., Veith, M., 2017. Up and down: *B. barbastellus* explore lattice towers. *Hystrix* 28, 277–279. <https://doi.org/10.4404/hystrix-00009-2017>.
- Bunzel, K., Bovet, J., Thrän, D., Eichhorn, M., 2019. Hidden outlaws in the forest? A legal and spatial analysis of onshore wind energy in Germany. *Energy Res. Soc. Sci.* 55, 14–25. <https://doi.org/10.1016/j.erss.2019.04.009>.
- Christie, A.P., Amano, T., Martin, P.A., Shackelford, G.E., Simmons, B.L., Sutherland, W. J., 2019. Simple study designs in ecology produce inaccurate estimates of biodiversity responses. *J. Appl. Ecol.* 56, 2742–2754. <https://doi.org/10.1111/1365-2664.13499>.
- Cockrem, J.F., 2007. Stress, corticosterone responses and avian personalities. *J. Ornithol.* 148, 169–178. <https://doi.org/10.1007/s10336-007-0175-8>.
- Collaboration for Environmental Evidence. 2013. Guidelines for systematic review and evidence synthesis in environmental management. Version 4.2. Centre for Evidence-Based Conservation, Bangor University, UK.
- Coppes, J., Braunisch, V., Bollmann, K., Storch, I., Mollet, P., Grünschachner-Berger, V., Taubmann, J., Suchant, R., Nopp-Mayr, U., 2020a. The impact of wind energy facilities on grouse: a systematic review. *J. Ornithol.* 161, 1–15. <https://doi.org/10.1007/s10336-019-01696-1>.
- Coppes, J., Kämmerle, J.L., Grünschachner-Berger, V., Braunisch, V., Bollmann, K., Mollet, P., Suchant, R., Nopp-Mayr, U., 2020b. Consistent effects of wind turbines on habitat selection of capercaillie across Europe. *Biol. Conserv.* 244, 108529. <https://doi.org/10.1016/j.biocon.2020.108529>.
- De Lucas M, Perrow MR. 2017. Birds: Collisions in Perrow MR, editor. *Wildlife and wind farms, conflicts and solutions*. Volume 1 onshore: Potential effects. Pelagic Publishing, Exeter, UK.
- De Lucas, M., Janss, G.F.E., Ferrer, M., 2005. A bird and small mammal BACI and IG design studies in a wind farm in Malpica (Spain). *Biodivers. Conserv.* 14, 3289–3303. <https://doi.org/10.1007/s10531-004-0447-z>.
- De Lucas, M., Janss, G.F.E., Whitfield, D.P., Ferrer, M., 2008. Collision fatality of raptors in wind farms does not depend on raptor abundance. *J. Appl. Ecol.* 45, 1695–1703. <https://doi.org/10.1111/j.1365-2664.2008.01549.x>.
- DeVault, T.L., Seamans, T.W., Linnell, K.E., Sparks, D.W., Beasley, J.C., 1994. Scavenger removal of bird carcasses at simulated wind turbines: does carcass type matter? *Ecosphere* 8:e01994. DOI. <https://doi.org/10.1002/ecs2.1994>.
- Diffendorfer, J.E., Compton, R.W., 2014. Land cover and topography affect the land transformation caused by wind facilities. *PLoS One* 9, e88914. <https://doi.org/10.1371/journal.pone.0088914>.
- Diffendorfer, J.E., Dorning, M.A., Keen, J.R., Kramer, L.A., Taylor, R.V., 2019. Geographic context affects the landscape change and fragmentation caused by wind energy facilities. *PeerJ* 7, e7129. <https://doi.org/10.7717/peerj.7129>.
- Dorka, U., Straub, F., Trautner, J., 2014. Wind power above forest - courtship of the woodcock at risk? Findings from a case study in Baden-Wuerttemberg (Northern Black Forest). *Naturschutz und Landschaftsplanung* 46, 69–78.
- Drewitt, A.L., Langston, R.H.W., 2006. Assessing the impacts of wind farms on birds. *Ibis* 148, 29–42. <https://doi.org/10.1111/j.1474-919X.2006.00516.x>.
- Drewitt, A.L., Langston, R.H.W., 2008. Collision effects of wind-power generators and other obstacles on birds. *Ann. N. Y. Acad. Sci.* 1134, 233–266. <https://doi.org/10.1196/annals.1439.015>.
- EEA, 2009. *Europe's Onshore and Offshore Wind Energy Potential - an Assessment of Environmental and Economic Constraints*. European Environment Agency, Copenhagen, Denmark, p. 85.
- Elzay S, Tronstad L, Dillon ME. 2017. *Terrestrial invertebrates in Perrow M, editor. Wildlife and wind farms: conflicts and solutions*. Volume 1 onshore: Potential effects. Pelagic Publishing, Exeter, UK.

- Erickson, W.P., Wolfe, M.M., Bay, K.J., Johnson, D.H., Gehring, J.L., 2014. A comprehensive analysis of small-passerine fatalities from collision with turbines at wind energy facilities. *PLoS One* 9, e107491. <https://doi.org/10.1371/journal.pone.0107491>.
- Fernández-Bellón, D., Wilson, M.W., Irwin, S., O'Halloran, J., 2019. Effects of development of wind energy and associated changes in land use on bird densities in upland areas. *Conserv. Biol.* 33, 413–422. <https://doi.org/10.1111/cobi.13239>.
- Foo, C.F., Bennett, V.J., Hale, A.M., Korstian, J.M., Schildt, A.J., Williams, D.A., 2017. Increasing evidence that bats actively forage at wind turbines. *PeerJ* 5, e3985. <https://doi.org/10.7717/peerj.3985>.
- Frankham, R., Ballou, J., Briscoe, D., 2010. *Introduction to Conservation Genetics*. Cambridge University Press, Cambridge.
- García, D.A., Canavero, G., Ardenghi, F., Zambon, M., 2015. Analysis of wind farm effects on the surrounding environment: assessing population trends of breeding passerines. *Renew. Energy* 80, 190–196. <https://doi.org/10.1016/j.renene.2015.02.004>.
- Gasparatos, A., Doll, C.N.H., Esteban, M., Ahmed, A., Olang, T.A., 2017. Renewable energy and biodiversity: implications for transitioning to a Green Economy. *Renew. Sust. Energ. Rev.* 70, 161–184. <https://doi.org/10.1016/j.rser.2016.08.030>.
- González, M.A., García-Tejero, S., Wengert, E., Fuertes, B., 2016. Severe decline in Cantabrian capercaillie *Tetrao urogallus cantabricus* habitat use after construction of a wind farm. *Bird Conservation International* 26, 256–261. <https://doi.org/10.1017/S0959270914000471>.
- Hanssen, F., Roel, M., van Dijk, J., Rød, J.K., 2018. Spatial multi-criteria decision analysis tool suite for consensus-based siting of renewable energy structures. *Journal of Environmental Assessment Policy and Management* 20, 1–28. <https://doi.org/10.1142/S1464333218400033>.
- Hanssen, F., May, R., Nygård, T., 2020. High-resolution modeling of uplift landscapes can inform micro-siting of wind turbines for soaring raptors. *Environ. Manag.* 66, 319–332. <https://doi.org/10.1007/s00267-020-01318-0>.
- Hastik, R., Basso, S., Geitner, C., Haida, C., Poljanec, A., Portaccio, A., Vrscaj, B., Walzer, C., 2015. Renewable energies and ecosystem service impacts. *Renew. Sust. Energ. Rev.* 48, 608–623. <https://doi.org/10.1016/j.rser.2015.04.004>.
- Hayes, M.A., 2013. Bats killed in large numbers at United States wind energy facilities. *BioScience* 63, 975–979. <https://doi.org/10.1525/bio.2013.63.12.10>.
- Heldin JO, Skarin A, Neumann W, Olsson M, Jung J, Kindberg NW. 2017. Terrestrial mammals in Perrow M, editor. *Wildlife and wind farms: conflicts and solutions*. Volume 1 onshore: Potential effects. Pelagic Publishing, Exeter, UK.
- Horn, J.W., Arnett, E.B., Kunz, T.H., 2008. Behavioral responses of bats to operating wind turbines. *J. Wildl. Manag.* 72, 123–132. <https://doi.org/10.2193/2006-465>.
- Hötter H. 2017. *Birds: displacement*. Pages 119–154 in M P, editor. *Wildlife and Wind Farms: Conflicts and Solutions*, vol 1. Pelagic, Exeter, UK.
- Hurlbert, S.H., 1984. Pseudoreplication and the design of ecological field experiments. *Ecol. Monogr.* 54, 187–211.
- Johnson, G.D., Perlik, M.K., Erickson, W.P., Strickland, M.D., 2004. Bat activity, composition, and collision mortality at a large wind plant in Minnesota. *Wildl. Soc. Bull.* 32, 1278–1288. [https://doi.org/10.2193/0091-7648\(2004\)032\[1278:BACACM\]2.0.CO;2](https://doi.org/10.2193/0091-7648(2004)032[1278:BACACM]2.0.CO;2).
- Johnston, N.N., Bradley, J.E., Otter, K.A., 2014. Increased flight altitudes among migrating golden eagles suggest turbine avoidance at a rocky mountain wind installation. *PLoS One* 9, e93030. <https://doi.org/10.1371/journal.pone.0093030>.
- Jones, N., Pejchar, L., 2013. Comparing the ecological impacts of wind and oil and gas development: a landscape scale assessment. *PLoS One* 8, e81391. <https://doi.org/10.1371/journal.pone.0081391>.
- Jones, N.F., Pejchar, L., Kiesecker, J.M., 2015. The energy footprint: how oil, natural gas, and wind energy affect land for biodiversity and the flow of ecosystem services. *Bioscience* 65, 290–301. <https://doi.org/10.1093/biosci/biu224>.
- Kirkpatrick, L., Oldfield, I.F., Park, K., 2017. Responses of bats to clear fell harvesting in Sitka spruce plantations, and implications for wind turbine installation. *For. Ecol. Manag.* 395, 1–8. <https://doi.org/10.1016/j.foreco.2017.03.033>.
- Klich, D., Łopucki, R., Ścibior, A., Gołębiowska, D., Wojciechowska, M., 2020. Roe deer stress response to a wind farms: methodological and practical implications. *Ecol. Indic.* 117. <https://doi.org/10.1016/j.ecolind.2020.106658>.
- Koschinski, S., Culik, B.M., Damsgaard Henriksen, O., Tregenza, N., Ellis, G., Jansen, C., Kathé, G., 2003. Behavioural reactions of free-ranging porpoises and seals to the noise of a simulated 2 MW windpower generator. *Mar. Ecol. Prog. Ser.* 265, 263–273.
- Kunz, T.H., Arnett, E.B., Erickson, W.P., Hoar, A.R., Johnson, G.D., Larkin, R.P., Strickland, M.D., Thresher, R.W., Turtle, M.D., 2007. Ecological impacts of wind energy development on bats: questions, research needs, and hypotheses. *Front. Ecol. Environ.* 5, 315–324. [https://doi.org/10.1890/1540-9295\(2007\)5\[315:EIOWED\]2.0.CO;2](https://doi.org/10.1890/1540-9295(2007)5[315:EIOWED]2.0.CO;2).
- Kuvlesky, W.P.J., Brennan, L.A., Morrison, M.L., Boydston, K.K., Ballard, B.M., Bryant, F. C., 2007. Wind energy development and wildlife conservation: challenges and opportunities. *J. Wildl. Manag.* 71, 2487–2498. <https://doi.org/10.2193/2007-248>.
- Law, B., Park, K.J., Lacki, M.J., 2016. Insectivorous bats and silviculture: Balancing timber production and bat conservation. In: Voigt, C., Kingston, T. (Eds.), *Bats in the Anthropocene: Conservation of bats in a changing world*. Springer, Cham, pp. 105–150.
- Lemaître, J., Lamarre, V., 2020. Effects of wind energy production on a threatened species, the Bicknell's thrush *Catharus bicknelli*, with and without mitigation. *Bird Conservation International* 30, 1–16. <https://doi.org/10.1017/S095927092000012X>.
- Loesch, C.R., Walker, J.A., Reynolds, R.E., Gleason, J.S., Niemuth, N.D., Stephens, S.E., Erickson, M.A., 2013. Effect of wind energy development on breeding duck densities in the Prairie Pothole Region. *J. Wildl. Manag.* 77, 587–598. <https://doi.org/10.1002/jwmg.481>.
- Long, C.V., Flint, J.A., Lepper, P.A., 2011. Insect attraction to wind turbines: does colour play a role? *Eur. J. Wildl. Res.* 57, 323–331. <https://doi.org/10.1007/s10344-010-0432-7>.
- Łopucki, R., Mróz, I., 2016. An assessment of non-volant terrestrial vertebrates response to wind farms - a study of small mammals. *Environ. Monit. Assess.* 188, 1–9. <https://doi.org/10.1007/s10661-016-5095-8>.
- Łopucki, R., Klich, D., Gielarek, S., 2017. Do terrestrial animals avoid areas close to turbines in functioning wind farms in agricultural landscapes? *Environ. Monit. Assess.* 189, 343. <https://doi.org/10.1007/s10661-017-6018-z>.
- Loss, S.R., Will, T., Marra, P.P., 2013. Estimates of bird collision mortality at wind facilities in the contiguous United States. *Biol. Conserv.* 168, 201–209. <https://doi.org/10.1016/j.biocon.2013.10.007>.
- Lovich, J.E., Ennen, J.R., 2013. Assessing the state of knowledge of utility-scale wind energy development and operation on non-volant terrestrial and marine wildlife. *Appl. Energy* 103, 52–60. <https://doi.org/10.1016/j.apenergy.2012.10.001>.
- Madsen, J., Boertmann, D., 2008. Animal behavioral adaptation to changing landscapes: spring-staging geese habituate to wind farms. *Landsc. Ecol.* 23, 1007–1011. <https://doi.org/10.1007/s10980-008-9269-9>.
- Marques, A.T., Batalha, H., Rodrigues, S., Costa, H., Pereira, M.J.R., Fonseca, C., Mascarenhas, M., Bernardino, J., 2014. Understanding bird collisions at wind farms: an updated review on the causes and possible mitigation strategies. *Biol. Conserv.* 179, 40–52. <https://doi.org/10.1016/j.biocon.2014.08.017>.
- May, R., Nygård, T., Falkdalen, U., Astrom, J., Hamre, O., Stokke, B.G., 2020. Paint it black: efficacy of increased wind turbine rotor blade visibility to reduce avian fatalities. *Ecology and Evolution* 10, 8927–8935. <https://doi.org/10.1002/ece3.6592>.
- McClure, C.J.W., Martinson, L., Allison, T.D., 2018. Automated monitoring for birds in flight: proof of concept with eagles at a wind power facility. *Biol. Conserv.* 224, 26–33. <https://doi.org/10.1016/j.biocon.2018.04.041>.
- Merlin, T., Newton, S., Ellery, B., Milverton, J., Farah, C., 2013. *Systematic Review of the Human Health Effects of Wind Farms*. National Health and Medical Research Council, Australia.
- Möstl, E., Palme, R., 2002. Hormones as indicators of stress. *Domest. Anim. Endocrinol.* 23, 67–74. [https://doi.org/10.1016/S0739-7240\(02\)00146-7](https://doi.org/10.1016/S0739-7240(02)00146-7).
- Müller, J., Brandl, R., Buchner, J., Pretzsch, H., Seifert, S., Strätz, C., Veith, M., Fenton, B., 2013. From ground to above canopy - bat activity in mature forests is driven by vegetation density and height. *For. Ecol. Manag.* 306, 179–184. <https://doi.org/10.1016/j.foreco.2013.06.043>.
- Northrup, J.M., Wittemyer, G., 2013. Characterising the impacts of emerging energy development on wildlife, with an eye towards mitigation. *Ecol. Lett.* 16, 112–125. <https://doi.org/10.1111/ele.12009>.
- Paula, J.J.S., Bispo, R.M.B., Leite, A.H., Pereira, P.G.S., Costa, H.M.R.G., Fonseca, C.M.M.S., Mascarenhas, M.R.T., Bernardino, J.L.V., 2014. Camera-trapping as a methodology to assess the persistence of wildlife carcasses resulting from collisions with human-made structures. *Wildl. Res.* 41, 717–725. <https://doi.org/10.1071/WR14063>.
- Pearse, A.T., Brandt, D.A., Krapu, G.L., 2016. Wintering Sandhill Crane exposure to wind energy development in the central and southern Great Plains, USA. *Condor* 118, 391–401. <https://doi.org/10.1650/CONDOR-15-99.1>.
- Peste, F., et al., 2015. How to mitigate impacts of wind farms on bats? A review of potential conservation measures in the European context. *Environ. Impact Assess. Rev.* 51, 10–22. <https://doi.org/10.1016/j.eiar.2014.11.001>.
- Pullin, A., Stewart, G., 2006. Guidelines for systematic review in conservation and environmental management. *Conserv. Biol.* 20, 1647–1656. <https://doi.org/10.1111/j.1523-1739.2006.00485.x>.
- Pylant, C.L., Nelson, D.M., Fitzpatrick, M.C., Gates, J.E., Keller, S.R., 2016. Geographic origins and population genetics of bats killed at wind-energy facilities. *Ecol. Appl.* 26, 1381–1395. <https://doi.org/10.1890/10.1890-15-0541>.
- Rabin, L., Coss, R., Owings, D., 2006. The effects of wind turbines on antipredator behavior in California ground squirrels (*Spermophilus beecheyi*). *Biol. Conserv.* 131, 410–420. <https://doi.org/10.1016/j.biocon.2006.02.016>.
- Raynor, E.J., Whalen, C.E., Bomberger Brown, M., Powell, L.A., 2017. Location matters: evaluating greater Prairie-Chicken (*Tympanuchus cupido*) boom chorus propagation. *Avian Conservation and Ecology* 12, 17. <https://doi.org/10.5751/ACE-01126-120217>.
- Renewable Energy Network. 2018. *Renewables Global Status Report - A Comprehensive Annual Overview of the State of Renewable Energy*. REN21, Paris.
- Reynolds DS. 2006. Monitoring the potential impact of a wind development site on bats in the northeast. *Journal of Wildlife Management* 70:1219-1227. DOI: [https://doi.org/10.2193/0022-541X\(2006\)70\[1219:MTPIOA\]2.0.CO;2](https://doi.org/10.2193/0022-541X(2006)70[1219:MTPIOA]2.0.CO;2).
- Roscioni, F., Russo, D., Di Febraro, M., Frate, L., Carranza, M.L., Loy, A., 2013. Regional-scale modelling of the cumulative impact of wind farms on bats. *Biodivers. Conserv.* 22, 1821–1835. <https://doi.org/10.1007/s10531-013-0515-3>.
- Roscioni, F., Rebelo, H., Russo, D., Carranza, M.L., Di Febraro, M., Loy, A., 2014. A modelling approach to infer the effects of wind farms on landscape connectivity for bats. *Landsc. Ecol.* 29, 891–903. <https://doi.org/10.1007/s10980-014-0030-2>.
- Rydell, J., Bach, L., Dubourg-Savage, M.J., Green, M., Rodrigues, L., Hedenström, A., 2010a. Bat mortality at wind turbines in northwestern Europe. *Acta Chiropterologica* 12, 261–274. <https://doi.org/10.3161/150811010X537846>.
- Rydell, J., Bach, L., Dubourg-Savage, M.J., Green, M., Rodrigues, L., Hedenström, A., 2010b. Mortality of bats at wind turbines links to nocturnal insect migration? *Eur. J. Wildl. Res.* 56, 823–827. <https://doi.org/10.1007/s10344-010-0444-3>.

- Saidur, R., Rahim, N.A., Islam, M.R., Solangi, K.H., 2011. Environmental impact of wind energy. *Renew. Sust. Energ. Rev.* 15, 2423–2430. <https://doi.org/10.1016/j.rser.2011.02.024>.
- Santos, H., Rodrigues, L., Jones, G., Rebelo, H., 2013. Using species distribution modelling to predict bat fatality risk at wind farms. *Biol. Conserv.* 157, 178–186. <https://doi.org/10.1016/j.biocon.2012.06.017>.
- Schmal, V.G., 2015. Sensitivity of the woodcock to wind power plants – contribution to the current discussion. *Naturschutz und Landschaftsplanung* 47, 043–048.
- Sheriff, M.J., Dantzer, B., Delehanty, B., Palme, R., Boonstra, R., 2011. Measuring stress in wildlife: techniques for quantifying glucocorticoids. *Oecologia* 166, 869–887. <https://doi.org/10.1007/s00442-011-1943-y>.
- Sirén, A.P.K., Maynard, D.S., Kilborn, J.R., Pekins, P.J., 2016. Efficacy of remote telemetry data loggers for landscape-scale monitoring: a case study of American martens. *Wildl. Soc. Bull.* 40, 570–582. <https://doi.org/10.1002/wsb.680>.
- Sirén, A.P.K., Pekins, P.J., Kilborn, J.R., Kanter, J.J., Sutherland, C.S., 2017. Potential influence of high-elevation wind farms on carnivore mobility. *J. Wildl. Manag.* 81, 1505–1512. <https://doi.org/10.1002/jwmg.21317>.
- Sjoegren, E., 1989. *Forests of the World: Diversity and Dynamics*. Studies in Plant Ecology/Vaexteknologiska Studier, Almqvist and Wiksell International, Uppsala.
- Skarin, A., Åhman, B., 2014. Do human activity and infrastructure disturb domesticated reindeer? The need for the reindeer's perspective. *Polar Biol.* 37, 1041–1054. <https://doi.org/10.1007/s00300-014-1499-5>.
- Skarin, A., Alam, M., 2017. Reindeer habitat use in relation to two small wind farms, during preconstruction, construction, and operation. *Ecology and Evolution* 7, 3870–3882. <https://doi.org/10.1002/ece3.2941>.
- Skarin, A., Nellemann, C., Rönnegård, L., Sandström, P., Lundqvist, H., 2015. Wind farm construction impacts reindeer migration and movement corridors. *Landsc. Ecol.* 30, 1527–1540. <https://doi.org/10.1007/s10980-015-0210-8>.
- Skarin, A., Sandström, P., Alam, M., 2018. Out of sight of wind turbines - reindeer response to wind farms in operation. *Ecology and Evolution* 8, 9906–9919. <https://doi.org/10.1002/ece3.4476>.
- Smallwood, K.S., 2007. Estimating wind turbine-caused bird mortality. *J. Wildl. Manag.* 71, 2781–2791. <https://doi.org/10.2193/2007-006>.
- Smallwood, K.S., 2013. Comparing bird and bat fatality-rate estimates among North American wind-energy projects. *Wildl. Soc. Bull.* 37, 19–33. <https://doi.org/10.1002/wsb.260>.
- Smallwood, K.S., Karas, B., 2009. Avian and bat fatality rates at old-generation and repowered wind turbines in California. *J. Wildl. Manag.* 73, 1062–1071. <https://doi.org/10.2193/2008-464>.
- Smallwood, K.S., Bell, D.A., 2020. Effects of wind turbine curtailment on bird and bat fatalities. *J. Wildl. Manag.* 84, 685–696. <https://doi.org/10.1002/jwmg.21844>.
- Smallwood, K.S., Neher, L., Bell, D.A., 2009. Map-based repowering and reorganization of a wind resource area to minimize burrowing owl and other bird fatalities. *Energies* 2, 915–943. <https://doi.org/10.3390/en20400915>.
- Smallwood, K.S., Bell, D.A., Snyder, S.A., Didonato, J.E., 2010. Novel scavenger removal trials increase wind turbine caused avian fatality estimates. *J. Wildl. Manag.* 74, 1089–1096. <https://doi.org/10.2193/2009-266>.
- Smallwood, K.S., Bell, D.A., Standish, S., 2020. Dogs detect larger wind energy effects on bats and birds. *J. Wildl. Manag.* 84, 852–864. <https://doi.org/10.1002/jwmg.21863>.
- Smith, J.A., Dwyer, J.F., 2016. Avian interactions with renewable energy infrastructure: an update. *Condor* 118, 411–423. <https://doi.org/10.1650/condor-15-61.1>.
- Smith, K.T., Taylor, K.L., Albeke, S.E., Beck, J.L., 2020. Pronghorn winter resource selection before and after wind energy development in south-central Wyoming. *Rangeland Ecology and Management* 73, 227–233. <https://doi.org/10.1016/j.rama.2019.12.004>.
- Sovacool, B.K., 2009. Contextualizing avian mortality: a preliminary appraisal of bird and bat fatalities from wind, fossil-fuel, and nuclear electricity. *Energy Policy* 37, 2241–2248. <https://doi.org/10.1016/j.enpol.2009.02.011>.
- Stokke, B.G., Nygård, T., Falkdalen, U., Pedersen, H.C., May, R., 2020. Effect of tower base painting on willow ptarmigan collision rates with wind turbines. *Ecology and Evolution* 10, 5670–5679. <https://doi.org/10.1002/ece3.6307>.
- Straub, V.F., Trautner, J., Dorka, U., 2015. Woodcocks are sensitive to wind power plants, and their harming can break legislation on species protection – reply to Schmal (2015) in the context of the publication by Dorka et al. (2014). *Naturschutz und Landschaftsplanung* 47, 049–058.
- Thaxter, C.B., et al., 2017. Bird and bat species' global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. *Proc. R. Soc. B Biol. Sci.* 284, 20170829. <https://doi.org/10.1098/rspb.2017.0829>.
- Thomas, E.H., Brittingham, M.C., Stoleson, S.H., 2014. Conventional oil and gas development alters forest songbird communities. *J. Wildl. Manag.* 78, 293–306. <https://doi.org/10.1002/jwmg.662>.
- Thompson, M., Beston, J.A., Etterson, M., Diffendorfer, J.E., Loss, S.R., 2017. Factors associated with bat mortality at wind energy facilities in the United States. *Biol. Conserv.* 215, 241–245. <https://doi.org/10.1016/j.biocon.2017.09.014>.
- Tsegaye, D., Colman, J.E., Eftestøl, S., Flydal, K., Røthe, G., Rapp, K., 2017. Reindeer spatial use before, during and after construction of a wind farm. *Appl. Anim. Behav. Sci.* 195, 103–111. <https://doi.org/10.1016/j.applanim.2017.05.023>.
- Underwood, A.J., 1992. Beyond BACI: the detection of environmental impacts on populations in the real, but variable, world. *J. Exp. Mar. Biol. Ecol.* 161, 145–178. UNFCCC, 2015. Paris agreement. Change UNFCCC, Paris.
- Volpato, G.H., Prado, V.M., dos Anjos, L., 2010. What can tree plantations do for forest birds in fragmented forest landscapes? A case study in southern Brazil. *For. Ecol. Manag.* 260, 1156–1163. <https://doi.org/10.1016/j.foreco.2010.07.006>.
- Wind, F.A., 2017. *Entwicklung der Windenergie im Wald - Ausbau, planerische Vorgaben und Empfehlungen für Windenergiestandorte auf Waldflächen in den Bundesländern*. Fachagentur Windenergie an Land, Berlin, Germany.
- Zeiler, H.P., Grünschnacher-Berger, V., 2009. Impact of wind power plants on black grouse, *Lyrurus tetrix* in Alpine regions. *Folia Zool.* 58, 173–182.
- Zimmerling, J.R., Pomeroy, A.C., d'Entremont, M.V., Francis, C.M., 2013. Canadian estimate of bird mortality due to collisions and direct habitat loss associated with wind turbine developments. *Avian Conservation and Ecology* 8, 10. <https://doi.org/10.5751/ACE-00609-080210>.
- Zwart, M.C., Dunn, J.C., McGowan, P.J.K., Whittingham, M.J., 2016. Wind farm noise suppresses territorial defense behavior in a songbird. *Behav. Ecol.* 27, 101–108. <https://doi.org/10.1093/beheco/arv128>.