

Capercaillie and Wind Energy

An international research project

JULIA TAUBMANN, JOY COPPES & HENRIK ANDRÉN

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Preface

The Vindval research programme is a collaboration between the Swedish Energy Agency and the Swedish Environmental Protection Agency that aims to develop and communicate science-based facts about the impacts of wind power on humans, nature and the environment. The programme's first three phases in 2005–2018 produced nearly 50 research papers and four so-called synthesis reports. In the synthesis reports, experts compile and assess overall research results and experiences regarding the effects of wind power, both nationally and internationally, in four areas: human interests, birds and bats (updated in 2017), marine life and land mammals. The results have provided the basis for environmental impact assessments and for the planning and permitting processes associated with wind power installations.

Results from the programme will also be useful in oversight and monitoring programmes, as well as guidance for government agencies.

The current phase of the programme is focused on planning procedures and the trade-offs between environmental and socio-economic interests:

The projects in this phase will develop methods and tools to elucidate these trade-offs.

Vindval sets high standards for the scientific review of research applications and research results, as well as for decisions on approving reports and publishing results.

This report is part of an international five-year research project, “Capercaillie and Wind Energy” that investigates whether there are scientifically verifiable effects of wind turbines on capercaillie, as well as what these effects are. The project was financed by Vindval and the Swedish Environmental Protection Agency.

This report has been written by Julia Taubmann (project manager, Sweden), University of Freiburg, Wildlife Ecology and Management and FVA-Wildlife Institute, Forest Research Institute of Baden-Württemberg, Germany, Joy Coppes, (project manager, Germany and Austria) FVA-Wildlife Institute, Forest Research Institute of Baden-Württemberg, Germany and Henrik Andrén (project leader, Sweden), Swedish University of Agricultural Sciences.

The authors are responsible for the content, conclusions and recommendations.

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Summary

Do wind turbines influence forest grouse and specifically capercaillie (*Tetrao urogallus*)? To-date this question is much discussed and difficult to answer, as few studies are available and standards for post-constructional or Before-After-Control-Impact (BACI) designs are not always followed. The international research project “Capercaillie and wind energy” investigated six study areas in Germany, Austria and Sweden whether effects of wind turbines on capercaillie can be measured using five approaches in an BACI or post-constructional design. In Sweden, capercaillie were studied in the Jädraås wind park for a 4-year post-construction period. We addressed potential impacts of wind energy facilities (WEF) on the species’ individual and population level, by studying resource and habitat selection, movement ecology, reproduction success, risk of predation and stress physiology. We could not find significant differences in mean capercaillie sign density between WEF and control sites, nor between before and after construction sites, when analysing all European study sites. Within the WEF sites, however, habitat selection was reduced up to approximately 650 m distance to wind turbines overall study areas. Our study further revealed a decrease in resource selection within a distance of approximately 865 m around WEF (784 – 1025 m), when individual birds were tracked with GPS transmitters (N = 18) in Sweden. In addition, turbine shadow, turbine noise, turbine density, turbine visibility and turbine access roads were found to decrease resource selection, in lekking and summer season with varying magnitude. We found individual behaviour to be influenced by turbine visibility, as movement speed was discovered to slow down while wind turbine visibility increased (up to 6 WEF). The high correlation between WEF predictors (distance, shadow, noise, visibility), prevented to clearly pinpoint single factors. In contrast, additional methods addressing stress physiology, reproduction success and risk of predation did not reveal any relation to WEF. If our findings bear any fitness costs for capercaillie and affect population survival is beyond the study’s capabilities and also strongly depends on the species’ regional and national status. For Sweden, we propose to apply our estimated distance threshold of 865 m to at least capercaillie leks and summer habitats under consideration of the local forestry, to minimize the risk of negative population-level effects by the presence of wind turbines and their accompanying infrastructure. Future studies should apply reproduction and predator track monitoring on multiple impact-control areas, to underpin or reject a potential WEF influence on capercaillie populations. Finally, direct mortality of capercaillie by turbine collisions is another factor future research should try to answer.

1 Introduction

Coppes J, Braunisch V, Bollmann K, Storch I, Mollet P, Grünsbachner-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.

To counter anthropogenic climate change, renewable energy sources are increasingly being exploited worldwide (Renewable Energy Network 2018). Currently the fastest growing renewable energy source is on-shore wind power (GWEC 2018). According to the goal of the Swedish government to reach 100 % renewable electricity production by 2040, wind turbines are constructed at high pace. The annual Swedish wind energy statistics reported about 4495 wind turbines producing 27 Terawatt hours per year (TWh) for 2020, which contributed 17 % to the total energy production (Ekonomifakta 2020). Compared to a previous Swedish report about the effects of wind energy facilities (WEF) on birds and bats (Rydell et al. 2017), the wind turbine construction especially onshore led to almost two-fold higher annual energy production since 2016.

In areas where high wind speeds overlap with areas containing species of conservation concern conflicts can arise. The direct and indirect influences of WEF have been mainly studied for birds (De Lucas and Perrow 2017; Hötker 2017; Rydell et al. 2017), bats (Barclay et al. 2017; Rydell et al. 2011) and marine and terrestrial mammals (Koschinski et al. 2003; Helldin et al. 2017). Despite the numerous studies reporting that WEF do affect a wide range of taxa, the magnitude of impact on the local and national populations is often hard to estimate. In many intervention projects species protection is only addressed using the precautionary principle, and long-term effects cannot be properly assessed. In particular, there is a large research deficit for forest-dwelling species (Hötker et al. 2005; Hovick et al. 2014). A fundamental problem of most studies concerning wind energy facilities, to-date, is that hardly any are based on a Before-After-Control-Impact design (Conner et al. 2016), but focus mainly on direct collisions, or habitat use alone (Hötker et al. 2005; Hovick et al. 2014). In the conflict between wind energy and species protection, direct effects, such as collisions of birds and bats with the turbines and blades, have been the main focus of research and intervention planning in recent years (Arnett et al. 2008; Loss et al. 2013). The effects of collisions, causing increased mortality, are not classified as population-relevant for bird species in general (Osborn et al. 2000). But especially for species with high collision rates (Hunt and Hunt 2006; Everaert and Stienen 2007), with high conservation concern or *K*-strategists as vultures (Carrete et al. 2009), even low collision rates can impact population size. Indirect effects, such as habitat loss and avoidance, as well as fragmentation of habitats and wildlife corridors, are often more difficult to quantify and as such receive less attention (Kuvlesky et al. 2007). However, these possible influences on the survival of wildlife populations are considered to be particularly

serious. Emigration from and avoidance of important and high-quality habitats can negatively impact energy resources and reproductive rates of many individuals, and could thus affect the whole population (Hoover & Morrison 2005; Pruett et al. 2009; Winder et al. 2014b).

Animals which typically exhibit high site fidelity, such as many grouse species (Tetraonidae), are particularly vulnerable. They may give up traditional lekking sites and breeding areas, which could prove detrimental (Walker et al. 2007; Zeiler and Grünschachner-Berger 2009; Harju et al. 2010; Winder et al. 2014a). Five out of eight studied grouse species were found to collide with wind turbine towers (Coppes et al. 2020a). For one grouse species, painting the base of turbine towers black reduced collisions by 48 % (Stokke et al. 2020). For seven grouse species, behavioural responses to WEF were found including avoidance of areas up to 500 m distance, displacement of leks and breeding sites (Coppes et al. 2020a). Both in Central-Europe and Scandinavia there is an overlap between habitat of grouse species and high-wind speed areas, therefore increasing numbers of wind turbines are constructed in their habitats (Suchant & Braunisch 2008). Even though capercaillie (*Tetrao urogallus*), as well as the closely related black grouse (*Lyrurus tetrix*), were influenced by the construction of wind turbines in their habitats (Zeiler and Grünschachner-Berger 2009; González and Ena 2011; González et al. 2015), the severity on individual and population level is still unclear. Capercaillie populations seem stable in the majority of their wide Eurasian distribution range (Coppes et al. 2015; BirdLife International 2016), but are locally fragmented, declining or threatened (Storch 2007) across Europe, and therefore red-listed in many central European countries. Since the construction of WEF is expected to further expand within the next decades, it is highly important that this does not conflict with species protection, especially since capercaillie is considered an umbrella species for avian biodiversity (Suter et al. 2002). They may be driven to travel larger distances to find appropriate seasonal habitat, ideally of similar quality to their previous habitat. This can be particularly energetically demanding during chick rearing. However, direct evidence is still lacking.

To inform future policymakers and to ensure that wind power can be developed while considering the effects on capercaillie, more detailed knowledge about possible influences on individual and population level is needed. Therefore, the Forest Research Institute of Baden-Württemberg (FVA, Germany) and the University of Natural Resources and Life Sciences (BOKU, Austria) started a research project in 2014. This five-year research project has the goal to study the effects of wind turbines on capercaillie by applying different research methods in several European study areas in the Before-After-Control-Impact (BACI) design. The applied design affords the potential to transfer the possible influence of wind turbines and to derive management recommendations for decision-making and authorization procedures. As Sweden provides stable capercaillie populations in central and northern forest landscapes (ArtDatabanken 2018) but also ongoing wind energy construction,

the international study area including Germany and Austria was expanded in 2016 to the Jädraås wind park, Dalarna, in cooperation with the Swedish University of Agricultural Sciences (SLU). The focus of the international research project was to study the (1) habitat- and resource selection of capercaillie, (2) reproductive success of capercaillie, (3) mesopredator densities and (4) capercaillie stress physiology in the context of the possible anthropogenic disturbance caused by WEF. Habitat selection and stress physiology were also used to improve the international comparability. With respect to the initial Swedish funding period covering the years 2016–2017, the project-accompanying advisory board decided to deviate from the actual BACI design in Germany and Austria. Instead a Gradient design (Underwood 1994) was used to study resource selection. Reproduction and predator densities however were studied in a Control-Impact design. Both designs were thus not dependent on the uncertainties of permissions and constructional time schedules of the wind power companies. Here we present the results of the research project with a focus on the results from the Swedish study area.

2 Material and methods

2.1 Study areas

Sweden

The main study area is located in lowland forests in Dalarna and Gävleborg County, Sweden (Figure 1). The study area with a total surface of approx. 10.000 ha encompasses the Jädraås wind park with 68 Vestas V112 turbines (66 turbines owned by Arise and 2 turbines owned by other company), operational since 2013, and the Mombyåsen wind farm with 10 Vestas V126 turbines, operational since 2016. The control area (approx. 3 000 ha) without wind turbines is located three kilometres from the wind park to the East. The dominant tree species in the study area is Scots pine (*Pinus sylvestris*), followed by Norway spruce (*Picea abies*) interspersed with small amounts of silver birch (*Betula pendula*). Most parts of the forest covering the study area are managed with regular thinnings, clearcuttings and replantation for timber production. Ornithological surveys preceding our study in 2015, revealed capercaillie occurrence and lekking sites with up to five capercaillie males in the study area (Eric Ringaby, unpubl. report 2015).

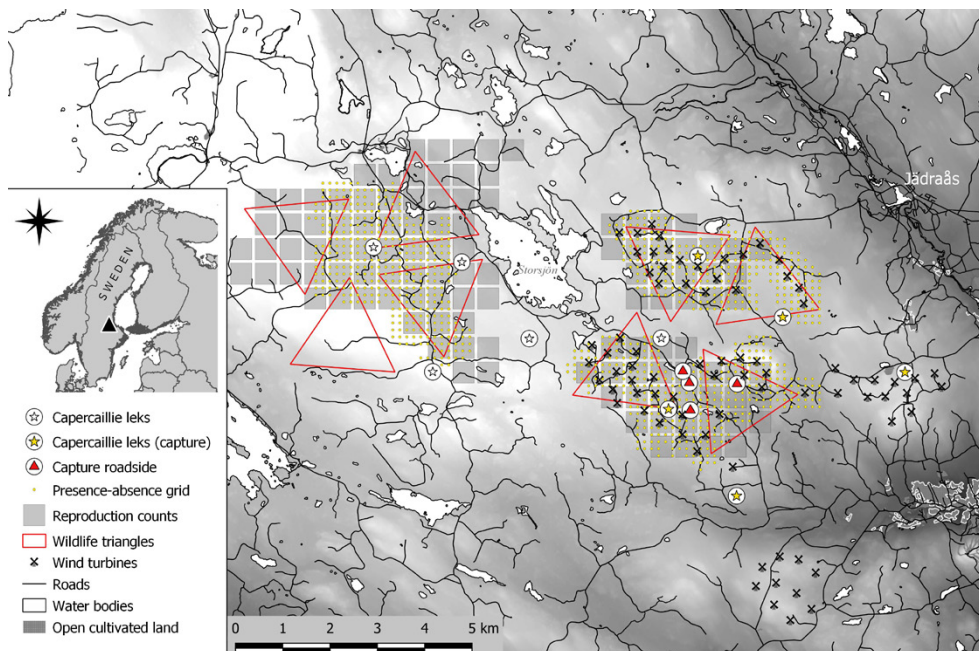


Figure 1. Location of the study area at the Jädraås wind park. The area west of the central lake is defined as the control and the eastern part is defined as the impact area, where 68 turbines are operational since 2013. Resource selection of capercaillie was studied in the impact area only. Wildlife triangles, presence-absence mapping and reproduction counts were conducted both in control and impact area.

Germany and Austria

Several methods were not only applied in the Swedish study area, but also in study areas in Germany and Austria as part of the international “Capercaillie and wind energy project” to enable study the effects of WEA in three different biogeographical regions across Europe: Fennoscandia (Sweden), the Alps (Austria) and central European low altitude mountain ranges (Germany). Furthermore, it was possible to cover a wide range of capercaillie habitats. Two study areas were located in the Black Forest, Germany. Both German study areas included a wind turbine (ENERCON E-70 and Südwind S70). Three study areas were located in Austria, here the number of turbines varied between six and 14, the type of turbines varied between the study sites: Repower MM92, Vestas V112, ENERCON E82 –E4.

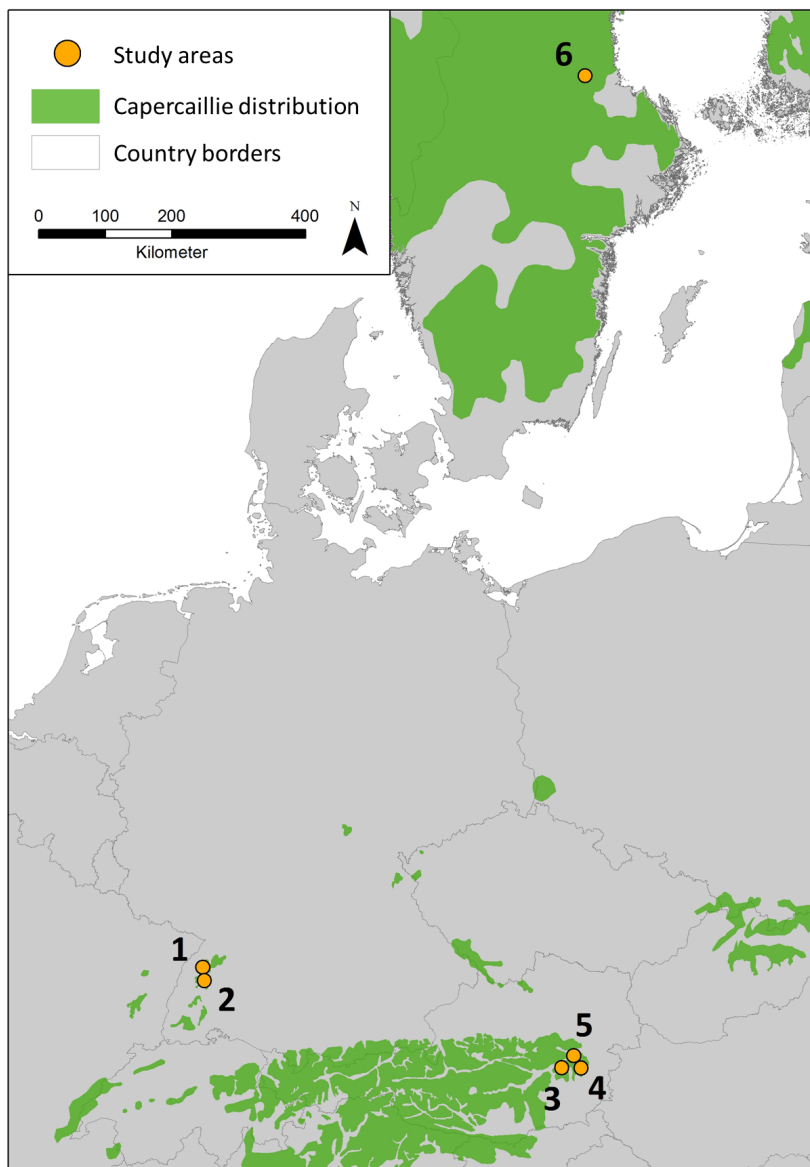


Figure 2. Locations of the six study areas in Germany (1-2), Austria (3-4-5) and Sweden (6). The capercaillie distribution is coloured in green (Coppes et al. 2015).

2.2 Resource selection: GPS telemetry

Taubmann J, Kämmerle J-L, Andrén H, Braunisch V, Storch I, Fiedler W, Suchant R, Coppes J (2021) Wind energy facilities affect resource selection of capercaillie Tetrao urogallus. Wildlife Biology. 2021(1): <https://doi.org/10.2981/wlb.00737>.

Capture and tracking

Capercaillie leks were searched for within and around the WEF in early springtime 2016–2019. In total, six active leks were found with a minimum distance of 325 m to the closest wind turbine. As the research goal was to study potential effects of WEF parameter on individual capercaillie, birds were caught as close as possible to wind turbines. Birds were caught by placing walk-in nets at lekking sites and around sand baths, while observing the nets from camouflage tents. On average a capture site was 587 meters away from the nearest wind turbine (ranging between 325 m and 950 m). Birds were fitted with GPS-3D-acceleration transmitters (E-obs digital telemetry, Munich) and released within a maximum handling time of 10 min. Capture and tagging was permitted by the Swedish Animal Ethics Committee (permit DNR C 40/16). Backpack transmitters were used, as this transmitter stays close to the bird's centre of gravity, which has the least impact on the birds' movement and allows more discrete acceleration measurements. The transmitters weighed 38 to 48 g, which is approximately up to 2 % of the body weight, depending on the sex. A 3% limit is seen as a maximum weight which should be put onto flying bird species (Casper 2009). Previous telemetry projects on capercaillie in the wild and in reserves, carried out by the MPI for Ornithology, the Forest Research Institute of Baden-Württemberg and the University of Freiburg, have indicated no adverse effects of the transmitter type on the birds nor a decreased survival rate (internal reports, pers. comm. and also see Coppes et al. 2017). By using teflon and silicon band for fitting the transmitter, this soft and durable material prevents the bird from being excoriated. Solar tags and battery tags were used to maximize the effort in terms of sampling duration and sampling scheme. The solar tags (38 g, both sexes) enabled high-resolution GPS measurements every 5 min at full battery, whereas below a certain threshold 3 GPS points/24 h could be sampled at subsequent cloudy days. Battery tags enabled a constant sampling of 3 GPS points/24 h, which should provide data for at least one year (males, 48 g) and 7 months (females, 38 g), respectively. Both tags, solar and battery were programmed to sample also high resolution acceleration data every 3 min for 10 s with a frequency of 20 Hz per axes. The data was downloaded in regular intervals (2 weeks) using a handheld device, at a distance of several hundred meters. When the GPS points clustered and the acceleration 3D-axes showed flat line, the bird was expected to be dead, so the tag was recovered and the situation on site recorded. Predator identification as a cause of death was carried out similar as in Smith and Willebrand (1999).

Data management

The data was assigned to two biologically meaningful seasons: “lekking” for males (N = 8) and “summer” for males (N = 11) and females (N = 4). During the lekking season in springtime, the males return to the lekking ground every day, which is why their habitat use is strongly influenced by the location of the lekking area. The lekking season includes the period where males attended the lek at night and the close feeding areas during the day (Storch 1997) until they leave the lek by the end of May to beginning of June. Contrary to Storch (1993) we defined the summer period from June to October for both sexes, as only few data from few individuals were received. Although the females started to incubate, this period was not analysed separately because the nests were abandoned or preyed upon, hence the data was included in the summer season analysis. The home ranges were calculated based on the minimum convex polygon (MCP) including 100% of GPS locations, as large-scale outliers due to locational error or true movement were not detected. Analyses were performed in the `adehabitatHR` package in R (Calenge 2006, R Core Team 2017). In order to minimize the effect of capture and tagging on the data to be analysed, data of the first 72 hours after capture were excluded.

We assessed the possible influence of GPS deviation on our data by analysing the accuracy of the GPS transmitter locations. The aim of this test was to select a partial data set with “exact” locations, with the help of which the possible influence of imprecise points in the comparison of the total and partial data set should be determined. Stationary GPS transmitters in various habitat types were used for this. The location of the respective transmitter was measured using a handheld GPS device (Garmin Alpha 100), paying attention to the handheld device’s GPS accuracy as high as possible. The deviation from the actual location of the transmitter resulted in a measure of the horizontal deviation of the GPS locations. With the help of these values, the quality for the GPS accuracy calculated by the GPS transmitter (for which the number of satellites used is an indication) could be evaluated. The actual deviation and the internal accuracy value were strongly correlated, but the scatter of the points around an estimated regression line increased with increasing horizontal deviation. A threshold value with a GPS accuracy of 25 (units on the value scale of the transmitter module) was derived from this ratio, above which the classification of the locational accuracy of the points was too imprecise. By separating the data at this threshold value, a partial data set was created for the evaluation with a scope of approx. 70 % of the original data (i.e. 30 % of the data had an inaccuracy above this threshold value) and an average real location deviation of 12 m.

Environmental variables

Variables potentially explaining the behaviour and habitat selection of capercaillie were obtained from various sources. Data on topography and land cover in the study area were obtained by the Swedish land registration authority (Lantmäteriet 2017a, b). Forestry data were made available by the SLU and the Swedish forest agency (SLU Skogsdata 2017; Skogsstyrelsen 2018). Considered predictors were classified in the categories land cover, forestry and infrastructure (Table 1) and processed in 25 x 25 m resolution raster maps, using QGIS 2.16.2 (QGIS Development Team 2016). Forest land cover data was processed in four different classes to distinguish between pine or spruce dominated forest if the raster cell included ≥ 75 % of either tree species, mixed forest if pine and spruce included < 75 % of either species in a raster cell and “other forest” if a raster cell included less abundant tree species like birch or unknown forest types. Distance calculations were carried out with raster distance analysis in QGIS. Areas bordering bogs were considered by calculating distances to bogs located in forests and distances to bogs located in open areas. Forest structures were characterized by including stand density and mean tree diameter of stands. Retrieved clear-cut data with maximum age of 20 years was subsampled to clear-cuts < 5 years and > 5 years, respectively, using 2018/2019 as reference year. In total, we included six wind energy related predictors potentially influencing capercaillie tracked in the study area: 1) turbine shadow, 2) turbine noise, 3) number of turbines within 800 m (density), 4) distance to closest turbine, 5) number of visible turbines and 6) distance to access roads. Noise and shadow effects of the wind turbines were calculated with windPro 3.1 (EMD International 2016). The expected meteorologically plausible amount of shadow (h/year) were calculated based on solar statistics, turbine site topography, technical specifications and operating hours divided by wind direction. The expected noise emitted by the turbine models in our study was calculated with the ISO 9613-2 method in decibel (dB), including the maximum noise volume levels (at 95 % turbine capacity) as available in the windPro database. The turbine density was estimated by calculating the number of turbines within 800 m for each location (Coppes et al. 2020b). We calculated the distance of each location to the closest wind turbine in meters. Visibility of turbines was modelled for each ground-location based on high resolution aerial LIDAR data (Lantmäteriet 2018) and validated on site using in-situ observations if the turbine was visible or not. Distance to access roads was calculated from each location to the closest road, which were constructed or widened for the wind park construction and maintenance work.

Table 1. Predictors considered for analysing habitat selection of capercaillie in the Jädraås wind park, Sweden. Notes: Variables correlated > 10.51 and/or with no explanatory power were rejected from the multivariate full-model "Model lek" and "Model summer", respectively. Variable types are described as categorical (cat.) or continuous (cont.).

Category	Description	Unit	Type	Model lek	Model summer
Land cover	Land cover types	Pine (<i>Pinus sylvestris</i>) forest	cat.		+
		Spruce (<i>Picea abies</i>) forest			+
		Mixed forest			+
		Other forest			+
		Open bog			+
		Forest bog			+
		Clear-cut < 5 years			+
		Clear-cut > 5 years			+
		Distance to open marsh	m	cont.	+
Distance to forest marsh	m	cont.	+	+	
Forestry	Mean tree diameter	cm	cont.	+	+
	Mean stand density	m ² /ha	cont.		+
	Distance clear-cut < 5 years	m	cont.	+	+
	Distance clear-cut > 5 years	m	cont.	+	+
Infrastructure	Turbine shadow	h/year	cont.	+	+
	Turbine noise	dB	cont.	+	+
	Turbine density in 800 m		cont.	+	+
	Distance to turbine	m	cont.		+
	No. visible turbines		cont.	+	+
	Distance to access roads	m	cont.	+	+

Resource selection analysis

Resource selection analyses were conducted in the seasonal home ranges, following an approach where individuals are tracked and resource use and availability is analysed separately (Design III; Johnson et al. 2006; Thomas and Taylor 2006). To avoid an unbalanced sample (i.e. due to different tags with higher sampling rates and associated high spatial and temporal autocorrelation) we adopted a conservative approach by randomly selecting three locations per 24 hours (i.e. the minimum sampling rate), with at least 5 hours' time between the locations. We defined "use" as the GPS locations sampled by the transmitters inside the seasonal home range of each individual and contrasted these by a set of random locations (i.e. available) within the seasonal home range (RSF 'sampling protocol A' in a use-available design, Manly et al. 2002). The number of random locations per presence location is important because depending on the possible preference of certain habitat types and the spatial resolution of the environmental data, if the sample size is insufficient (i.e. the random locations), incorrect model results can arise. Therefore, we applied a sensitivity analysis (Ciuti et al. 2018) to determine the optimal ratio of presence to random locations for the respective

data set. Generalized linear mixed models (GLMM, R package lme4, Bates et al. 2015) containing all variables were fitted with varying sample sizes of random locations, generated in 15 steps in increasing ratio to presence locations (1:1 to 1:30 presence: random locations). The stability of the estimate was checked by repeating this process 30 times. A ratio of 1:15 (presence: random locations) was determined to be optimal for this data set for all covariates.

GLMM with presence (1) and random (0) locations as the dependent variable and the individual as a “random intercept” were calculated for each time period (lekking season, summer season). A total of six wind turbine and seven environmental variables were included in the analyses. Due to convergence problems on the small dataset of the lekking season, the variables land cover and mean stand density were omitted from the lekking season models. Correlated variables (Pearson’ $R > |0.5|$) with weak explanatory power were dropped from the dataset. Due to the high correlation, not all wind turbine predictors could be included in a model at the same time. Therefore, four different models were built, each including the number of visible wind turbines (turbine visibility) and the distance to the wind turbine access roads, plus either (a) the turbine shadow, (b) the turbine noise emission, (c) the distance to the closest turbine or (d) the number of wind turbines within a radius of 800 m around the point (turbine density) (Table 1). The radius of 800 m was determined by comparing AIC values from the multivariate models, each of which contained the number of wind turbines within gradually increasing circumferences (between 800 m and 3 000 m radius). For the models in the lekking season, the distance to the wind turbine was excluded, because the location of animal home ranges was considered biased by the location of the lekking ground, where the individuals were caught. We included higher-order polynomials when a non-linear response was expected and retained them if there was support. We otherwise compared and interpreted full models for each season and predictor combination. The final models were applied to the partial data set to evaluate the influence of the location accuracy. There was no significant influence of inaccurate GPS locations on the estimated model coefficients. In the following, the entire data set and the corresponding GLMMs based on it were therefore used. Before proceeding with building the RSF, we evaluated the stability of beta coefficient estimates in the final models (and particularly the higher-order terms) by means of blocked cross-validation (CV; Roberts et al. 2017). Owing to our limited sample size (i.e. $N = 8$ and $N = 12$ animals, lekking and summer season) we assigned CV-folds by leaving out single animals to ensure model convergence. We refitted all final models in both seasons on each fold and extracted beta values and associated p-values. Selection scores $w(x)$ were obtained for all models in both seasons by including the model coefficients in a resource selection function, omitting the model intercept. The following exponential form was assumed: $w(x) = \exp(\beta_1 \times x_1 + \beta_2 \times x_2 + \dots + \beta_n \times x_n)$. Here β_n stands for the model coefficients which are associated with the environment variable x_n .

(Manly et al. 2002; Lele et al. 2013). The resulting scores $w(x)$ reflect the strength of the selection or avoidance of an environmental variable on a positive scale. The results of the summer season were visualized by calculation the selection score for the area around the wind park with the full models as well as with models where the WEF predictors were set to their lowest values as well as by calculating the difference between the two models, showing the areas which have a reduced selection score due to the WEF predictors.

2.3 Movement behaviour

Kämmerle J-L, Taubmann J, Andrén H, Fiedler W, Coppes J (Submitted for publication) Get a move on: environmental and seasonal correlates of capercaillie movement traits in a wind farm.

Selection of local resource units and the establishment of home-ranges are connected by animal movement behaviour, which is a fundamental property of biological systems (Nathan et al. 2008; Van Moorter et al. 2016). Detailed knowledge on animal movement is thus of great relevance for science and conservation alike. Using locational data of 13 capercaillie individuals captured in the Jädraås wind park (see chapter 3.2 Resource selection for details on capture and data availability), we assessed whether capercaillie movement behaviour was affected by wind turbines. Movement behaviour was defined by means of movement speed (i.e. step length) and relative turning angle using a 5-minute sampling interval. The analysis of high-resolution tracking data is particularly challenged by locational error, because – although present in all tracking data (Cagnacci et al. 2010; Frair et al. 2010) – the distance covered between two locations taken at a high sampling rate may be in the same order of magnitude as the typical measurement error. Capercaillie provide such an example, because they primarily walk at a slow speed. Nonetheless, a large number of behavioural decisions occur at a fine temporal resolution, including resource selection. We approached this issue by applying a two-step approach. We first filtered potentially unreliable movement steps using classification of activity and movement state based on accelerometer data and step characteristics, before analysing movement behaviour (i.e. movement speed and directionality) in relation to wind turbines and other covariates.

Statistical analysis

We used all fixes that were successfully taken on a regular sampling schedule and belonged to movement bursts (i.e. a succession of steps) that were ≥ 50 fixes long (i.e. approx. corresponding to a four-hour period), thus rendering 172 068 steps. We then processed steps to exclude steps with a high probability of representing ‘false movement’, i.e. with large locational bias resulting from high locational inaccuracy while the animal remained stationary.

To this end, we classified tag acceleration data using a threshold-based approach in which continuously collected total tag acceleration data is assigned to an active or resting state by unsupervised classification using the R package ‘activity tools’ (under development; Max Kröschel 2020 personal communication). In addition, we employed hidden Markov models to either belong to a stationary or transient state based on step-length (in meters) and relative turning angle (in Radians) in R package moveHMM (Michelot et al. 2016). We thus identified steps classified as “resting-transient” to have a high likelihood of depicting GPS scatter, while the animal was in fact stationary, and removed those from the data (final sample size: 154 172 steps).

We then analysed movement speed and relative turning angle (i.e. pooling left and right turns as $0 \leq \alpha \leq \pi$) in generalized additive mixed models in R package mgcv (Wood 2011, 2017). In this approach, movement is fast for large step lengths and directional for small turning angles (i.e. small directional change relative to previous step). We assumed a gamma distribution for both response variables using a log-link and included random intercepts for animal ID. We tested for a relationship of movement behaviour with a) turbine shadow, b) the number of visible turbines and c) the distance to turbine access roads. In addition, we included a number of habitat covariates (forest stand characteristics, land cover type) and accounted for daily and seasonal variation by including time of the day (continuous) as well as Julian date. Since there was considerable autocorrelation in movement steps at lag one (i.e. the first consecutive step), we included the length of the previous step as a covariate in the step length model. Model assumptions were met.

2.4 Habitat selection: indirect signs

Coppes J, Kämmerle J-L, Grünsachner-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. – Biological Conservation 244: 108529. <https://doi.org/10.1016/j.biocon.2020.108529>.

The effects of WEF on capercaillie habitat selection were studied by systematically mapping indirect capercaillie signs (i.e. feathers, droppings in six study areas. The results have been published by Coppes et al. (2020b), here we provide a short summary of the methods and results applied.

We selected and surveyed study sites in pairs, one site with turbines present or under development (‘impact site’) and a control site of comparable topography and habitat composition without turbines (‘control site’), whenever possible. At the impact and the control sites the occurrence of capercaillie was surveyed using a systematic grid of sampling plots with a regular grid cell length of 100 to 200 m, depending on the size of the study area (135–2295 ha). Between July and August, capercaillie signs were mapped in a 5 m radius around each plot centre for a duration of 10 min. Mapping of indirect capercaillie signs (i.e. feathers, droppings) is a standard method to

study capercaillie occurrence and habitat selection (Storch 2002; Summers et al. 2007; Moss et al. 2014; Zohmann et al. 2014; Coppes et al. 2018), since capercaillie signs, especially droppings, are detectable over long periods after defecation (Poggenburg et al. 2018). In addition, we mapped a set of environmental (biotic and abiotic) characteristics known to be related to capercaillie habitat use and suitability in a 20 m radius around the plot centre. These environmental characteristics included ground vegetation and canopy cover, the composition of the tree and shrub layer as well as information on topography (Storch 2002; Bollmann et al. 2005; Bollmann et al. 2008; Coppes et al. 2018).

Habitat selection analysis

We analysed the effects of wind turbines at two spatial scales: (1) at the level of the study sites (henceforth: ‘large-scale’) we used the percentage of samples plots with signs (i.e. signs density) of capercaillie presence per study site in a given year; (2) at the scale of individual plots within each study site (henceforth: ‘small-scale’) we used the presence or absence of capercaillie at a plot in a given year to analyse small-scale habitat selection (Coppes et al. 2020b). To test for differences in capercaillie sign densities before and after turbine construction, we calculated the percentage of sampling plots that had capercaillie signs at each study site and in each study year, including only the study sites that met the criteria of a BACI-design (i.e. for which data from before and after turbine construction at both an impact and control site were available). Here we excluded data from the Swedish and one German study area, as these only included data from after turbine construction. To address the effects of habitat suitability on capercaillie habitat use and to be able to disentangle habitat effects from that of the turbine predictors, we predicted the probability of finding capercaillie signs at a plot based on environmental covariates (i.e. as a habitat suitability index) without wind turbine effects based on the data from the control sites and from impact sites before construction of wind turbines (i.e. including data from all study areas in order to model habitat suitability) (Coppes et al. 2020b).

To study the large-scale effects, we fitted linear mixed-effect models in R package lme4 (Bates et al. 2015) with a random intercept for study site ID to correct for differences in baseline sign density between study sites. We fitted two models, one depicting the BACI design, and one model we used the years since turbine construction interacting with ‘Control-Impact’. We analysed the small-scale habitat selection at wind turbine sites after the construction of the turbines using generalized additive mixed models from package gamm4 (Wood and Scheipl 2017) with a binary response (0/1 = capercaillie not present/present). We included the index of habitat suitability as a regular linear term and the WEA-Predictors in individual models, due to the high collinearity of the WEA-predictors. By including a nested random intercept, we accounted for the grouped nature of the data and the differences in detection probability among sites and years.

2.5 Reproduction monitoring

The success of reproduction is a decisive factor for the development of a population. If the mortality (death rate) is higher than the reproductive success, the population numbers decrease, the reverse is true if the reproductive success is higher than the mortality. There are a variety of factors that affect mortality and reproductive success. In grouse, for example, habitat quality (Börset and Krafft 1973; Storaas et al. 1982; Baines et al. 2004), weather conditions (Swenson et al. 1993; Moss et al. 2001) and the density of predators (Storaas et al. 1999; Baines et al. 2004; Tornberg et al. 2012) are important factors that can influence the success of reproduction. Due to those factors, capercaillie and black grouse reproductive success have been found to decline but stabilize at low levels in most regions in Central Europe and Scandinavia in the last 80 years (Jahren et al. 2016). The authors state despite stabilisation that adult survival is too low to compensate the low reproductive level and will lead to further population decline. The reproductive success of grouse is often quantified by the ratio of chicks per hen in an area; this can be determined by brood counts in late summer (Moss 1985; Baines et al. 2004). The resulting value is to be regarded as an index for the success of reproduction. It is therefore not an absolute value that measures the number of chicks in an area, but a relative measure of reproductive success in different years or areas.

Reproduction monitoring was initially carried out in the study areas in the Black Forest and in Austria using line taxation. This method had previously proven itself in the Black Forest when collecting an index for the breeding success of capercaillie over larger areas. The index collected was the ratio of chicks to adult hens in an area (hereinafter referred to as the “reproductive index”). After the first few years however it became clear that this method was unsuitable for measuring reproductive success on a small scale in the area of influence of the wind turbines. Although there was evidence of reproduction in the areas (e.g. sighting of chicks or finds of eggshells), due to the small sample size it was not possible to provide a robust index for the reproductive success before and after the construction of the wind turbine in the areas in close vicinity of planning areas. Thus, no data could be collected that would allow a statement to be made about the effect of wind turbines on the reproductive success of capercaillie in the Austrian areas and in the Black Forest.

The Swedish study area however provided promising conditions, with regard to the forest landscape and given grouse densities in Dalarna and Gävleborg County. Additionally, professional trained pointing dogs were available, as this is a common monitoring method to detect grouse over large areas (Caizergues and Ellison 1997; Moss et al. 2001; Wegge and Rolstad 2011). The annual reproductive success was estimated by counting capercaillie and their offspring in wind turbine areas as well as control areas to study the effect of wind turbines on capercaillie reproduction. Black grouse, hazel grouse and woodcock were recorded also, but the focus was

placed on capercaillie when selecting the study area. To calculate the reproductive rate per year, a minimum number of approx. 11 hens per site had to be detected in our study area (Naturvårdsverket, M. Hörnell-Willebrand, pers. comm.). The data was collected in August for four consecutive years (2016 to 2019). Randomly selected grids of 0.5 km² cell size (Figure 1) were sampled evenly by walking free transects within, covering suboptimal to high quality habitat, using professional pointing dogs. Grouse was searched for on average 3 hours per grid cell in optimal weather conditions (no/light precipitation, no/medium wind speed). One grid was searched in the morning and another in the afternoon, using each dog for one grid per day only. The detected birds were classified as cock, hen, chick or unknown. Up to three teams, consisting of one dog and a handler, searched for grouse in different grids at the same time and were tracked using GPS devices (Garmin Alpha 100). The handler could follow the dog's position in real time on the device and received a signal when the dog was on point. Subsequently, the handler did walk to the position, while the dog hold on point without the grouse flying up or running away (the birds hide on the ground in response to the dog, which is seen as a predator (Storaas et al. 1999)). On arrival, the team approached closer until the brood or bird was flushed. This teamwork made it possible to determine the species (capercaillie, black grouse, hazel grouse, woodcock) as well as the number, sex (male or female) and age (adult or young).

We analysed the effects of wind turbines by comparing the number of observed chicks recorded in each grid and included number of adult females observed in each grid as an offset to get the chicks per hen index. We use a linear mixed-effect model (package lme4 in R, Bates et al. 2015) to compare the control area with the impact area. In the model we included treatment (control or impact area) as a fixed factor, year as fixed categorical factor and grid number as a random factor. We used Poisson distribution of errors, as observations are positive integers.

2.6 Mesopredator track densities

Predation by red fox (*Vulpes vulpes*) and pine marten (*Martes martes*) is assumed to be one of the most important factors influencing grouse populations (Henttonen 1989; Jahren et al. 2016). Also, experimental studies revealed negative effects of increased predation by both species (Marcström et al. 1988; Jahren et al. 2016). Red fox and pine marten are common mesopredator species in Scandinavian boreal forests (Kurki et al. 1998; Helldin 2000), and especially fox density and activity are often positively correlated with the degree of fragmentation of forest landscape (Kurki et al. 1998; Frey and Conover 2010). Therefore, predator densities and activities could be significantly higher within wind farms in forests, where the amount of fragmentation by extended road networks and clearcuttings increases. The Finnish wildlife triangle method was used in our study, to count mammalian snow

tracks on site, using a scheme described by Lindén et al. (1996). Between January and March 2016–2019 predator snow tracks were recorded along two (2016) and eight triangles (Figure 1) in impact and control area, to estimate the abundance and relative density of mammalian predators. The triangles had to be decreased in size to 9 km (3 km side length) compared to Lindén et al. (1996), to sufficiently cover the entire study area. Due to the ongoing organisational procedure with landowners and field technicians when funding was approved in January 2016, only two triangles were sampled in the first season. Censuses were undertaken by a professional hunter who has proven experience in identifying wildlife snow tracks. We analysed the effects of wind turbines by comparing the number of red fox and pine marten recorded for each triangle. We use a linear mixed-effect model (package `lme4` in R, Bates et al. 2015) to compare the control area with the impact area. In the model we include treatment (control or impact area) as a fixed factor, year as fixed categorical factor and triangle number as a random factor. We used Poisson distribution of errors, as observations are positive integers.

2.7 Stress physiology

Stress physiological methods are increasingly being applied to study the factors influencing wildlife (Hadinger et al. 2015; Goymann 2012; Touma and Palme 2005). By analysing non-invasively collected samples (i.e. droppings) for stress hormone metabolites, it is possible to assess stress levels of free-living animals if the method is validated to the given species. The analysis of stress hormone metabolites is validated (Thiel et al. 2005) and has been applied to study capercaillie (Thiel et al. 2008, 2011; Coppes et al. 2018b). For example, several studies found increased concentration of faecal corticosteroid metabolites in capercaillie droppings due to human recreational activities in winter (Thiel et al. 2008, 2011; Coppes et al. 2018b). Here we studied whether wind turbines affect the concentration of faecal corticosteroid metabolites (from here on referred to as FCM) in capercaillie droppings in Austria (three study areas), Sweden and Germany (one area each).

Capercaillie droppings (from here on referred to as samples) were collected in winter, during snow conditions, to ensure the FCM concentrations were affected as little as possible since the time after defecation (Thiel et al. 2005). Samples were cooled during transport and stored at -32 °C until further analysis. Samples were collected in impact sites as well as control areas, both before and after the construction of the wind turbines in the impact areas. All samples were dried before FCM analysis. Samples were homogenized and glucocorticoid metabolites were extracted with 60 % methanol (0.5 g droppings plus 5 ml) according to Palme et al. (2013). We used a cortisone enzyme immunoassay (EIA; Rettenbacher et al. 2004) to measure FCM metabolites.

Statistical analysis

We applied two analyses to test for an effect of wind turbines on capercaillie FCM levels: first we studied the effect on the study site level by we fitted a linear mixed-effect model from package lme4 (Bates et al. 2015) with the FCM level as response and representing the BACI design as an interaction of two factorial predictors (before-after with control-impact). We included the years of the study within the individual pairs of impact and control sites as nested random intercepts to control for differences in mean FCM level between years and sites. In a second step we tested for spatial variation in FCM levels with regards to wind turbines by fitting generalized additive mixed-effect models from package gamm4 (Wood and Scheipl 2017) with Gaussian distribution of errors and log-transformed FCM levels as response. For this analysis we only used data from wind turbine sites (N=353; i.e. as control sites had no turbines to model turbine effects). As above, we included years within study site as a random effect into the model. We modelled spatial effects of wind turbines using cubic regression splines with shrinkage (Wood 2006) for the distance to the turbine and the meteorologically likely amount of shadow per location, fitting one spline for the period before and after construction of turbines.

3 Results

3.1 Resource selection: GPS telemetry

Capture and home ranges

We captured twelve capercaillie males and six females from mid-April until end of May in 2017 and 2018 (Table 2). On average a capture site was 587 meters away from the nearest wind turbine, ranging between 325 m and 950 m. Due to defective transmitters, migration or predation events, the periods over which GPS locations were available varied between individuals (between 50 and 400 days; Table 2). Two females died within 30 days after capture (predation by mammals, presumably red fox) and were therefore excluded from the analysis due to insufficient data. Data were sufficient (≥ 45 days tracked per season) for RSF analysis for eight males in the lekking season and 15 individuals (4 females, 11 males) in the summer season (Table 2). For the lekking season the average MCP home range size of eight males was 30 ± 17 ha. For the summer season the average home range size of 11 males (504 ± 301 ha) was more than twice as large as those of four females (133 ± 75 ha). The home ranges of the birds were located around the lekking sites during the lekking season, but moved away from the lekking sites during the summer season. During both seasons the home ranges were located both within and surrounding the wind park (S1; S2).

Table 2. Overview of the capercaillie included in the analysis. The column “Type” indicates the tag type: solar or battery. Days tracked and numbers of GPS locations are given per individual and per season. Minimum convex polygons (MCP) contain 100 % of GPS locations included for the analysis per season in hectares. The check marks indicate which individuals were included in the RSF models for the lekking and summer season, respectively.

Animal ID	Year	Sex	Type	Days lek	Locations lek	MCP lek	Days summer	Locations summer	MCP summer	Model lek	Model summer
1	2017	m	solar	43	127	30	167	446	457	✓	✓
2	2017	m	solar	44	130	19			-	✓	
3	2017	m	battery	45	133	19	26	74	136	✓	✓
5	2017	m	solar	31	89	46	139	409	526	✓	✓
6	2017	m	battery	33	98	36	92	272	454	✓	✓
9	2017	m	solar	-	-	-	153	430	832		✓
4	2017	f	solar	-	-	-	106	312	116		✓
8	2017	f	battery	-	-	-	54	158	260		✓
10	2017	f	solar	-	-	-	69	201	82		✓
11	2017	f	solar	-	-	-	51	151	74		✓
14	2018	m	solar	39	113	7	105	311	475	✓	✓
15	2018	m	solar	-	-	-	88	258	131		✓
16	2018	m	battery	29	83	63	73	215	243	✓	✓
17	2018	m	solar	18	52	18	123	358	622	✓	✓
18	2018	m	solar	-	-	-	147	433	1284		✓
19	2018	m	battery	-	-	-	173	512	1166		✓

Lekking season

Of the three models compared (Table 3), the model with the number of turbines within 800 m best explained capercaillie resource selection. The model for wind turbine shadow, however, was similar ($\Delta AIC = 2.6$; Table 3a), followed by the model for turbine noise ($\Delta AIC = 8.3$; Table 3b). Marginal and Conditional R-squared ranged between 0.221 and 0.249 and 0.310 and 0.411 respectively, with both values highest for the model including turbine noise (Table 3). Blocked cross-validation led to considerable variation in the size of the estimated beta coefficients, but all wind turbine effects had a constant sign and support for higher-order polynomial terms was stable (Taubmann et al. 2021, AX1). Regardless of the habitat suitability, the following effects of wind turbines on resource selection were found: The use of an area (expressed as Selection Score $w(x)$) decreased with turbine shadow of approx. ≥ 14 h/year (0.14 – 24.5 h; Figure 3a; Table 3a) and with increasing noise emission (Figure 3b; Table 3b). Also, the probability of selection declined with high turbine density (Figure 3c; Table 3c) and in areas with more than four (4.5) visible turbines (1.3 – 5 turbines; Figure 3d). The magnitude of effects (i.e. the selection score) was highly variable and larger for all wind turbine predictors in the lekking season models than in the summer models (compare Figure 3 and 4). In addition, a strong negative effect of turbine access roads on resource selection of capercaillie males was prevalent in all three models (Table 3; Taubmann et al. 2021, AX3). The other environmental variables showed known effects for forest grouse (Table 3; Storch 1995; Miettinen et al. 2010).

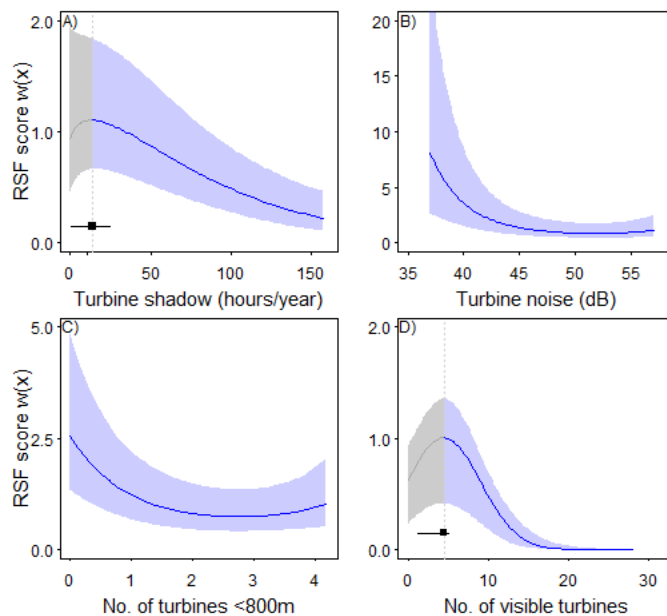


Figure 3. Conditional effect plots for capercaillie resource selection during the lekking season (expressed by the RSF selection score $w(x)$) in dependence of wind turbine predictors. All other covariates were held at their mean. Predictions for the number of visible turbines were obtained using the model containing the number of turbines < 800 m (i.e. model (c) in Table 3). Crossbars and shaded areas in the background denote estimated effect thresholds and associated uncertainty estimates (95 % quantile range in cross-validation).

Table 3. Results of the GLMMs estimating capercaillie resource selection during the lekking season in response to (a) turbine shadow, (b) turbine noise and (c) the number of turbines within 800 meters. AIC, marginal R² and conditional R² are provided for the models. Model coefficients (β), standard errors (SE) default p-values are provided for the predictors.

a) Turbine shadow			
AIC: 5888.6 ($\Delta 2.6$)		Marginal R²: 0.221	
		Conditional R²: 0.310	
Predictor	β	SE	p-value
Intercept	-2.888	0.258	
Turbine shadow	-0.271	0.112	0.015
Turbine shadow ²	-0.186	0.070	0.008
No. visible turbines	-0.010	0.068	0.879
No. visible turbines ²	-0.160	0.045	< 0.001
Distance access road	0.617	0.103	< 0.001
Mean tree diameter	-0.119	0.065	0.070
Mean tree diameter ²	-0.064	0.034	0.060
Distance clear-cut < 5y	-0.403	0.119	< 0.001
Distance clear-cut >5y	0.302	0.087	< 0.001
Distance forest bog	0.079	0.110	0.472
Distance forest bog ²	0.269	0.054	< 0.001
Distance open bog	0.467	0.091	< 0.001
Distance open bog ²	0.156	0.042	< 0.001

b) Turbine noise			
AIC: 5888.6 ($\Delta 2.6$)		Marginal R²: 0.250	
		Conditional R²: 0.310	
Predictor	β	SE	p-value
Intercept	-3.191	0.358	
Turbine noise	-0.443	0.140	0.002
Turbine noise ²	0.309	0.082	< 0.001
No. visible turbines	-0.052	0.068	0.442
No. visible turbines ²	-0.181	0.046	< 0.001
Distance access road	0.710	0.109	< 0.001
Mean tree diameter	-0.100	0.066	0.129
Mean tree diameter ²	-0.052	0.034	0.120
Distance clear-cut < 5y	-0.221	0.126	0.080
Distance clear-cut >5y	0.382	0.090	< 0.001
Distance forest bog	0.233	0.113	0.039
Distance forest bog ²	0.210	0.056	< 0.001
Distance open bog	0.469	0.090	< 0.001
Distance open bog ²	0.101	0.045	0.023

c) No. of turbines < 800 m		Marginal R ² : 0.249	
AIC: 5886.0 (Δ0.0)		Conditional R ² : 0.366	
Predictor	β	SE	p-value
Intercept	-3.181	0.304	
No. turbines < 800 m	-0.577	0.109	< 0.001
No. turbines < 800 m ²	0.275	0.076	< 0.001
No. visible turbines	-0.056	0.068	0.407
No. visible turbines ²	-0.176	0.046	< 0.001
Distance access road	0.786	0.110	< 0.001
Mean tree diameter	-0.121	0.066	0.066
Mean tree diameter ²	-0.068	0.034	0.048
Distance clear-cut < 5y	-0.314	0.121	0.010
Distance clear-cut >5y	0.283	0.089	0.002
Distance forest bog	0.187	0.106	0.080
Distance forest bog ²	0.212	0.056	< 0.001
Distance open bog	0.479	0.091	< 0.001
Distance open bog ²	0.091	0.044	0.040

Summer season

Of the four compared models (Table 4), the model including the number of turbines within a radius of 800 m matched the data best (Table 4c). Second place model contained distance to the closest wind turbine (Δ AIC = 23.6; Table 4d), followed by the model for turbine noise emissions (Δ AIC = 38.8; Table 4b) and the model for turbine shadow (Δ AIC = 118.4; Table 4a). Marginal and conditional R-squared ranged between 0.195 and 0.205 and 0.199 and 0.211 respectively, with both values highest for the model including the number of wind turbines < 800 m (Table 4). Blocked cross-validation led to less variation in the size of the estimated beta coefficients as compared to the lekking season. Wind turbine effects had likewise a stable sign and higher-order polynomial terms were supported (Taubmann et al. 2021, AX4 and AX5). Selection decreased with increasing proximity to the wind turbine, levelling off at a distance of approx. 865 m (784 – 1 025 m; Figure 4d; Table 4d) and with increasing turbine density (Figure 4c; Table 4c). The probability of selection also decreased with increasing noise emissions from 43 dB onwards (40 – 45 dB; Figure 4b; Table 4b), below this value no effect could be demonstrated. Furthermore, the probability of selection was reduced in areas with more than 8 hours of meteorologically probable shadow per year (2.25 – 22.47 h; Figure 4a; Table 4a). Selection probability also decreased in areas where more than four (4.6) wind turbines were visible (3.2 – 5.2 turbines; Figure 4e) as well as with increasing proximity to turbine access roads (Figure 4f). The selection scores of the wind turbine predictors were similar between the models, although comparatively low (compare Figure 3 and 4 and Taubmann et al. 2021, AX3 and AX6).

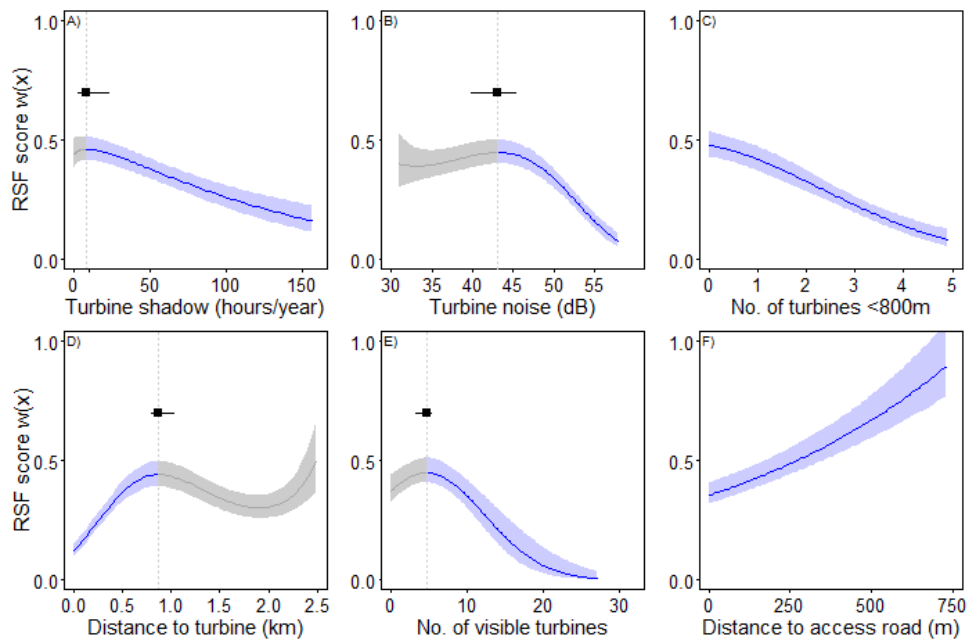


Figure 4. Conditional effect plots for capercaillie resource selection during the summer season (expressed by the RSF selection score $w(x)$) in dependence of wind turbine predictors. All other covariates were held at their mean. Predictions for the number of visible turbines and the distance to access roads were obtained using the model containing the number of turbines < 800 m (i.e. model (c) in Table 4). Crossbars and shaded areas in the background denote estimated effect thresholds and associated uncertainty estimates (95 % quantile range in cross-validation).

Environmental variables

In both seasons, capercaillie selected for areas away from open bogs and clear-cuts > 5 years old, while the probability of selection was higher close to clear-cuts < 5 years old, although the selection against older clear-cuts was more pronounced than selection for more recent ones (Tables 3, 4; Taubmann et al. 2021, AX3, AX6). Stands with intermediate mean tree diameter were selected for during summer season (Taubmann et al. 2021, AX6). During lekking season stands with smaller tree diameter were selected, although this effect was not significant for the model including turbine shadow (Table 3a) and turbine noise (Table 3b; Taubmann et al. 2021, AX3). Capercaillie also selected for intermediate stand density during summer (Taubmann et al. 2021, AX6). The probability of selection increased with increasing distance from forest bogs during the lekking season, while this effect was reversed during the summer season, when sites close to forest bogs were strongly selected for (Taubmann et al. 2021, AX3, AX6). Finally, the probability of selection during summer was highest for young clear-cuts, followed by forest bogs and pine forests while the probability of selection was lowest for open bogs and spruce-dominated forest stands (Taubmann et al. 2021, AX6).

Table 4. Results of the GLMMs estimating capercaillie resource selection during the summer season in response to (a) turbine shadow, (b) turbine noise, (c) the number of turbines within 800 meters and (d) the distance to the closest turbine. AIC, marginal R² and conditional R² are provided for the models. Model coefficients (β), standard errors (SE) and default p-values are provided for the predictors. Land cover types are compared with the intercept “clear-cut < 5y”.

a) Turbine shadow			
Marginal R²: 0.195			
AIC: 32341.5 (Δ118.4)			
Conditional R²: 0.199			
Predictor	β	SE	p-value
Intercept	-1.954	0.087	
Shadow	-0.062	0.027	0.021
Shadow ²	-0.066	0.016	< 0.001
No. visible turbines	-0.004	0.027	0.879
No. visible turbines ²	-0.073	0.015	< 0.001
Distance access road	0.163	0.016	< 0.001
Mean tree diameter	0.417	0.027	< 0.001
Mean tree diameter ²	-0.164	0.023	< 0.001
Distance clear-cut < 5y	-0.044	0.020	0.029
Distance clear-cut >5y	0.138	0.019	< 0.001
Distance forest bog	-0.219	0.028	< 0.001
Distance forest bog ²	0.024	0.012	0.037
Distance open bog	0.052	0.023	0.022
Distance open bog ²	0.034	0.013	0.006
Mean stand density	0.077	0.028	0.006
Mean stand density ²	-0.050	0.017	0.004
LU: clear-cut >5y	-0.760	0.120	< 0.001
LU: forest bog	-0.459	0.091	< 0.001
LU: open bog	-1.789	0.228	< 0.001
LU: mixed forest	-0.789	0.073	< 0.001
LU: other forest	-0.568	0.106	< 0.001
LU: pine forest	-0.534	0.074	< 0.001
LU: spruce forest	-1.203	0.123	< 0.001

b) Turbine noise			
Marginal R²: 0.201			
AIC: 32261.9 (Δ38.8)			
Conditional R²: 0.207			
Predictor	β	SE	p-value
Intercept	-1.841	0.089	
Turbine noise	-0.012	0.044	0.786
Turbine noise ²	-0.160	0.021	< 0.001
Turbine noise ³	-0.062	0.019	< 0.001
No. visible turbines	0.010	0.027	0.700
No. visible turbines ²	-0.070	0.016	< 0.001
Distance access road	0.166	0.016	< 0.001
Mean tree diameter	0.404	0.027	< 0.001
Mean tree diameter ²	-0.165	0.024	< 0.001
Distance clear-cut < 5y	-0.042	0.020	0.037
Distance clear-cut >5y	0.140	0.020	< 0.001
Distance forest bog	-0.193	0.028	< 0.001
Distance forest bog ²	0.029	0.012	0.014
Distance open bog	0.071	0.023	0.002
Distance open bog ²	0.029	0.013	0.020
Mean stand density	0.075	0.028	0.007

Mean stand density ²	-0.047	0.017	0.007
LU: clear-cut >5y	-0.821	0.120	< 0.001
LU: forest bog	-0.474	0.091	< 0.001
LU: open bog	-1.834	0.229	< 0.001
LU: mixed forest	-0.805	0.073	< 0.001
LU: other forest	-0.595	0.106	< 0.001
LU: pine forest	-0.557	0.075	< 0.001
LU: spruce forest	-1.210	0.123	< 0.001

c) No. of turbines < 800 m		Marginal R²: 0.205	
AIC: 32223.0 (Δ0.0)		Conditional R²: 0.211	
Predictor	β	SE	p-value
Intercept	-1.938	0.088	
No. turbines < 800 m	-0.156	0.046	< 0.001
No. turbines < 800 m ²	-0.068	0.023	0.003
No. visible turbines	0.024	0.026	0.356
No. visible turbines ²	-0.072	0.016	< 0.001
Distance access road	0.166	0.016	< 0.001
Mean tree diameter	0.404	0.027	< 0.001
Mean tree diameter ²	-0.166	0.023	< 0.001
Distance clear-cut < 5y	-0.035	0.020	0.089
Distance clear-cut >5y	0.133	0.019	< 0.001
Distance forest bog	-0.190	0.028	< 0.001
Distance forest bog ²	0.031	0.012	0.008
Distance open bog	0.078	0.023	< 0.001
Distance open bog ²	0.026	0.013	0.040
Mean stand density	0.073	0.028	0.008
Mean stand density ²	-0.050	0.017	0.040
LU: clear-cut >5y	-0.829	0.120	< 0.001
LU: forest bog	-0.468	0.091	< 0.001
LU: open bog	-1.826	0.228	< 0.001
LU: mixed forest	-0.805	0.073	< 0.001
LU: other forest	-0.597	0.106	< 0.001
LU: pine forest	-0.557	0.074	< 0.001
LU: spruce forest	-1.209	0.123	< 0.001

d) Distance to the closest turbine		Marginal R²: 0.201	
AIC: 32246.6 (Δ23.6)		Conditional R²: 0.208	
Predictor	β	SE	p-value
Intercept	-1.724	0.093	
Distance turbine	0.031	0.036	0.385
Distance turbine ²	-0.345	0.031	< 0.001
Distance turbine ³	0.118	0.014	< 0.001
No. visible turbines	0.006	0.027	0.820
No. visible turbines ²	-0.069	0.016	< 0.001
Distance access road	0.163	0.016	< 0.001
Mean tree diameter	0.402	0.027	< 0.001
Mean tree diameter ²	-0.168	0.024	< 0.001
Distance clear-cut < 5y	-0.039	0.021	0.060
Distance clear-cut >5y	0.133	0.020	< 0.001
Distance forest bog	-0.185	0.028	< 0.001
Distance forest bog ²	0.027	0.012	0.022
Distance open bog	0.065	0.023	0.005
Distance open bog ²	0.026	0.013	0.043
Mean stand density	0.073	0.028	0.008
Mean stand density ²	-0.042	0.017	0.016
LU: clear-cut >5y	-0.866	0.121	< 0.001
LU: forest bog	-0.506	0.091	< 0.001
LU: open bog	-1.887	0.229	< 0.001
LU: mixed forest	-0.821	0.074	< 0.001
LU: other forest	-0.605	0.106	< 0.001
LU: pine forest	-0.587	0.075	< 0.001
LU: spruce forest	-1.208	0.123	< 0.001

To describe the combined effect of many WEF in a landscape, we estimated the potential habitat selection score with WEF predictors set to their minimum values (Figure 5a) and the habitat selection score including “distance to turbine” and “number of visible turbines” (Figure 5b). The difference between the two habitat selection scores (Figure 5c), showed that the combined effect of many WEF reduced selection score at landscape scale, i.e. the selection scores were reduced within the entire wind park. Habitat patches with high scores within the wind park (green areas in Figure 5a), disappeared within the wind park when the effects on WEF were included (Figure 5b).

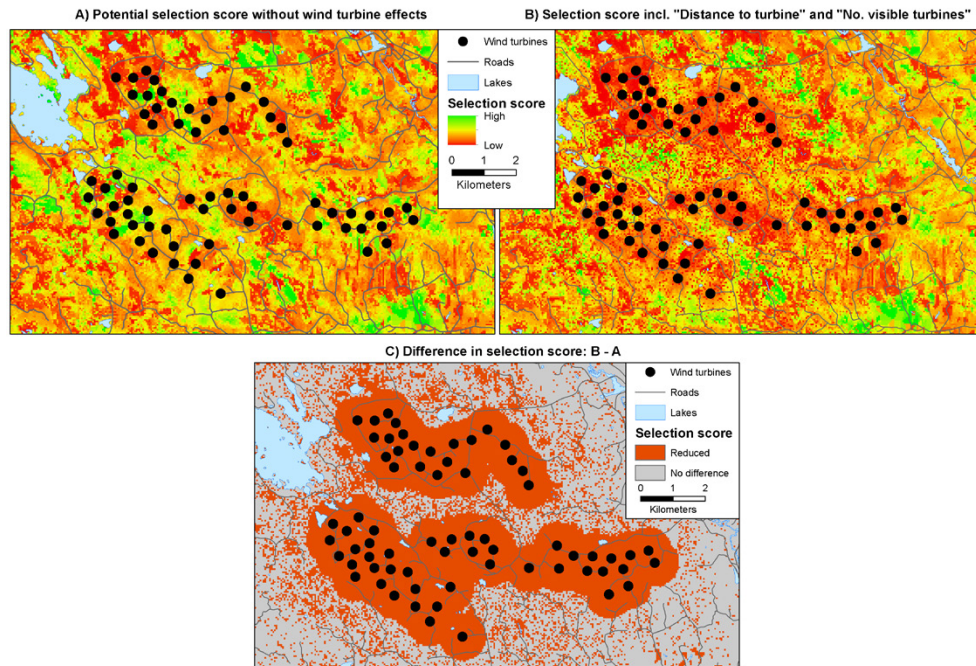


Figure 5. Potential selections score for the model “distance to turbine” in the summer season with the WEF predictors set to their minimum value (a), the selection score of the model including the distance to wind turbine and number of wind turbines visible (b), as well as the difference between the selection scores (c), indicating the areas which have a reduced selection score due to the wind turbine predictors. The predictor “distance to roads” was included in both models, therefore the impact of the access road is not visualized in the figure. Figures of the models including the other WEF predictors can be found in the supplementary material (S3-S5).

3.2 Movement behaviour

Capercaillie movement speed was significantly related to wind turbine visibility and the distance to turbine access roads, but not turbine shadow (Figure 6). Movement directionality was related to turbine shadow (Figure 6d), but not turbine visibility. The largest differences in movement speed and directionality were related to land cover type and daily and seasonal variation. Movement speed decreased with increasing turbine visibility up to ≥ 6 turbines (Figure 6a) and with increasing distance to turbine access roads (Figure 6e), where movement was also more directed (approximately $\geq 200\text{m}$; Figure 6f). While movement speed was unaffected by turbine shadow, it was more directional at intermediate amounts of shadow (Figure 6d). Accordingly, capercaillie moved slower if exposed to a larger number of visible turbines, but increased their speed in the vicinity of turbine access roads.

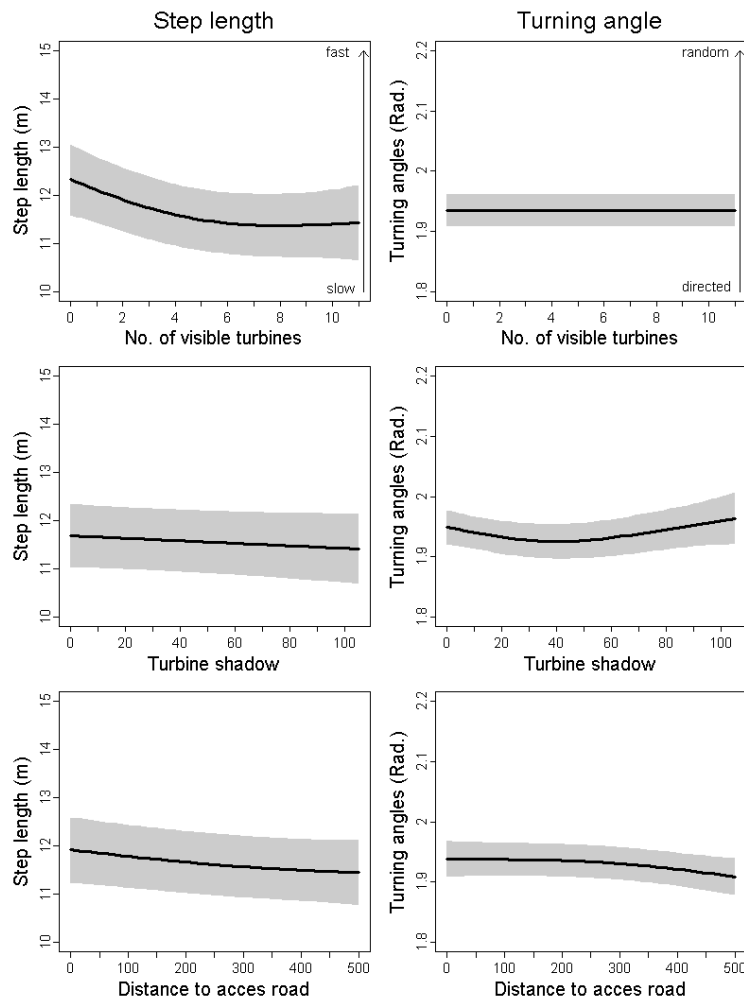


Figure 6 Effect plots displaying variation in step length (left column) and turning angle (right column) as a function of wind turbine predictors. Larger values for step length denote higher movement speed, while small values indicate a higher degree of stationarity. For turning angles, small values indicate higher directionality of movement and large values a higher degree of undirected movement or GPS scatter. All other covariates were held at their mean.

3.3 Habitat selection: indirect signs

Large scale

The density of capercaillie signs was higher in the control site (48.1%) compared to the turbine site (17.9 %) in the Swedish study area (Figure 7). However, as we cannot exclude that the placement of the control area affected the outcome due to no before-construction data, we excluded this data for the large-scale analysis. For this we included the study areas where data was available both before and after the construction of the wind turbines (N = 4), including control sites. We could not find significant differences in mean capercaillie sign density between impact and control sites (Figure 8), nor between years before and after construction of the turbines when analysing the data including only the study areas with before and after construction data (i.e. excluding the Swedish study area).

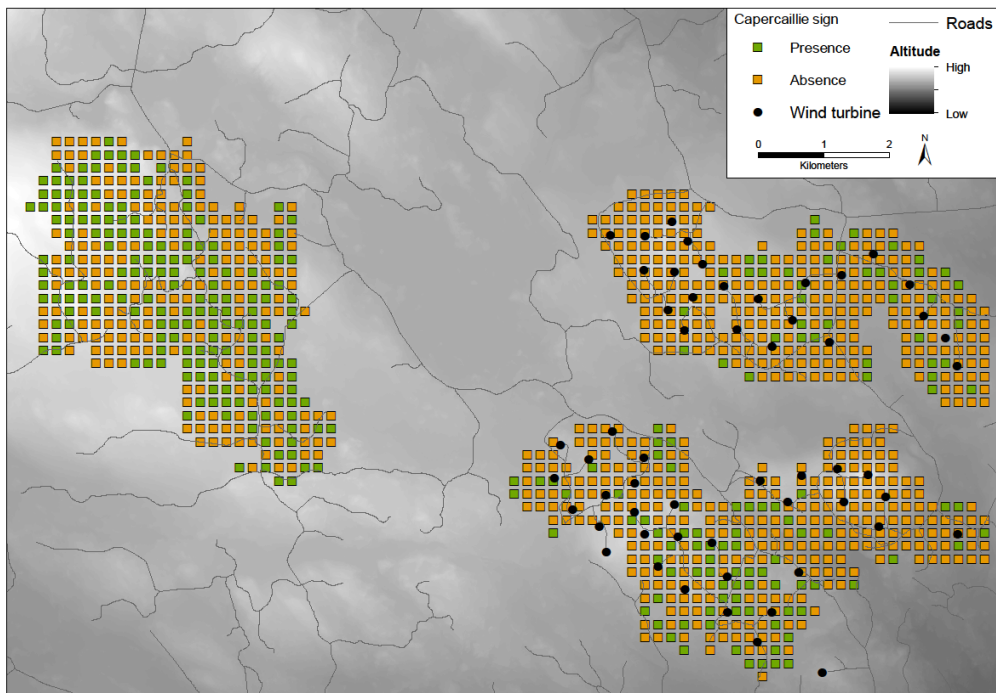


Figure 7 Presence (green) and absence (orange) of capercaillie signs at the sampling plots in the wind farm (right) and control area (left).

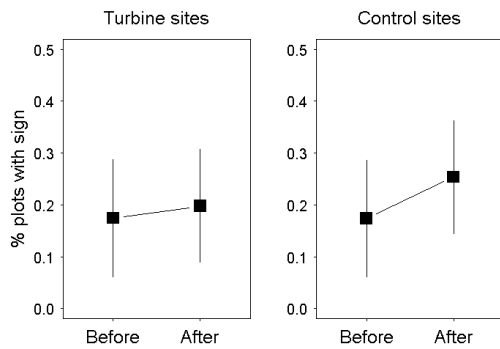


Figure 8. Effects of wind turbine presence on capercaillie sign density (i.e. % of plots with capercaillie signs) at the study area with a complete BACI design (N =4) as predicted by the large-scale GLMMs.

Small scale

In the plot scale analysis, we found a significant positive effect of the predicted index of habitat suitability on the probability of capercaillie presence (Figure 9d). Three out of four wind turbine predictors significantly negatively affected capercaillie probability of presence (Figure 9): The probability of capercaillie presence at a plot increased with increasing distance to the turbine for distances up to approximately 650 m; it decreased with increasing shadow for plots with over 2 h of meteorologically plausible turbine shadow per year; and it decreased with increasing turbine noise emissions for values exceeding approximately 30–35 dB (Coppes et al. 2020b). No significant effect of turbine visibility could be found on the probability of capercaillie presence.

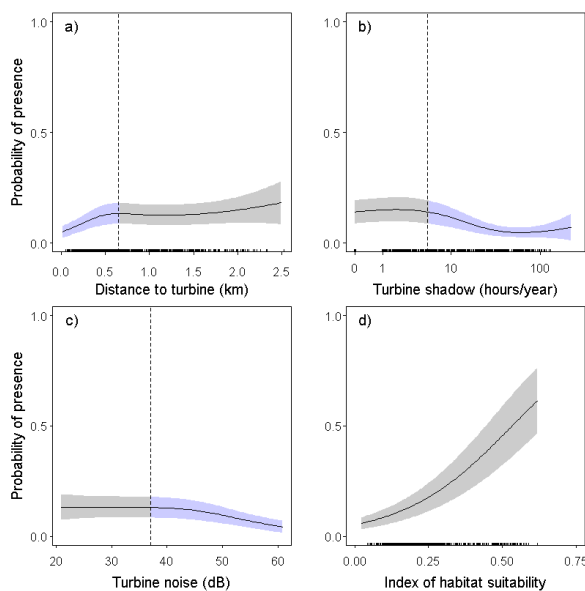


Figure 9. Conditional effect plots of wind turbine effects (a: distance to turbine, b: turbine shadow, c: turbine noise) on capercaillie habitat selection at six study sites across Europe as predicted by the small scale GAMMs. Predicted capercaillie occurrence was held at its mean to depict turbine effects independently of habitat suitability. Dashed lines indicate approximate effect thresholds. The effect plot for the index of habitat suitability (d) was exemplified using the turbine shadow model, holding all other predictors at their mean.

3.4 Reproduction monitoring

Over the four-year study period (2016–2019) a total number of 92 raster cells were sampled in the WEF area and 96 raster cells in the control area, respectively. Out of 601 detected birds, 295 capercaillie and 248 black grouse were counted. Remaining detections were recorded as hazel grouse, woodcock or unknown and excluded from further analysis. A total number of 99 capercaillie hens were observed, where approx. 50 % of counted hens were found with brood (N = 50) and 134 chicks were counted in total. Mean brood size varied between years, ranging from 2.2 to 5.0 in the control area and 1.4 to 4.0 chicks per brood in the WEF area (Table 5). Chicks per hen index also varied between years and were highest in 2016 for control area (2.1) and WEF area (2.0), respectively (Table 5; Figure 10). A negative trend in reproductive success were observed in both areas overall years (Figure 10). The chicks per hen index was significantly higher in 2016 than in the other years ($p = 0.05$), but there was significant difference between 2017, 2018 and 2019 ($p = 0.40$). No significant difference in the reproductive success between impact and WEF area could be detected ($p = 0.81$). Black grouse detections decreased rapidly overall years and areas, and could not be analysed in terms of productivity.

Table 5. Reproduction monitoring in the Jädraås wind park (WEF) and control area in 2016-2019. Provided are the number of raster cells sampled per area and year, number of capercaillie hens with brood, mean brood size and the chicks per hen index.

Year	Area	Raster sampled	Number of hens	Hens with brood	Number of chicks	Mean brood size	Chicks per hen
2016	WEF	22	12	6	24	4.0	2.0
2016	Control	25	12	5	25	5.0	2.1
2017	WEF	27	14	8	17	2.1	1.2
2017	Control	31	13	6	18	3.0	1.4
2018	WEF	18	11	4	12	3.0	1.1
2018	Control	24	12	5	11	2.2	0.9
2019	WEF	25	12	10	14	1.4	1.2
2019	Control	16	13	6	13	2.2	1.0

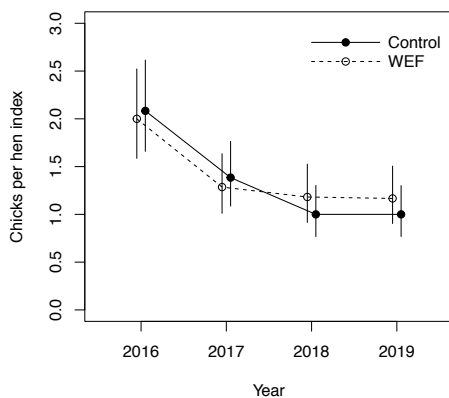


Figure 10. Chicks per hen index of capercaillie (\pm SE) in the Jädraås WEF (open dots and dotted line) and control area (dots and black line) between 2016 and 2019.

3.5 Mesopredator track densities

Snow tracks of the mammalian predators red fox and pine marten were identified on the triangle transects. Fox tracks were more frequent overall years and both study areas than pine marten tracks (Table 6). Slightly higher track densities were found in the WEF area for red fox overall years, whereas pine marten track densities varied between years and areas (Table 6, Figure 11). Lowest track densities were found for both species in 2016, which is probably caused by surveying only one triangle (9 km) per area. However, we could not detect any significant differences between the control and impact area ($p = 0.13$ for red fox and $p = 0.45$ for pine marten).

Table 6. Number of snow tracks and mean relative density (snow tracks per km) of fox and pine marten in wildlife triangle censuses covering the Jädraås WEF (impact) and control area between 2016 and 2019.

	Year	Study area N Triangles	Control		WEF	
			Mean (\pm SD)	Range	Mean (\pm SD)	Range
Red fox	2016	1	0.4	-	0.7	-
	2017	4	1.4 (0.6)	0.4-1.9	1.7 (0.9)	0.8-3.1
	2018	4	1.4 (0.8)	0.1-2.2	1.7 (0.9)	0.8-3.1
	2019	4	1.1 (0.9)	0.2-2.6	1.5 (0.8)	0.4-2.2
Pine marten	2016	1	0.1	-	0.4	-
	2017	4	0.2 (0.2)	0.0-0.6	0.8 (0.5)	0.3-1.7
	2018	4	0.9 (0.3)	0.3-1.1	0.5 (0.4)	0.1-1.0
	2019	4	0.3 (0.1)	0.2-0.3	0.4 (0.3)	0.1-0.9

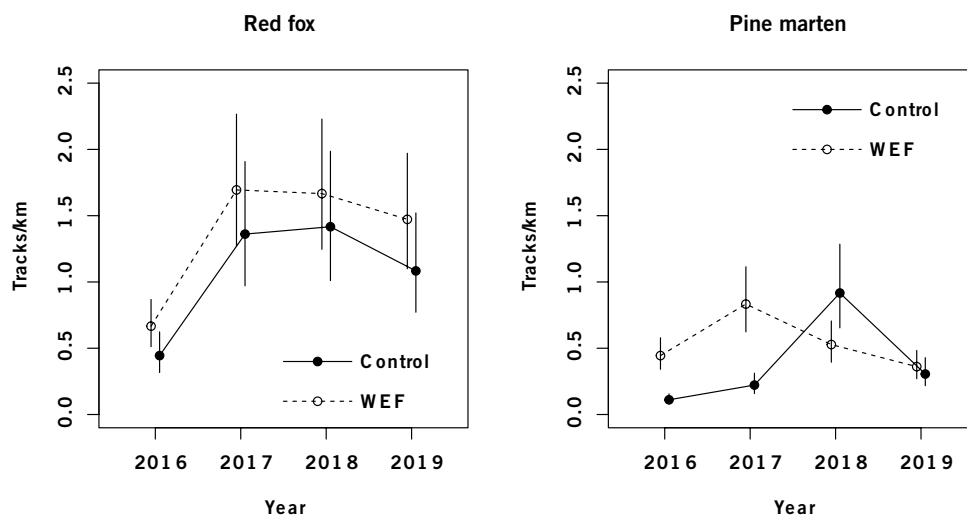


Figure 11. Mean relative density (snow tracks per km \pm SE) of red fox (left) and pine marten (right) in wildlife triangle censuses covering the Jädraås WEF (open dots and dotted line) and control area (dots and black line) between 2016 and 2019.

3.6 Stress physiology

A total of 579 capercaillie droppings could be collected in five different study areas, where samples were collected in both control as well as impact areas. In one study area in Germany and one in Austria it was possible to collect samples both before and after the construction of the wind turbines. In one Austrian study area samples were collected during the construction phase and after construction of the wind turbines and in two study area (Sweden and Austria) samples were only collected after construction of the wind turbines. This resulted in 202 samples before construction, 16 during construction and 361 samples after construction of the wind turbines.

When analysing the effect of wind turbines on the FCM levels, no significant effect could be found. There was no significant difference in FCM level between before and after construction of wind turbines and no significant difference between the control and impact areas. Similarly, no effect of wind turbine predictors (shadow flickering, sounds and proximity to nearest turbine) could be found on the FCM level in capercaillie droppings. Also, no effect of the season and human recreation activities on FCM levels could be found. However, there was clear seasonal variation in FCM levels during the collection period, with stress levels decreasing over time.

4 Discussion

4.1 Resource and habitat selection

Our study shows that wind energy facilities (WEF) affect capercaillie resource selection in seasons most important for the species' productivity, i.e. lekking and summer. Although we did not find absolute displacement from wind turbine areas, our results clearly reveal a reduced selection of areas under increasing WEF influence (Taubmann et al. 2021). The majority of studies about WEF effects on birds are conducted in open landscapes (Hötker 2017), and our study contributes to the knowledge about WEF impact on a typical species inhabiting boreal landscapes. Reduced selection of areas by capercaillie under WEF influence is in line with the results of our presence-absence mapping via indirect signs (s. also Coppes et al. 2020b). Beyond that, we were able to include two biologically important seasons and two additional turbine variables in our resource selection analysis showing that not only proximity to WEF, shadow and noise but also turbine density and access roads affect capercaillie behaviour. In contrast to presence mapping results, resource selection analysis could also reveal a negative impact of turbine visibility on resource selection of capercaillie. Reduced use of areas close to turbines, but also lek displacement and decreasing number of lekking males were found in other wind farms for capercaillie or black grouse (Rønning 2017; Zwart et al. 2015; Gonzalez et al. 2011, 2016). We found six capercaillie lekking sites with males and females present in distance of 325 to 950 m of WEF (Figure 1; S1), due to the lack of data from before the WEF construction, we cannot infer whether the location or number of males at the lekking sites was affected by the WEF in our study area. The high site fidelity grouse are known for and their relative long life span could also result in a slow displacement or extinction process of lekking sites close to wind turbines. At the end of the study in 2019, two of six leks in the wind farm were abandoned. The reason for abandonment remains unknown, it might also be related to logging at the location of the lekking sites.

The distance threshold of approximately 865 m found in our resource selection analysis is larger than the effect of wind turbines on capercaillie presence mapping with up to approximately 650 m in our five European study areas in total, still indicating that capercaillie are affected by wind turbines in similar magnitude as the birds fitted with GPS transmitters. Distances documented for black grouse in Austria (Grünschachner-Berger and Kainer 2011) and Scotland (Zwart et al. 2015) were shorter (500–600 m) for the influence of wind turbines. In contrast, line taxation in Spain revealed reduced indirect signs of capercaillie over an even greater distance from the wind turbine (1 000 m) (Gonzalez et al. 2011, 2016). What caused this difference, however, remains unclear. Compared to the avoidance of recreational infrastructure (i.e. hiking trails, mountain bike routes, cross-country ski trails, ski slopes) by capercaillie (Coppes et al. 2017), the effects of wind turbines seem to be effective over a greater distance.

Previous studies investigating resource selection of grouse under WEF worldwide also found effects on their study species behaviour. Female greater prairie-chicken (*Tympanuchus cupido*) doubled their home ranges in the breeding season after WEF construction in Kansas (Winder et al. 2014a). Greater sage-grouse (*Centrocercus urophasianus*) were found to reduce selection of brood and summer habitats when WEF associated surface disturbance increased (LeBeau et al. 2017). However, no negative effect has been found on survival of female greater prairie-chicken (Winder et al. 2014b) or on survival and nest site selection of greater sage-grouse (LeBeau et al. 2017). Proett (2017) observed that Columbian sharp-tailed grouse (*Tympanuchus phasianellus columbianus*) chick survival decreased by 50 % with more than 10 turbines within 2.1 km of the nest. This effect was however not detected in the following study (Proett et al. 2019). Species specific behaviours, the research question and the method used to investigate possible species response to WEF, can explain differences found in our study and the studies above. Where possible, future studies should try to account for these factors by focusing on a BACI design, including different methods to measure resource selection and survival. Our study was limited to data of capercaillie which were caught close to wind turbines, thus it might be argued that those birds had habituated to the presence of the WEF. Habituation to wind turbines has been shown for other bird species (Madsen and Boertmann 2008) and it is therefore possible that the effects of WEF on capercaillie might even be stronger, i.e. causing complete avoidance during the first years after construction (Pearce-Higgins et al. 2012). On the opposite, according to their long life span and high site fidelity, older individuals may stick to their traditional lek and surroundings no matter what, whereas following generations could avoid resources in the same area.

Wind turbines can potentially influence their environment by a couple of factors such as noise by construction and the operational blades or visibility of turbines. As similar to Coppes et al. (2020b), some turbine variables showed a high correlation in our study and a trace back to a single trigger is often challenging (Langston and Pullan 2003). We could not completely clarify if one or a combination of turbine variables affected resource selection of our study species. However, there are different plausible ways why capercaillie may have respond towards WEF. Moving turbine blades as well as shadow flickering may cause anti-predatory response of capercaillie, in fear of aerial predators. This is also supported by the decrease in movement speed as wind turbine visibility increased, as being inconspicuous is an anti-predator response in capercaillie (Klaus et al. 1989). We thus suggest that the visual cues provided by visible turbines may provoke an anti-predator response in the birds (Figure 6a). Continuously at risk, they may leave areas highly influenced by turbines, thus resulting in reduced resource and habitat selection. Their known sensitivity to anthropogenic disturbance e.g. by recreational infrastructure (Summers et al. 2007; Moss et al. 2014; Coppes et al. 2018b) may indicate that maintenance work with accompanying traffic and turbine noise emissions can lead to avoidance of turbine pads and access

roads. Also, linear structures such as new and broader roads within the forest landscape may be used more frequently by mammalian predators (red fox, pine marten) (Helldin et al. 2017; Sirén et al. 2017), likewise increasing predation risk on site (Gómez-Catasús et al. 2018). During winter, access roads are cleared of snow for WEF maintenance service, which could additionally increase predator activity in otherwise remote and hardly accessible areas. Our wildlife triangle results however did not support this change in predator behaviour.

The magnitude of WEF impact on capercaillie might also be dependent on habitat suitability or availability. Given a wide-ranging forest landscape with regularly distributed high-quality habitat patches, avoidance of WEF by capercaillie may be more likely than in low-quality areas, where the few attractive patches might be close to turbines (Percival 2005). During summer the birds preferred stands with intermediate density and intermediate tree diameter (i.e. denser and older stands), which reflect, among others, the canopy cover in a forest stand (Miettinen et al. 2010). Stands with low to intermediate canopy cover are an important factor for capercaillie habitat suitability (Storch 1995). Capercaillie males select within the summer range for older forests and especially females for denser forests due to coverage from predators (Rolstad et al. 1988, Storch 1993). The selection of areas bordering forest bogs in our study may be explained by a usually dominant bilberry (*Vaccinium myrtillus*) field layer (Wegge and Rolstad 2011) on mesic sites surrounding the wetland, providing an important food resource for the capercaillie. Rolstad (1989) and Wegge et al. (2005) e.g. suggested spruce mires to present a favourable summer habitat for capercaillie.

Home range sizes of capercaillie males during the lekking season were relatively small, fitting to the fact that the birds stay close to the lekking site during the season (Klaus et al. 1989). Summer home range sizes of males in our study were larger (504 ± 301 ha) than reported by Rolstad et al. (1988) in Norway (170 ha) and Storch (1993) from the Bavarian Alps (248 ha), but of similar size to those found in the Black Forest. Even though the landscapes differ between our study area and the Black Forest (i.e. more mountainous in the Black Forest compared to the Swedish study area), the home ranges of males and females are similar in magnitude to those found in the Black Forest (581 and 207 ha, respectively, Coppes et al 2017). When comparing female summer ranges, our results (150 ha) were in line with findings in the above-mentioned studies (Rolstad et al. 1988: 103 ha; Storch 1993: 162 ha). Home ranges of eight birds (four males and four females) did overlap to a large extent during summer, especially those of males caught at the same lekking ground. This pattern of non-territoriality in summer is commonly known for the species (Rolstad et al. 1988; Storch 1995). As our study covered the post-construction period of the wind farm, we could not determine whether capercaillie home range size or selection was affected by the presence of the wind turbines or associated infrastructure, as has been reported for greater prairie-chicken (Winder et al. 2014a).

4.2 Reproductive success

Based on the data collected, no difference in the reproduction success between WEF and the control area could be determined. Thus, no negative effects of WEF on the reproductive success of capercaillie were detectable at the area level. Rather, the reproductive output seemed to depend mainly on the annual variation within the study period. Overall areas, values for capercaillie chicks per hen were highest for 2016, with a considerable decline of chicks per hen in the following years. This trend was also prevalent for the mean brood size, but not detectable for the number of hens with brood. Strong fluctuations in abundance and reproductive success are known for capercaillie (Lindström 1996), which is partly caused by the annually changing weather conditions and predation. Since the decrease in reproductive success was present in both areas, this development was probably caused by suboptimal weather conditions and/or by predators. The natural or forestry-related changes in the habitat were low over this period and were comparable in both areas, but the habitat suitability can change quickly due to forestry measures (e.g. large-scale clear-cuts). There were also no changes in data collection. However, the results only reflect the reproduction success after the WEF were built. Since there is no data on the reproduction success before the construction of WEF in this study area, it is not possible to draw any comparisons before and after the construction of the WEF.

4.3 Mesopredator track densities

Mesopredator track analyses did not reveal significant differences between WEF and control area. Slightly higher red fox track densities were found in the WEF area compared to the control area, but this was not significant. As track densities are a measure of abundance, this could imply higher fox activities or densities (Lindström 1989; Thompson et al. 1989) and may increase the predation risk for grouse around turbines and their infrastructures. This is a possible scenario which has to be considered, as higher mesopredator densities in boreal landscapes fragmented by human activities is a well-known phenomenon (Kurki et al. 1998; Prugh et al. 2009; Kämmerle et al. 2017). However, as the track densities are influenced by other factors such as prey density and snow conditions, it is important in wildlife triangle censuses to cover several years, and accounting for e.g. high or low vole population years (Kurki et al. 1998). In our study, four seasons were covered for assessing track densities in control and WEF area, but only three years included four triangles per area. Thus, the results may indicate a difference in mesopredator densities between both areas, but this needs to be interpreted with caution and indicates the importance of 1) a long-term wildlife triangle monitoring on a large-scale and 2) additional research methods for assessing mesopredator densities in boreal landscapes under WEF influence.

4.4 Stress physiology

Although capercaillie show a behavioural response to the wind turbines our results show no evidence for increased FCM levels in capercaillie due to the presence of WEF. In contrast, roe deer show a behavioural response (i.e. reduced use of areas close to wind turbines (Łopucki et al. 2017)) which is accompanied by increased FCM levels (Klich et al. 2020). Capercaillie show a behavioural response to human recreation activities (Summers et al. 2007; Moss et al. 2014; Coppes et al. 2017), which is accompanied by a stress response, reflected in increased FCM levels close to recreation infrastructure (Thiel et al. 2008; Thiel et al. 2011; Coppes et al. 2018a). It is possible that although capercaillie show a behavioural response to WEF, the fact that we did not find increased FCM levels related to FCM is caused by methodological drawbacks associated with our study. As we were unable to correct for endogenous (i.e. individual heterogeneity, sex) as well as exogenous (i.e. habitat suitability, food conditions, predators, weather) factors which are known to affect FCM levels in wildlife.

5 Synthesis

Our review revealed a large number of potential effects of WEF on grouse, especially with regard to changes in resource and habitat selection behaviour. Also, collisions of grouse, including capercaillie, with the towers of wind turbines have been documented many times (Gonzalez 2018; Langgemach and Dürr 2019). The reason why birds collide with towers may be linked to weather conditions with poor visibility. But escape reactions of willow ptarmigan led to turbine tower collisions even in good weather and visibility conditions (Falkdalen et al. 2013). This fatal effect of WEF can be minimized by the use of contrast painting to the tower, as presented in the recent study of Stokke et al. (2020). However, in the case of forest grouse, no systematic survey for turbine collision victims has been conducted, nor is there any experience if the tower colour reduces the risk of collision. Also, the synthesis report of Rydell et al. (2017) did not report any case where forest grouse collision rates have been estimated so far in Sweden. It therefore remains unclear how often or how many capercaillie collide with wind turbines. When new wind turbines are built in capercaillie areas, it must be taken into account however that capercaillie are likely to collide with wind turbines.

The influence of WEF on presence and persistence of grouse leks and its magnitude includes total abandonment, decreasing lekking males, temporarily disturbance with lek recovery after WEF construction and no effect at all (Coppes et al. 2020a). In our study, we found active capercaillie leks evenly distributed in the wind farm, which seems a positive sign for renewable energy while species conservation. But without any data before WEF construction and a subsequent long-term monitoring, that finding holds few valuable information.

The influence of wind turbines on the resource and habitat selection behaviour of capercaillie was investigated using two different methods. Both the systematic search for indirect signs of capercaillie (Storch 2002; Poggenburg et al. 2018; Coppes et al. 2018a; Zohmann et al. 2014) and the tracking of individual capercaillie (Storch 1993; Storch 1995; Coppes et al. 2017) are established methods for recording presence data. The results show that capercaillie use areas influenced by wind turbines less than other areas with comparable habitat suitability. Due to the high correlation between the distance to the wind turbine, turbine shadow, noise emission and visibility, it was not possible to conclusively clarify which factor or which combination caused these effects. It is therefore possible that the species' behaviour is influenced by the noise emissions, turbine shadows, the visibility of the wind turbine and its rotating rotor blades or other factors caused by wind turbines.

In the following, we will primarily deal with the predictor “distance to wind turbine” because it is the simplest to take into account as a central influencing variable, especially for construction planning of wind turbines in capercaillie habitats and environmental impact assessments. In six European study areas indirect sign mapping revealed that the use of an area by

capercaillie was lower the closer the area was to the wind turbine. Similar effect was found for resource selection of tracked animals in Sweden. A distance threshold for both methods could be determined, were capercaillie used areas up to a distance of 650 m and 865 m, respectively, less intensive than areas further away. The results of the telemetry data relate to the resource selection by individuals, while the indirect signs relate to habitat selection of the entire population. Although the methods are very different, the distance effects are of a comparable magnitude. The effects of turbine shadow and noise emissions found with the different methods were also similar in terms of their magnitude.

The distance-dependent impairment of the habitat and resource selection of capercaillie in the vicinity of wind turbines is a consistent result in all of our study areas. From this it can be deduced that habitats around wind turbines are no longer available to capercaillie without being impaired. The impairment of the habitat use by wind turbines was also found in study areas in which the wind turbines had been standing for a long time. It can therefore be assumed that the impairment will not only have a short-term effect during or immediately after the construction phase, but also in the long-term.

Capercaillie selected areas close to wind turbines less, but we could not determine any significant differences between areas with and without wind turbines in the capercaillie indirect sign density of the total study area. Although there were lower detection rates in the WEF areas compared to the control areas, the difference was not significant. As we found different results for the habitat selection scores based at individual level and the indirect signs at populations, the population level effects of WEF clearly needs to be studied further (see below). However, it can be assumed that the determined influence of WEF on capercaillie habitat selection can lead to a lower density of capercaillie signs. The effects found in our study are likely to be closely related to the suitability of the habitat and the density of capercaillie signs also in the wider surroundings. If there is suitable habitat outside the WEF area, it is unlikely that the capercaillie density in the wider surrounding will be negatively influenced by the construction or the presence of WEF. However, if WEF are built in the remaining areas that offer suitable habitat in small patches (e.g. due to the topography or forestry), it is more likely that the habitat impairment in the vicinity of the WEF can also have an impact on the capercaillie density in the entire landscape. With regard to a possible compensation for the negative effects caused by WEF, the results show that the impairment caused by the WEF cannot be compensated for on the same area, since the avoidance of wind turbines is independent of the habitat quality of the area. The analysis of GPS locations of capercaillie has also shown that resources are selected less the closer they are to the access roads to WEF. This indicates a further, indirect impairment of the birds, which is caused by an accompanying WEF infrastructure.

For the evaluation of the effects of WEF on the reproductive success, it was only possible to systematically collect data in the study area in Sweden.

The transferability of the results to other areas is not scientifically guaranteed without further investigations. The index for the reproductive success (number of chicks per hen) was similar in the Swedish WEF Jädraås to the control area without wind turbines. Thus, an influence of WEF on the reproductive success of capercaillie could not be found. However, no data from the period prior to the construction of the WEF could be taken into account.

The analysis of stress hormone products from 579 capercaillie faeces samples from five study areas did not reveal any evidence that WEF lead to an increase in the stress hormone level in capercaillie. Since an animal's stress hormone level is influenced by a variety of environmental factors and physical responses, the natural variation in such data is very high. In capercaillie, this is also due to individual differences. As the samples could not be assigned to individuals, it was not possible to take individual differences into account in the analyses. Therefore, the results should be viewed with this restriction.

In summary, it can be deduced from the results of the research project that the following effects of wind turbines must be taken into account when building WEF in areas relevant to the capercaillie:

- Risk of collision
- Impairment of the resource and habitat selection in the vicinity of the WEF
- Impairment of the resource and habitat selection through accompanying infrastructure

6 Management implication

Our study indicates that capercaillie resource selection is affected by the presence of wind turbines. Depending on the method used, we derived a distance threshold between 650–865 m beyond which turbine effects appear negligible. This result can be easily applied in conservation and WEF planning, especially where capercaillie show distinct or patchy distribution patterns. We included study areas from three different European countries, where every nation holds its own guideline and precautionary principle to deal with grouse conservation and wind energy construction. Thus, with regard to the national, regional or even local population status of capercaillie, different aspects and regulation methods have to be considered. For areas with a wide-ranging capercaillie distribution and stable population as in Sweden (Wirdheim and Green 2021), our estimated distance thresholds should at least be considered for those locations most important for capercaillie survival, such as brood summer habitats and lekking grounds. Buffer zones of one kilometre around leks with more than five (Rydell et al. 2011) and more than ten capercaillie males (SOF-BirdLife 2014) are recommended, respectively. In addition, we propose to apply our estimated distance thresholds also for capercaillie summer habitats under consideration of the local forestry. Also, Rydell et al. (2017) propose a stronger focus on habitat suitability for the capercaillie, which includes the lekking sites, in the landscape. This could be done by incorporating habitat suitability maps into planning of protected areas for capercaillie (Länsstyrelsen Jönköping 2014), as the population level effects WEF could depend on the amount of suitable habitat in the landscape and whether the WEF are built in the remaining patches of suitable habitat or not. Although it remains unknown whether the detected effects bear actual fitness costs, particularly in small or threatened populations additional causes of habitat deterioration should be minimised. We therefore advise to apply the precautionary principle and, in areas with threatened and/or small populations, e.g. those with unfavourable conservation status according to EU legislation, avoid WEF construction within 865 m from capercaillie occurrence, to minimize the risk of negative population-level effects by the presence of wind turbines.

7 Recommendations for future studies

Although our study gives insight in the effects of WEF on capercaillie there still remain questions unanswered. Here we provide some insights in possible study designs and methods applied to further study the effects of WEF on capercaillie.

Study design: BACI vs CI

The initial aim of our study was to perform research in as many study areas as possible using the before-after-control-impact study design. During our study this however proved very complicated: as wind farms are constructed in relatively short time after permission has been granted, we also collected data in areas where wind turbines were being planned, but due to the long planning phase of wind turbines (e.g. often several years) this resulted in data collection also in areas where wind turbines were not constructed in the time of our study. Therefore, including multiple BACI sites in a study has proven to be difficult and resource consuming even for a study expanding six years. Although using a multiple BACI study design is desirable, we assume that it is also possible to apply a multiple control-impact design (i.e. no before construction data but replications on several sites and years) that can give valuable insights in the effects of WEF on capercaillie. As this would only be based on already constructed WEF, planning and running the project is less complicated. It must however be stressed that the control sites are carefully selected to be as similar as possible (i.e. habitat conditions, forestry, other human disturbance such as recreation or roads) to the respective impact site and that multiple control-impact sites are studied (>5 impact sites).

Reproduction success

In our telemetry study we focused on the effects of WEF on an individual level and were unable to assess the effects of WEF on capercaillie populations. To further study the effects of WEF on capercaillie population level we propose that the reproduction success, with the methods used in our study, is performed in multiple impact and control sites, to see if the results of our study are confirmed. It is however important to also correct for habitat conditions, forestry measures and other impact factors on capercaillie.

Increased mortality

Despite the fact that the majority of WEF in Sweden are constructed in forests, only few carcass searches around wind turbines have been done in woodlands (Rydell et al. 2017). However, there are documented cases of capercaillie and black grouse colliding with the towers of WEF (Coppes et al. 2020a), which have been found accidentally without systematic searches. To quantify the collision risk of capercaillie and to assess whether this might

affect local population size systematic searches using standardized protocols should be applied in wind farms with capercaillie occurrence. In terms of effectivity, carcass search around turbines in forest landscapes should be conducted within a multi-species approach, where bird and bat carcasses are simultaneously and systematically searched for by wildlife detection dogs-teams (Mathews et al. 2013; Smallwood et al. 2020).

Mesopredator density

We found slightly higher, yet non-significant, red fox track densities in the wind farm compared to the control area. Repeating this method to assess mesopredator densities in multiple impact and control sites might answer if mesopredator densities increase with wind turbine developments, which in turn is expected to negatively influence grouse survival.

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An international research project

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The authors assume sole responsibility for the contents of this report, which therefore cannot be cited as representing the views of the Swedish EPA.

This report is part of an international five-year research project, “Capercaillie and Wind Energy” that investigates whether there are scientifically verifiable effects of wind turbines on capercaillie, as well as what these effects are.

In Sweden, Capercaillie were studied in the Jädraås wind park for a 4-year post-construction period. Potential impacts of wind energy facilities on the species’ individual and population level were analysed by studying resource and habitat selection, movement ecology, reproduction success, risk of predation and stress physiology. The researchers could not find significant differences in mean capercaillie sign density between wind energy facilities and control sites. The study revealed a decrease in resource selection within a distance of approximately 865 m around wind energy facilities.

For Sweden, the researchers propose a focus on suitable habitat in the landscape in combination with a distance threshold of 865 m to capercaillie leks and summer habitats, to minimize the risk of negative population-level effects by the presence of wind turbines and their accompanying infrastructure. The effect of population survival strongly depends on the species’ regional and national status.

The project was financed by Vindval and the Swedish Environmental Protection Agency.

The Vindval research programme collects, creates and communicates information and facts about the environmental impact of wind power on the environment, the social landscape and people’s perception of wind power installations. Vindval provides funding for research, including literature reviews and syntheses regarding the effects and experiences of wind power.

