Journal of Ornithology (2020) 161:1–15
https://doi.org/10.1007/s10336-019-01696-1

REVIEW

The impact of wind energy facilities on grouse: a systematic review

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Received: 17 January 2019 / Revised: 1 July 2019 / Accepted: 18 July 2019 / Published online: 1 August 2019

Abstract

There is increasing concern about the impact of the current boom in wind energy facilities (WEF) and associated infrastructure on wildlife. However, the direct and indirect effects of these facilities on the mortality, occurrence and behaviour of rare and threatened species are poorly understood. We conducted a literature review to examine the potential impacts of WEF on grouse species. We studied whether grouse (1) collide with wind turbines, (2) show behavioural responses in relation to wind turbine developments, and (3) if there are documented effects of WEF on their population sizes or dynamics. Our review is based on 35 sources, including peer-reviewed articles as well as grey literature. Effects of wind turbine facilities on grouse have been studied for eight species. Five grouse species have been found to collide with wind turbines, in particular with the towers. Fifteen studies reported behavioural responses in relation to wind turbine facilities in grouse (seven species), including spatial avoidance, displacement of lekking or nesting sites, or the time invested in breeding vs. non-breeding behaviour. Grouse were affected at up to distances of 500 m by WEF infrastructure, with indications of effects also at bigger distances. In six cases, a local reduction in grouse abundance was reported in areas with wind turbines, which possibly affected population size. Due to the differences in study duration and design, we cannot provide general conclusions on the effects of WEF on grouse populations. We advise applying the precautionary principle by keeping grouse habitats free of wind energy developments, in particular where populations are small or locally threatened. Future studies should preferably apply a long-term before-after-control-impact design for multiple areas to allow for more general conclusions to be drawn on the effects of WEF on rare and threatened wildlife species.

Keywords Tetraoninae · Collision · Displacement · Habitat suitability · Wind turbine · Before-after-control-impact design

Zusammenfassung

Der Einfluss von Windenergieanlagen auf Raufußhühner: eine systematische Literaturübersicht.

Der fortschreitende Ausbau von Windenergieanlagen und der dazugehörigen Infrastruktur weckt zunehmend Bedenken über deren Auswirkungen auf Wildtiere. Allerdings ist über die direkten und indirekten Auswirkungen von Windenergieanlagen auf die Sterblichkeitsrate, das Vorkommen und das Verhalten seltener und bedrohter Wildtierarten nur wenig bekannt. Wir haben eine systematische Literaturrecherche durchgeführt, um potentielle Auswirkungen von Windenergieanlagen auf

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Communicated by F. Bairlein.

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Raufußhuhn-Arten zusammenzufassen. Wir analysierten dabei, ob Raufußhühner (1) mit Windenergieanlagen kollidieren, (2) Verhaltensreaktionen in Bezug auf Windenergieanlagen zeigen und (3) ob Auswirkungen auf die Populationsgröße oder -dynamik dokumentiert sind. Insgesamt flossen 35 Quellen (sowohl begutachtete Artikel als auch graue Literatur) in unsere Analyse ein. Die Auswirkungen von Windenergieanlagen auf Raufußhühner wurden bislang für acht Arten untersucht. Bei fünf Raufußhuhn-Arten wurden Kollisionsopfer gefunden. Die Vögel kollidierten vor allem mit den Türmen der Windenergieanlagen und nicht mit den sich bewegenden Rotorblättern. 15 Studien (über 7 Raufußhuhn-Arten) berichteten über Verhaltensreaktionen in Bezug auf Windenergieanlagen, hierzu zählten eine räumliche Meidung und die Verschiebung von Balz- oder Nistplätzen. Effekte auf Raufußhühner zeigten sich bis zu einer Entfernung von 500 m von der Windenergieinfrastruktur, was auf weiträumige Auswirkungen hindeutet. In sechs Fällen wurde in Gebieten mit Windkraftanlagen ein lokaler Rückgang der Raufußhühner-Abundanz beobachtet. Aufgrund der unterschiedlichen Studiendauer und -methoden können wir keine generellen Rückschlüsse auf die Auswirkungen von Windenergieanlagen auf Raufußhuhn-Populationen ziehen. Insbesondere bei kleinen oder lokal bedrohten Populationen empfehlen wir, das Vorsorgeprinzip anzuwenden und daher Raufußhuhn-Lebensräume frei von Windenergieanlagen zu halten. Zukünftige Studien sollten vorzugsweise ein langfristiges Studiendesign anwenden, das Erhebungen vor und nach der Erstellung von Windenergieanlagen in mehreren Studiengebieten vorsieht, um allgemein gültige Schlussfolgerungen über die Auswirkungen von Windenergieanlagen auf Raufußhühner zu ermöglichen.

Introduction

Concerns about human-induced climate change and resultant energy policies around the globe have stimulated progress in fostering renewable forms of energy production, with wind energy being the fastest increasing part of this sector worldwide (Renewable Energy Network 2018). Moreover, a further increase in wind energy production is expected in the near future (GWEC 2018). Being a renewable energy source, wind power is generally considered a ‘green energy’ with comparatively low ecological impacts in terms of environmental pollution or water consumption (Saidur et al. 2011). However, deadly collisions between wild animals and wind energy facilities (WEF), in addition to their less obvious negative effects, have been highlighted as ecological drawbacks of their development (Kuvlesky et al. 2007; Drewitt and Langston 2008). Numerous animal taxa have been shown to be affected by WEF, ranging from insects (Long et al. 2011; Elzay et al. 2017) to birds (Drewitt and Langston 2006; De Lucas and Perrow 2017; Hötker 2017), bats (Rydell et al. 2010; Barclay et al. 2017), and marine (Koschinski et al. 2003) and terrestrial mammals (Rabin et al. 2006; Heldin et al. 2017). The most obvious impact of WEF on animals is death due to collision, as documented for birds and bats (Cryan and Barclay 2009; Krijgsveld et al. 2009; De Lucas and Perrow 2017). Birds have been found to collide both with the towers and the moving blades of WEF (Krijgsveld et al. 2009). A wide variety of species have been reported to collide with wind turbines, with susceptibility to collision being linked to morphological and behavioural traits (Smallwood et al. 2009; Marques et al. 2014). Mortality rates for animals vary widely between different wind parks, ranging from small numbers of deadly collisions for birds (De Lucas et al. 2008), which are not expected to affect population size, to higher numbers that possibly affect local population persistence (Hunt and Hunt 2006; Everaert and Stienen 2007). However, even low rates of mortality might yield distinct consequences at population levels in the case of *K*-strategists like vultures (Carrete et al. 2009), or for species of high conservation concern. A less obvious way in which wildlife are affected by wind turbines is a disturbance effect (Drewitt and Langston 2006; Hötker 2017). Here, we define as ‘disturbance’ when animals change their behaviour or are absent or less abundant in the presence of WEF than in their absence, e.g. based on areas with similar habitat conditions. Behavioural responses linked to WEF include changes in anti-predator behaviour (Rabin et al. 2006), territorial behaviour (Zwart et al. 2016) and habitat use (Hötker 2017). In the short term, animals may avoid the close vicinity of moving wind turbine blades, and thus, potentially, collision (Hoover and Morrison 2005); in the long term, habitats in the wider surroundings of a WEF may be avoided(Pearce-Higgins et al. 2009). Any avoidance of otherwise suitable habitat causes net habitat loss (Drewitt and Langston 2006; Plumb et al. 2018), and may result in reduced local populations (Pearce-Higgins et al. 2009). There is particular concern about such negative effects of WEF in locations where this is spatial overlap between areas which are highly suitable for wind power development with habitats of threatened species (Tabassum-Abbasi et al. 2014), especially in cases where alternative suitable habitat is not available or scarce.

Grouse (Tetraoninae) species have been shown to be particularly prone to collision mortality, including collisions with fences, power lines and ski lift cables (Catt et al. 1994; Baines and Summers 1997; Bevanger 1999; Bevanger and Brøseth 2004; Nopp-Mayr et al. 2016). Given the sensitivity of grouse to human recreational disturbances (Summers et al. 2007; Thiel et al. 2008,

Table 1 All grouse species listed in taxonomical order, their International Union for Conservation of Nature (IUCN) Red List of Threatened Species category (version 3.1; BirdLife International 2016) and their worldwide population trend as listed by the IUCN [Data compiled from http://www.iucnredlist.org]

Species		IUCN Red List category	Population trend
Siberian Grouse	*Falcipennis falcipennis*	Near threatened	Decreasing
Spruce Grouse	*Falcipennis canadensis*	Least concern	Stable
Franklin's grouse	*Falcipennis franklinii*	Least concern	Stable
Dusky Grouse	*Dendragapus obscurus*	Least concern	Decreasing
Sooty Grouse	*Dendragapus fuliginosus*	Least concern	Decreasing
Willow Ptarmigan	*Lagopus lagopus*	Least concern	Decreasing
Rock Ptarmigan	*Lagopus muta*	Least concern	Decreasing
White-tailed ptarmigan	*Lagopus leucura*	Least concern	Decreasing
Black Grouse	*Tetrao tetrix*	Least concern	Decreasing
Caucasian Black Grouse	*Tetrao mlokosiewiczi*	Near threatened	Decreasing
Black-billed Capercaillie	*Tetrao urogalloides*	Least concern	Decreasing
Western Capercaillie	*Tetrao urogallus*	Least concern	Decreasing
Hazel Grouse	*Bonasa bonasia*	Least concern	Decreasing
Chinese Grouse	*Bonasa sewerzowi*	Near threatened	Decreasing
Ruffed Grouse	*Bonasa umbellus*	Least concern	Decreasing
Greater Sage-grouse	*Centrocercus urophasianus*	Near threatened	Decreasing
Gunnison Sage-grouse	*Centrocercus minimus*	Endangered	Decreasing
Sharp-tailed Grouse	*Tympanuchus phasianellus*	Least concern	Decreasing
Greater Prairie Chicken	*Tympanuchus cupido*	Vulnerable	Decreasing
Lesser Prairie Chicken	*Tympanuchus pallidicinctus*	Vulnerable	Decreasing

2011; Braunisch et al. 2011; Storch 2013; Immitzer et al. 2014; Coppes et al. 2017, 2018) and to oil- and gas-producing facilities (Walker et al. 2007; Hovick et al. 2014; Bartuszevige and Daniels 2016), concerns about their response to WEF have arisen within the last decade (Pruett et al. 2009a, b; Braunisch et al. 2015). This is partially related to the fact that grouse habitats frequently overlap spatially with areas suitable for wind turbine development (Bright et al. 2008; Strickland et al. 2011; Braunisch et al. 2015). In conflicts between wind farm developers and nature conservationists, evidence-based risk assessments are needed. Despite extensive literature reviews on the general effects of WEF on birds and other wildlife (Kuvlesky et al. 2007; Drewitt and Langston 2008; Powlesland 2009; Marques et al. 2014; Wang and Wang 2015; Perrow 2017), a comprehensive review of the existing evidence on the effects of WEF on grouse is lacking. In this paper, based on a systematic search, we combined peer-reviewed literature with unpublished sources to explore whether grouse are affected by WEF. In this systematic review, we addressed the following questions: (1) are grouse susceptible to collisions with wind turbines? (2) Do grouse species show any behavioural responses to wind turbines, such as avoidance of areas close to wind turbine facilities? (3) Is there evidence of negative impacts of WEF on grouse populations? (4) Which recommendations can be derived from the existing literature with regard to mitigation of the negative effects of WEF on grouse, and for future impact assessments?

Methods

Study species

Grouse are galliformes of the Phasianidae family, comprising 20 species inhabiting a wide range of habitats across the northern hemisphere (Potapov and Sale 2013). As they are habitat specialists with requirements for a large habitat (Storch 1995), grouse have often been used as model species to study wildlife-habitat relationships, population dynamics, disturbance ecology and landscape ecology (Storch 2007). According to the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, seven grouse species are considered 'near threatened', 'vulnerable' or 'endangered' (BirdLife International 2016) (Table 1). Due to the large distribution range of most grouse species, they are not threatened on a global scale; however, the populations of 18 out of 20 species are considered to be decreasing (Table 1), with habitat deterioration and loss, as well as over-hunting, being major causes of population decline in several species (Storch 2007; BirdLife International 2016). Many grouse species show strong population declines leading to local extinctions, thus many are listed in national red data books (Storch 2007). There is a long history of grouse management with considerable efforts to protect local and national populations (Braun et al. 1977; Connelly et al. 2000; Hagen et al. 2004; Mollet et al. 2008; Suchant and Braunisch 2008; Braunisch and Suchant 2013), as well as reinforcements to support small populations or reintroductions in areas where the species became extinct (Reese and Connelly 1997; Snyder et al. 1999; Seiler et al. 2000; IUCN/SSC 2013; Siano and Klaus 2013).

Literature search

By applying a systematic literature search, our goal was to locate results from both peer-reviewed and unpublished sources, to synthesize evidence to answer our main questions. The search routines followed the guidelines of Pullin and Stewart (2006). We performed a search with a low specificity and sensitivity to include a wide variety of potentially relevant articles. We used a range of Boolean search terms to search the databases Google Scholar (URL https://scholar.google.com/) and the ISI Web of Knowledge (URL https://webofknowledge.com) and sorted the search results according to ‘relevance’. We selected and combined terms that covered parts of the names of all grouse species (e.g. grouse, Ptarmigan, Capercaillie and Prairie Chicken) as well as terms including those relevant to wind energy developments (i.e. ‘wind’, ‘turbine’, ‘energy’, ‘farm’). The search terms, listed as follows, were applied to all relevant search fields (title, abstract, full text, keywords): ‘grouse* AND wind* AND energy*’, ‘grouse* AND wind* AND farm*’, ‘grouse* AND wind* AND turbine*’, ‘Ptarmigan* AND wind* AND energy*’, ‘Ptarmigan* AND wind* AND farm*’, ‘Ptarmigan* AND wind* AND turbine*’, ‘Capercaillie* AND wind* AND energy*’, ‘Capercaillie* AND wind* AND farm*’, ‘Capercaillie* AND wind* AND turbine*’, ‘Prairie Chicken* AND wind* AND energy*’, ‘Prairie Chicken* AND wind* AND farm*’, ‘Prairie Chicken* AND wind* AND turbine*’.

In a second step, we read the abstracts of the publications listed in the results of each search engine to determine if the source was relevant to our study. A publication was considered relevant when a grouse species was mentioned in relation to wind power developments (both existing as well as new developments) and when it included new data (i.e. was not a review). If one search yielded more than 2000 results, only the abstracts of the first 2000 sources were read. The bibliographies of all relevant sources were searched for further relevant information and sources [i.e. constrained snowball sampling (Lecy and Beatty 2012)]. In cases of unpublished reports of which the results were published later in peer-reviewed literature, only the peer-reviewed articles were included. If reviews on the topic were found, these were read and checked for new relevant sources; when no new data were included in a review, it was not included in our study.

Results

The literature search yielded 35 sources relevant to our research questions. The majority of sources were articles in peer-reviewed journals ($n=19$, 54%), ten (29%) were unpublished reports, two (6%) were non-peer-reviewed M.Sc. theses and two (6%) were non-peer-reviewed publications. Furthermore, we included information from one (3%) online database and one (3%) website in the review (Table 2). The sources cover a wide geographic range in Europe and North America, and include data for eight different countries and eight grouse species. Four studies investigated two grouse species simultaneously, which resulted in a total number of 39 case studies. The majority of studies ($n=31$, 89%) were conducted in one single study area, whereas in the other four cases data of two to 18 study areas were included. The studies cover different time periods: one-third ($n=13$, 37%) of the studies were only carried out for 1 year, approximately another third ($n=10$, 29%) included data from 2 to 4 years, and the remaining studies ($n=12$, 34%) covered 5–15 years. Of the total studies on collision mortality ($n=13$, 37%), nine (69%) were conducted in a single year, and four (30%) were based on anecdotal observations (Fig. 1). The methods also distinctly varied between studies. For the assessment of collision mortality, standardized, systematic searches were applied in most (69%) cases; other methods included counting the number of males at lekking sites ($n=7$, 20%), searches for indirect signs of presence (i.e. feathers and droppings; $n=3$, 9%), bird censuses ($n=8$, 24%) or fitting birds with transmitters for telemetry ($n=9$, 26%) (Table 2).

Twenty-four studies investigated avoidance behaviour of grouse towards wind turbines, four of which included multiple grouse species. In 13 (46%) of the case studies investigating avoidance behaviour, data collection was done only after the construction of wind turbines, five thereof compared data from intervention (construction) areas with non-intervention areas (Table 2). In six cases (21%) the situation before and after the construction of a wind turbine tower at a given location was compared, while the remaining nine cases (32%) relied on a before-after-control-impact (BACI) design. Twenty-six studies (27 case studies) found a negative effect of wind turbines on grouse, nine studies (12 case studies) did not prove any effect of WEF on grouse. Eleven studies (11 case studies) exclusively investigated survival and vocalizations, or searched for collision victims after construction of wind turbines. In six case studies, the latter was combined with an avoidance behaviour study.

Table 2 All studies included in the systematic review ($n=35$), and the resulting number of species-specific case studies ($n=39$) for different grouse species included in a separate source

Species	Country	Study design[a]	Years (n)	Study sites (n)	Methods[b]	Data[c]	Effect	Impact[d]	Type	Source	Same source[e]
Black Grouse	Austria	A	1	2	Search	AN	Collision	Negative	NP	Deutz and Grünschachner-Berger (2006)	
Black Grouse	Austria	A	1	1	Presence mapping	S	Avoidance	Negative	PR	Grünschachner-Berger and Kainer (2011)	
Black Grouse	Austria	BA	8	1	Lek counts	S	Avoidance, collision	Negative	PR	Zeiler and Grünschachner-Berger (2009)	A
Black Grouse	Scotland	BA	15	7	Lek counts	S	Avoidance	Negative	PR	Zwart et al. (2015)	
Black Grouse	Scotland	BA	4	1	Lek counts	S	Avoidance	Negative	R	Percival et al. (2018)	D
Capercaillie	Germany	A	1	1	Search	AN	Collision	Negative	NP	Langgemach and Dürr (2019)	
Capercaillie	Sweden	A	5	1	Lek counts, search	S, AN	Avoidance, collision	Negative	W	Rönning (2017)-http://www.tjaderobs.se	
Capercaillie	Spain	BACI	5	1	Presence mapping	S	Avoidance	Negative	PR	González et al. (2016)	
Capercaillie	Spain	A	1	1	Search	AN	Collision	Negative	NP	González (2018)	
Capercaillie	Sweden	BACI	6	1	Presence mapping	S	Avoidance	Negative	R	Falkdalen et al. (2013)	B
Greater Prairie Chicken	USA	A	5	1	Lek counts	S	Avoidance	No effect	R	Vodehnal (2011)	C
Greater Prairie Chicken	USA	BACI	5	1	Telemetry	S	Avoidance	No effect	PR	McNew et al. (2014)	
Greater Prairie Chicken	USA	BACI	3	1	Telemetry	S	Avoidance	Negative	PR	Winder et al. (2014a)	
Greater Prairie Chicken	USA	BACI	3	1	Telemetry	S	Avoidance, survival	No effect	PR	Winder et al. (2014b)	
Greater Prairie Chicken	USA	BACI	3	1	Telemetry	S	Avoidance	No effect	PR	Winder et al. (2015)	
Greater Prairie Chicken	USA	A	8	1	Lek counts, behavioural	S	Avoidance	No effect	PR	Smith et al. (2016)	
Greater Prairie Chicken	USA	A	8	1	Telemetry	S	Avoidance	No effect	PR	Harrison et al. (2017)	
Greater Prairie Chicken	USA	A	8	1	Behaviour	S	Vocalizations	Negative	PR	Whalen et al. (2018)	
Greater Prairie Chicken	USA	A	2	1	Telemetry	S	Survival	No effect	PR	Smith et al. (2017)	
Greater Sage-grouse	USA	A	2	1	Telemetry	S	Survival	Negative	PR	LeBeau et al. (2014)	
Greater Sage-grouse	USA	BACI	1	1	Lek counts	S	Avoidance	Negative	PR	LeBeau et al. (2017a)	
Greater Sage-grouse	USA	AC	5	1	Telemetry	S	Avoidance	Negative	PR	LeBeau et al. (2017b)	
Rock Ptarmigan	Austria	BA	7	1	Lek counts	S	Avoidance	No effect	PR	Zeiler and Grünschachner-Berger (2009)	A
Ruffed Grouse	USA	A	1	1	Search	S	Collision	Negative	R	Jain et al. (2009)	
Ruffed Grouse	USA	BA	4	1	Census	S	Avoidance	Negative	R	Kerlinger (2002)	
Ruffed Grouse	USA	A	1	1	Search	S	Collision	Negative	R	Kerns and Kerlinger (2004)	
Sharp-tailed Grouse	Canada	A	1	1	Search	S	Collision	Negative	R	Brown and Hamilton (2004)	
Sharp-tailed Grouse	USA	A	5	1	Lek counts	S	Avoidance	Negative	R	Vodehnal (2011)	C
Sharp-tailed Grouse	USA	A	1	1	Search	S	Collision	Negative	T	Graff (2015)	
Sharp-tailed Grouse	USA	A	1	1	Telemetry	S	Avoidance	Negative	T	Proet (2017)	

Table 2 (continued)

Species	Country	Study design[a]	Years (*n*)	Study sites (*n*)	Methods[b]	Data[c]	Effect	Impact[d]	Type	Source	Same source[e]
Willow Ptarmigan	Norway	AC	3	1	Census, search	S	Avoidance, collision	Negative	R	Bevanger et al. (2010a)	
Willow Ptarmigan	Norway	A	1	1	Census, search	S	Avoidance, collision	Negative	R	Bevanger et al. (2010b)	
Willow Ptarmigan	Sweden	BACI	6	1	Census, search	S	Avoidance, collision	Negative	R	Falkdalen et al. (2013)	B
Willow Ptarmigan	Scotland	BACI	9	1	Census	S	Avoidance	No effect	PR	Meek et al. (1993)	
Willow Ptarmigan	Scotland	A	1	1	Search	S	Collision	Negative	R	Bioscan (2001)	
Willow Ptarmigan	Scotland	AC	NA	12	Census	S	Avoidance	No effect	PR	Pearce-Higgins et al. (2009)	
Willow Ptarmigan	Scotland	AC	3	1	Census	S	Avoidance	No effect	PR	Douglas et al. (2011)	
Willow Ptarmigan	Scotland	BA	4	1	Lek counts	S	Avoidance	No effect	R	Percival et al. (2018)	D
Willow Ptarmigan	Scotland	AC	3	18	Census	S	Avoidance	Negative	PR	Pearce-Higgins et al. (2012)	

NP Non-peer-reviewed article, *PR* peer-reviewed article, *R* report, *T* thesis, *W* website

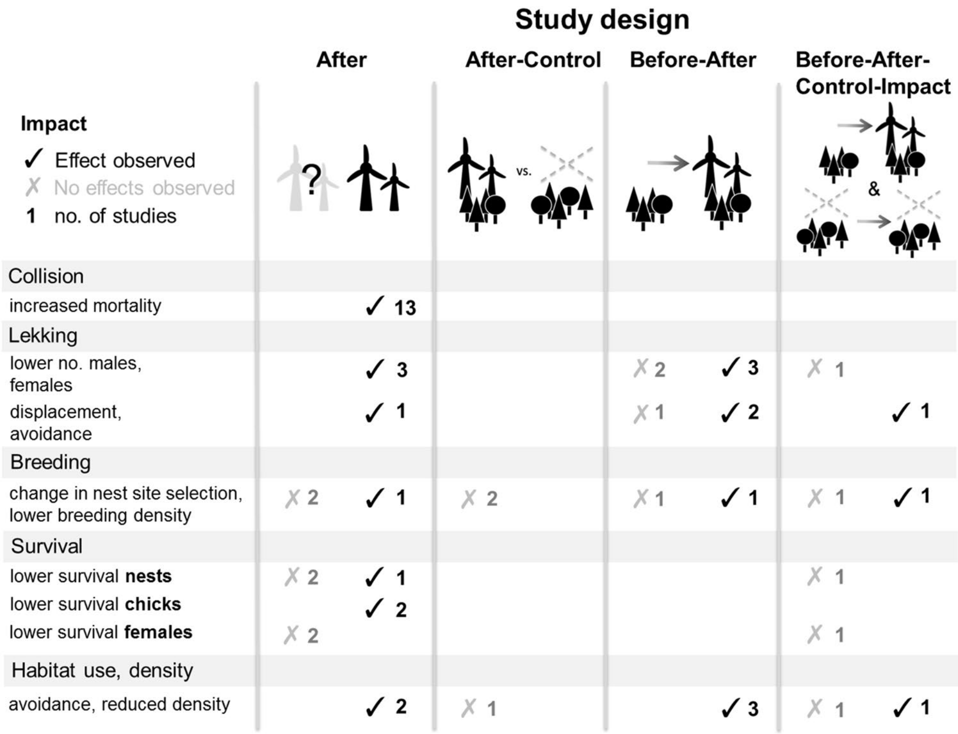
[a] Study performed after the construction of wind turbines (*A*); before and after construction (*BA*); after construction with a control area (*AC*); before, after and with a control area (before-after-control-impact; *BACI*)

[b] Search for collision victims (*Search*), habitat use mapped using evidence of presence (*Presence mapping*), number of birds at a lekking site counted (*Lek counts*), birds fitted with transmitters (*Telemetry*), behavioural observations recorded (*Behavioural*), bird censuses carried out (*Census*)

[c] Systematic (*S*) survey design vs. non-systematic, anecdotal (*AN*) results

[e] Negative impact of wind energy on grouse (e.g. avoidance or collision; *Negative*); no effect of WEF on grouse found (*No effect*)

[e] Where two grouse species were investigated in the same study, the source is listed twice and is indicated by the *same letter*



	After		After-Control	Before-After		Before-After-Control-Impact	
Collision							
increased mortality		✓ 13					
Lekking							
lower no. males, females		✓ 3		✗ 2	✓ 3	✗ 1	
displacement, avoidance		✓ 1		✗ 1	✓ 2		✓ 1
Breeding							
change in nest site selection, lower breeding density	✗ 2	✓ 1	✗ 2	✗ 1	✓ 1	✗ 1	✓ 1
Survival							
lower survival **nests**	✗ 2	✓ 1				✗ 1	
lower survival **chicks**		✓ 2					
lower survival **females**	✗ 2					✗ 1	
Habitat use, density							
avoidance, reduced density		✓ 2	✗ 1		✓ 3	✗ 1	✓ 1

Fig. 1 Overview showing the number of studies with different study designs (after, after-control, before-after or before-after-control-impact) and the recorded effects of wind energy facilities [with effect (black), without effect (grey)] separated by the type of impact (collision, lekking behaviour or number of individuals at the leks, breeding ecology, survival or habitat use)

Table 3 Grouse species which have been found to collide with wind turbine towers

Species	Countries	No. of documented collisions	Source
Black Grouse	Austria	6	Deutz and Grünschachner-Berger (2006); Zeiler and Grünschachner-Berger (2009); Langgemach and Dürr (2019)
Capercaillie	Germany, Sweden, Spain	8	Rönning (2017); González (2018); Langgemach and Dürr (2019)
Ruffed Grouse	USA	3	Kerns and Kerlinger (2004); Jain et al. (2009)
Sharp-tailed Grouse	USA	6	Brown and Hamilton (2004); Graff (2015)
Willow Ptarmigan[a]	Sweden, Norway, Scotland	74	Bioscan (2001); Bevanger et al. (2010a, b); Falkdalen et al. (2013)

[a] Willow Ptarmigan includes three subspecies (*Lagopus lagopus lagopus, Lagopus lagopus scotica, Lagopus lagopus variegatus*)

Collisions

Our literature search yielded 12 reports and one publicly available database (Langgemach and Dürr 2019) addressing collisions of five grouse species with wind turbines (Table 3). Overall, as inferred from the locations of carcasses, grouse have been found to collide with turbine towers rather than rotor blades.

Six Black Grouse collision victims, including both males and females, were reported for Austria (Deutz and Grünschachner-Berger 2006; Zeiler and Grünschachner-Berger 2009; Langgemach and Dürr 2019). All the carcasses were found very close to the towers of wind turbines indicating that the birds flew against the tower and not against the moving rotor blades (Zeiler and Grünschachner-Berger 2009). In two Black Grouse, post-mortems revealed typical signs of collision traumata [e.g. blunt trauma and internal bleeding (Deutz and Grünschachner-Berger 2006)]. In two countries, Western Capercaillie (henceforth ‘Capercaillie’) were found dead close to wind turbine towers: in Spain, a female Capercaillie (*Tetrao urogallus cantabricus*) was found next to a turbine tower by wind park workers (González 2018); in Sweden, six Capercaillies, both males and females, that had collided with WEF, were detected in four different wind parks in different locations (Rönning 2017). The remains of a Capercaillie female were found close to a wind turbine tower in Brandenburg, Germany (Langgemach and Dürr 2019), where collision with the wind turbine tower was suspected. However, this could not be verified due to the state of decomposition of the carcass (Zimmermann, personal communication). In Scotland, three Willow Ptarmigan (previously Red Grouse *Lagopus lagopus scotica*) collision victims were found near wind turbines. Examination of the bodies indicated that two had flown into the turbine tower and one most likely collided with moving turbine blades (Bioscan 2001). Three Ruffed Grouse individuals were recorded as collision victims in the state of New York, USA (Jain et al. 2009), three Sharp-tailed Grouse in North Dakota, USA (Graff 2015), and a further three Sharp-tailed Grouse in a wind park in Canada (Brown and Hamilton 2004). Willow Ptarmigan have been documented to collide with wind turbine towers in Sweden (Falkdalen et al. 2013), Norway (Bevanger et al. 2010a, b) and Scotland (Bioscan 2001). With a total number of 74 individuals involved in collisions, Willow Ptarmigan was the most common collision victim of a total of 26 bird species found in a Norwegian study (Bevanger et al. 2010a).

Behavioural responses and population dynamics

Lek site selection and lekking behaviour

Seven studies (ten case studies) examined the effects of WEF on grouse by counting them at lekking sites. During the construction work of a wind park in the Austrian Alps (performed during the lekking season), Zeiler and Grünschachner-Berger (2009) reported only a minimal behavioural response of male Black Grouse to construction activities near a lekking site (Zeiler and Grünschachner-Berger 2009). However, the number of males on the same lekking site was reported to decrease from 12 males before turbine construction to zero over a 2-year period after construction (Zeiler and Grünschachner-Berger 2009). The authors also suggested that sounds produced by the wind turbines masked the singing of cocks, reducing the distance at which Black Grouse display calls could be heard (Zeiler and Grünschachner-Berger 2009). Zwart et al. (2015) did not find a significant decrease in the total number of displaying males after WEF construction at seven Black Grouse lekking sites in Scotland over a period of 1–7 years before and 2–8 years after construction. However, they did find that lekking sites, initially located within 500 m of the wind turbines ($n = 4$ lekking sites), were further from them after construction, from a median distance of 250 m before construction to 803 m after construction. Interestingly, even lekking sites located at about 1000 m were found further away from the turbines after construction (Zwart et al. 2015). In a different wind park in Scotland, Black Grouse numbers were higher before construction (nine lekking males) and in the year of construction (eight males), compared to 2 years after construction (four females and zero males, respectively) (Percival et al. 2018). In the same wind park, Willow Ptarmigan (*Lagopus lagopus scotica*) numbers fluctuated between years, with low numbers both before and after the construction of the wind park (Percival et al. 2018). In Sweden, the number of males at a Capercaillie lekking site decreased from ten to four over a 7-year time period after construction of wind turbines in its direct vicinity, and was also relocated 600 m away from the nearest wind turbine (Rönning 2017). The number of displaying Rock Ptarmigan decreased from three before construction to zero after construction of a wind park over a period of 3 years in the Austrian Alps (Zeiler and Grünschachner-Berger 2009).

Vodehnal (2011) documented counts of displaying Greater Prairie Chickens after the construction of a wind park in Nebraska, USA, where the number decreased by 34% over a 5-year time period. Winder et al. (2015) observed a lower probability of lek persistence within 23 investigated leks in Kansas, USA; the probability of lek persistence was ~ 0.5 for leks within a 1-km zone around WEF, ~ 0.9 for leks within a 3-km zone, and 0.95 for leks farther than 6 km away, indicating that wind turbines caused Greater Prairie Chickens to abandon leks close to wind turbines. Based on detailed behavioural observations at Greater Prairie Chicken leks near an existing wind park in Nebraska, Smith et al. (2016) found no differences in the number of females close to the wind park (minimum distance between a lek and a wind turbine = 700 m) compared to areas located further away. However, male behaviour was affected at the lekking site: more non-displaying behaviour (i.e. standing, running, walking, flying, feeding, preening) was found with increasing distance from wind turbines, which might have been caused by reduced avian predator densities closer to the wind turbines (Smith et al. 2016). At the same wind park, Whalen et al. (2018) found vocalisations of males at lekking sites within 1 km of wind turbines to have higher sound pressure levels and shorter durations compared to those of males at lekking sites further away. However, LeBeau et al. (2017a) did not detect significant differences in numbers of Greater Prairie Chicken males at lekking sites compared with control sites before and after the construction of a wind park in Wyoming, USA.

Nest site selection and survival

Twelve studies investigated the effects of WEF on grouse nest site selection, breeding densities or survival rates. When combining bird survey data from 12 study sites, Pearce-Higgins et al. (2009) did not discover a significant reduction of breeding densities of Willow Ptarmigan (*L. lapogus scotica*) across Scotland. Similarly, Douglas et al. (2011) reported no significant change in breeding densities of Willow Ptarmigan after construction of a wind park and no differences between a control site and a wind park site. Tagging Willow Grouse with radio transmitters on the Norwegian island of Smøla revealed unexpectedly low survival rates of tagged birds ($n = 34$) in the wind park, compared to other areas; the majority of deaths, however, were attributed to avian predators (Bevanger et al. 2010a).

Six studies in the USA surveyed Greater Prairie Chickens via telemetry to study potential effects of wind turbines on this species (McNew et al. 2014; Winder et al. 2014a, b, 2015; Harrison et al. 2017; Smith et al. 2017). In Kansas, no difference in nest site selection or nest survival was found when comparing nests before and after the construction of wind turbines (McNew et al. 2014). Although the behaviour of females was affected in terms of increased home range sizes after construction of the wind turbines and an increasing avoidance of areas at decreasing distance to the turbines (Winder et al. 2014a), no effect on the survival of adult females could be found (Winder et al. 2014b). By tagging 64 Greater Prairie Chickens and searching for nests near the same wind park, Harrison et al. (2017) found that the main drivers of nest site selection and nest survival were habitat and landscape predictors and not parameters related to the wind turbines. They did, however, find that Greater Prairie Chicken avoided nesting close to roads, which might be more numerous in the course of wind turbine construction (Harrison et al. 2017). Smith et al. (2017) used telemetry to study spatial variation in the survival of 62 female Greater Prairie Chickens, and camera traps as well as point counts to monitor mammalian as well as avian predator occupancy within a 10-km radius around a wind park in Nebraska. At this scale, neither spatial avoidance of avian predators nor differences in daily survival rates of female Prairie Chickens were related to the WEF were found. Although the capture index for mammals was significantly lower with increasing proximity to the WEF, the capture frequency of the most important predator of adult chickens, the Coyote (*Canis latrans*), was not affected by wind turbines. In a study in Wyoming, LeBeau et al. (2014) tagged 31 female Greater Sage-grouse with radio transmitters to study potential effects of an already existing wind park. Whereas increased predation rates of nests and broods were found with increasing vicinity to the wind park, no effect on female survival was found. During summer, 346 females seemed to increase their distance to the wind turbines over the study period (6 years), indicating a possible time lag in their response; contrary, for nest site selection, habitat conditions were decisive while it was not influenced by the wind park when compared to a control site (LeBeau et al. 2017b). Female survival tended to decrease with the percentage of area, in a 1.2 km^2 surrounding, covered by the wind park, indicating that the surface occupied by a construction might be more important than the pure distance to the nearest wind turbine (LeBeau et al. 2017b). By tagging 135 Columbian Sharp-tailed Grouse (*Tympanuchus phasianellus columbianus*) with radio transmitters, Proet (2017) studied whether the number of, and distance to, WEF affected nest site selection, nest survival and chick survival. No effect on nest site selection or nest survival was found, but chick survival was affected: when ≥ 10 wind turbines were within 2.1-km of the nest, chick survival was reduced by 50% (Proet 2017).

Habitat use and population densities

Nine studies (ten case studies) focussed on the effects of WEF on grouse habitat use and population densities. Grünschachner-Berger and Kainer (2011) mapped indirect evidence of Black Grouse (i.e. feathers, droppings) for a wind park in the Austrian Alps to study the effects of a WEF on habitat use. They found less use of highly suitable habitat within 500 m of the wind turbines than expected based on a Black Grouse habitat model (Grünschachner-Berger and Kainer 2011).

In Spain, transect counts during winter revealed reduced numbers of indirect signs (i.e. feathers, droppings) of Capercaillie compared to the pre-construction year in the 4 years after the construction of a wind park (González and Ena 2011; González et al. 2016). In the control area (i.e. similar habitat without WEF) 1.5 km away, the numbers did not change over the same time period (González and Ena 2011; González et al. 2016). Falkdalen et al. (2013), using pointing-dogs, found reduced numbers of Capercaillie after construction of a wind park in Sweden compared to a control area.

Using systematic counts on line transects, Bevanger et al. (2010a) found no significant differences in the spring and autumn densities of Willow Ptarmigan between a wind park and a control area (i.e. without wind turbines) on the Norwegian island of Smøla. Furthermore, Willow Ptarmigan used areas within the wind park and did not leave the wind park after construction (Bevanger et al. 2010a). Similarly, no differences in Willow Ptarmigan densities were found between a wind park and the reference area in another Norwegian study area (Bevanger et al. 2010b). Using bird census data from before and after the construction of a wind park in Sweden, Falkdalen et al. (2013) found reduced numbers of territorial Willow Ptarmigan after construction. In contrast, no negative effect of a wind park on Willow Ptarmigan (*L. lapogus scotica*) was found using bird census on the Orkney islands in Scotland (Meek et al. 1993). In another Scottish study, however, Pearce-Higgins et al. (2012) reported that the number of Willow Ptarmigan significantly decreased during the construction of a wind park. However, the numbers returned to pre-construction levels within 1 year after construction (Pearce-Higgins et al. 2012), suggesting only short-term avoidance of the WEF during the construction phase. A single Ruffed Grouse was detected in bird censuses before the construction of a wind park in Vermont, USA, which then disappeared from the area (Kerlinger 2002). Whether this disappearance was related to the wind turbine construction, however, was unclear. Numbers of male Sharp-tailed Grouse were also found to decrease over a 6-year time period after construction of a wind park in Nebraska (Vodehnal 2011).

Discussion

Our literature review highlights documented grouse collisions with wind turbine towers and behavioural effects of WEF on grouse such as changes in their vocalisations or habitat use. Some studies have even ascribed negative effects on population size to wind turbines. However, it is important to note that the results between studies differ, and that some studies did not yield any evidence for negative effects of WEF on grouse. This might be partly due to the large range of sample sizes, study methods, study duration and study design, which have implications for the significance and informative value of the studies. Consequentially, considerable uncertainty remains about the generality of the conclusions and their significance for population biology when drawn from local-scale, short-term studies (Stewart et al. 2007). Apart from these methodological factors, the wide variety of habitats occupied by different species, ranging from prairie to forest and tundra ecosystems, as well as differences in local habitat conditions (i.e. habitat quality, amount and connectivity), have to be considered when evaluating the impacts of WEF on grouse. Furthermore, there is a wide variety of response types, which might be related to differences in the different grouse species' life histories and ecology.

Collisions

At least five species of grouse have been reported to collide with wind turbines (Table 3). Because grouse generally fly at a relatively low height above the ground, and thus mainly stay below the area covered by a wind turbine's rotors, they are reportedly more prone to collision with turbine towers than with the rotor blades. Poor visibility of the towers due to weather conditions [e.g. fog (but see Falkdalen et al. 2013)] or tower colour (T. Nygard, personal communication) may affect collision risk. The higher mortality compared to that recorded for natural conditions reported for Willow Ptarmigan on a Norwegian island might have had negative effects at the population level. For other species, only low numbers of collision victims were found. However, the study designs and protocols were inconsistent, and in cases of non-systematic, anecdotal reports of collisions, information on scavenger impacts on detection rates and other biases (see Bevanger 1995; Brown and Drewien 1995) is lacking. Thus, it remains unclear under what conditions and how often collisions occur, and if even a low reduction in survival rate of grouse associated with WEF can have a significant impact on a population, as observed in other long-lived bird species (Carrete et al. 2009).

Behavioural responses and population dynamics

A wide range of behavioural responses of grouse to WEF has been found in different studies, which is in line with reviews on other bird taxa (Hötker 2017). These responses include differences in vocalisations, which are most likely due to noise caused by wind turbines, increased home range sizes and avoidance behaviour. Reduced use of areas within 500 m of WEF was reported for Black Grouse in Austria and in Scotland. Contrary to the situation in Austria, the number of lekking males was not negatively affected in Scotland. This might be explained by differences in landscape patterns. in the Alps, Black Grouse mainly live around the upper tree line (Patthey et al. 2012; Sachser et al. 2017), a relatively narrow altitudinal zone where conditions 500 m up or down the slope are unsuitable for lekking. As a consequence, birds avoiding the immediate vicinity of WEF at this altitude for lekking lacked alternative nearby sites and leks were abandoned. This suggests that landscape characteristics might largely determine how grouse populations are affected by WEF. Hitherto observed distances of displacement of grouse species due to WEF range between 500 and 600 m. For most other bird species (i.e. 44 of 47 species), the median avoidance distance of WEF ranges between 0 (no avoidance) and 200 m (Hötker 2017). There are even indications that grouse are affected over distances of more than 1000 m; this is particularly likely for grouse species with relatively large home ranges [e.g. Capercaillie and Black Grouse can have home ranges of several hundreds of hectares (e.g. Storch 1995; Watson and Moss 2008; Coppes et al. 2017)]. Differences between grouse and other species might also be caused by differences in habitat or study design. The contradictory findings on temporally variable effects of WEF on grouse indicate that their impact could be species specific and differ in magnitude according to their construction and operation.

Which particular factors related to WEF development influence grouse remains unclear. These could be factors related to the actual presence of wind turbines, such as moving blades, noise or flickering shadows. Experiments with captive birds have shown a fear response to novel objects (Richard et al. 2008), therefore grouse might be affected by the mere presence of a wind turbine in their habitat. Greater and Lesser Prairie Chickens have been shown to avoid powerlines, which is suggested to be due to their potential as perches for raptors (Pruett et al. 2009b). This might not be the case for forest-dwelling grouse, however, since perches are abundant in forests. Forest clearings, however, have been associated with increased nest predation (King et al. 1998), which can be higher in fragmented forests (Van der Haegen and De Graaf 1996); both clearings and access roads, which are associated with the construction of wind turbines in forests, can be related to predation. Road construction associated with WEF can affect animal behaviour and cause fragmentation of natural habitats (e.g. Trombulak and Frissell 2000). Moreover, road construction can lead to additional human use of an area for hunting (Gratson and Whitman 2000), as well as for recreation, which can reduce an animal's use of an area due to disturbance (Storch 2013; Coppes et al. 2017, 2018). Furthermore, roads can increase the presence of mesopredators (Frey and Conover 2006), which can in turn affect the prey species living in an area (i.e. grouse).

With respect to predators, two different scenarios can be proposed with respect to the presence of WEF. On the one hand, grouse predator densities might locally increase due to enhanced food supply in the form of carcasses of collision victims (cf. Bevanger 1994) or habitat alterations (i.e. more clearings and roads). On the other hand, raptors themselves might undergo distinct declines due to collision mortality (Madders and Whitfield 2006; Bellebaum et al. 2013), or might avoid wind parks (Whitfield and Madders 2006; Johnston et al. 2014). Whereas the first scenario could raise predation rates in local grouse populations, the second one may reduce them. Mammalian predators, however, are not expected to suffer from higher mortality rates in wind parks. This potential difference, along with the locally varying compositions of raptors and mammalian predators, may explain why we did not find consistent effects in the grouse literature that we reviewed.

Habitat alteration and loss due to wind energy infrastructure

For the construction of WEF, roads have to be constructed or widened, and areas for construction of the turbine towers are cleared of vegetation (Silva and Passos 2017). This can reduce or alter vegetation (Silva and Passos 2017), and lead to more edge and openings in a forest. The direct destruction of habitat due to WEF is usually relatively small (i.e. up to 0.5 ha per WEF) (Langston and Pullan 2003; Drewitt and Langston 2006). The construction of roads associated with WEF might, however, cause fragmentation of habitats, changes in human disturbance and changes in predator habitat use. The fact that female Greater Sage-grouse survival was affected by the percentage area covered by wind parks (LeBeau et al. 2017b) might be attributed to habitat loss; the respective effects on grouse population dynamics remain, however, unclear.

Recommendations for future studies

Negative effects of WEF are well documented for several species of grouse, thus, concerns about wind park construction within grouse habitats are highly justified. However, inconsistencies in applied study methods and designs are obvious constraints for deriving general and widely applicable conclusions from the studies that we reviewed, and can, in turn, lead to confusing information for land managers or the general public (Anderson et al. 1999; Fox et al. 2006). Evidence for long-term population level effects of WEF is scarce. To provide more widely applicable results, future studies should be harmonized with respect to design and sampling protocol. Moreover, some of the applied methods can be criticized, e.g. lek counts might underestimate grouse population numbers (Jacob et al. 2010; Lentner et al. 2018), so future studies should preferably use robust methods to assess population effects as well as changes in habitat use around WEF. There is an urgent need for more studies with a BACI design, which is considered to provide more informative and robust results than studies focusing only on pre- and post-construction phases or comparisons with a control site (cf. Fig. 1). As there might be a time lag in the reaction of grouse to infrastructure developments and related disturbances (Harju et al. 2010), it is important that studies are performed over a number of years, ideally more than 10, to include natural population fluctuations (Lindström et al. 1996). Short-term studies may not be adequate to record the demographic consequences on grouse populations of new WEF constructions (Harju et al. 2010). Especially in fragmented populations and metapopulations, avoidance of wind turbines by grouse on small and isolated habitat patches (i.e. stepping stones) could potentially affect the exchange of individuals between sub-populations. So far, no study has assessed if, and how, wind turbines affect the dispersal behaviour of grouse.

Since avoidance behaviour in relation to anthropogenic disturbance has been shown to be modulated by habitat suitability (Coppes et al. 2018), studies addressing this issue should take into account local habitat suitability, also when studying the effects of wind turbines. Contrary to other taxonomic or ecological groups of birds (Hötker 2017), grouse are affected by collision mortality and show displacement responses. Thus, both these impacts of WEF on grouse populations should be better addressed in future studies. Especially collision fatalities and the resultant consequences for population dynamics should be addressed more explicitly and be based on systematic surveys in future studies, as the current data are quite scarce, anecdotal and fragmentary.

Conclusion

In the northern hemisphere, wind energy is currently a central element of many national policies to increase the production of renewable energy (GWEC 2018). Thus, the currently observed expansion of wind parks is expected to continue (GWEC 2018), and will have an impact on wildlife and their habitats, including grouse. We suggest that mitigating measures aimed at lowering the direct and indirect impacts of existing WEF in grouse habitats should account for the conservation status of the affected population. The Working Group of German State Bird Conservancies advises that wind turbines should not be constructed within 1000 m of areas where grouse (i.e. Capercaillie, Black Grouse, Hazel Grouse and Rock Ptarmigan) occur, and that corridors between subpopulations should be kept free of wind turbines (LAG 2015). For non-threatened populations, mitigation measures could include habitat improvement to compensate for habitat loss and displacement due to WEF construction (e.g. increased use of access roads to WEF by hunters and recreationists). Another mitigation measure may be painting wind turbine towers black, as this was found to reduce Willow Ptarmigan collision numbers in Norway (T. Nygard, personal communication). According to the precautionary principle (Myers 1993), we recommend forgoing planning agreement for wind turbines in areas with small or locally threatened grouse populations. Furthermore, there should be stringent application of the BACI design in studies examining the effects of WEF construction on grouse habitats, and the results of these studies should be made publicly available.

Funding This study was funded by the Ministry of the Environment, Climate Protection, the Energy Sector Baden-Württemberg and the Ministry for Rural Affairs and Consumer Protection Baden-Württemberg; it was co-funded by Elektrizitätswerk Mittelbaden, Energie Baden-Württemberg, Enercon, the German Wind Energy Association, Ökostromgruppe Freiburg, the Swedish Environmental Protection Agency (Vindval) and Windkraft Schonach. The funding organisations had no influence on the manuscript, study design, methods or interpretation of the results.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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