Inland Norway
University of
Applied Sciences

Faculty of Applied Ecology, Agricultural Sciences and Biotechnology

Cecilia Miltz

Master's thesis

Wolf use of areas planned for wind power development in Scandinavia

Master in Applied Ecology

2022

Abstract

The global energy demand is increasing, and the world is shifting towards using more renewable energy. As a result, onshore wind power development is increasing, though little is known about effects of wind power development on terrestrial mammals. This results in information about effects of wind power development on wildlife often not being included in environmental impact assessments (EIA), when planning new wind power plants.

In Norway and Sweden, the wolf (*Canis lupus*) distribution is partly overlapping with sites chosen for wind power development, but to my knowledge no studies on the effects of wind power development on wolves in Scandinavia have so far been done. A monitoring programme in Portugal has shown that wolves were influenced by wind power development especially during the construction phase, wherefore it could be assumed that this is applicable in this study area too.

Using GPS and VHF positions (wolf pair level: n = 56335; individual level: n = 17859) of wolves (wolf pair level: n = 58; individual level: n = 38) in Norway and Sweden, I investigated if there is the potential for wind power development to influence wolf area use by using wolf space use data from before the construction. This was done by looking at overlap of proposed and established wind power plants, consisting of one or several clusters of wind turbines, with wolf territories on the landscape level and on a finer scale in the immediate surroundings of the wind turbines. Since wolf pairs travel together most of the year, except during the denning season, I analysed observations on two levels: as individuals during the denning season and in wolf pairs for the remainder of the year.

My results indicate that on the wolf pair level the highest overlap is found during the denning season, followed by the rendezvous season, early winter and least in late winter. The same pattern was found for the probability of individual wind turbines being placed in the wolf activity centre. However, the proportion of areal overlap between wind power plants and the wolf activity centre were rather low on both the wolf pair level (mean: 0.02; range: 0.00 - 0.56; 95% CI [0.01; 0.02]) and the individual level (mean: 0.05; range: 0.00 - 0.61; 95% CI [0.01; 0.08]). On the individual level, sex, reproductive status, and time of day were affecting both the wolf usage index and probability of individual wind turbines being placed in the wolf activity centre. The wolf usage index at turbine sites for non-breeding wolves (mean: 0.31; range: 0.00 - 0.99; 95% CI [0.29, 0.33]) was higher compared to breeding wolves (mean: 0.21; range: 0.00 - 0.99; 95% CI [0.19, 0.21]). The probability of individual wind turbines being placed in the activity centre was low and no large differences between reproductive statuses and sex were found.

These findings are in accordance with previous findings, that wolves are most vulnerable to wind power development during the denning season. However, my findings indicate that wolf family groups might be vulnerable to wind power development also during the rendezvous and early winter season. To verify the findings of my study, quasi-experimental studies with a Before-After-Control-Impact (BACI) design on radio-collared wolves could be used. If this verifies my findings, the here used approach could be a more time- and cost-effective way than BACI studies to provide information for EIAs in the future.

Keywords: wind power, wolf, space use, environmental impact assessment, GPS positions, VHF positions

Table of Contents

List of figures

List of tables

1 Introduction

From 2009 to 2021, the global energy demand increased by 20% (REN21, 2021). In the light of climate change, many countries around the world are shifting towards using renewable energy. Especially wind power development has experienced an increase, and reached a record for new installations in 2020, where onshore wind power made up the majority of new installations (Global Wind Energy Council, 2021; REN21, 2021).

Wind power constructions come with alterations to the habitat including cleared vegetation, the turbine installation itself, and the construction of roads, buildings and power lines (Helldin et al., 2012; Kuvlesky Jr et al., 2007). The way wildlife is affected by wind power development is diverse. Direct disturbances by wind turbines are e.g. noise, visual disturbance, habitat alterations or direct mortality (Arnett et al., 2007; Helldin et al., 2012; Kuvlesky Jr et al., 2007; Lovich & Ennen, 2013). Such direct disturbances can for example lead to a disruption of vocal communication of animals, habitat fragmentation and barrier effects (Helldin et al., 2012). Indirect impacts of wind power development are e.g. increased human disturbance due to improved access, such as for hunting and recreational activities (Helldin et al., 2012).

Human disturbance can alter activity and movement patterns (see e.g. Andersen et al., 1996a; Naylor et al., 2009; Olsson et al., 2007). For example moose (*Alces alces*) increased home ranges during large scale military manoeuvres in Norway (Andersen et al., 1996) and North American elk (*Cervus elaphus*) increased their travel time due to recreational disturbances in Oregon, USA (Naylor et al., 2009). More specifically to wind power development, Skarin et al. (2018) found that reindeer (*Rangifer tarandus*) shifted their home range selection away from wind power plants. A shift of home ranges was also found for wolves (*Canis lupus*) in Portugal due to wind power plant construction (Álvares et al., 2011, 2017). Furthermore, an increase in traffic on the new built road network is expected with the largest increase during the constructions phase (Ferrão da Costa et al., 2018). Other outcomes of human disturbances can also be reduced survival or reproduction (Frair et al., 2008; Gill et al., 2001). For example, Frair et al. (2008) found an increased mortality risk for elk with increasing road density.

The way wildlife responds to these changes and disturbances in their habitat does not need to be permanent. For example Helldin et al. (2012) states that studies on ungulates and large carnivores demonstrate that these species avoid wind farms during the construction phase, but that the changes might only be temporary. In addition, wildlife may show different behavioural responses to human disturbances based on their ecology and role in the ecosystem, and these responses do not necessarily have to be negative for their fitness (Helldin et al., 2012). For example, Zimmermann et al. (2014) found that wolves use gravel roads for travelling because it eases their travel and might minimize energy expenditure and maximises travel speed.

Most studies on effects of wind power development on wildlife have been focussing on avian species and bats (Kuvlesky Jr et al., 2007). Consequences for those species can be both direct effects such as mortality due to collisions or indirect effects due to for example habitat changes (Rydell et al., 2012). But there have also been studies on terrestrial and marine mammals, such as harbour seal (*Phoca vitulina*) and porpoise (*Phocoena phocoena*) (Koschinski et al., 2003), reindeer (Skarin et al., 2018), roe deer (*Capreolus capreolus*) (Klich et al., 2020) and wolf (Álvares et al., 2011, 2017; Ferrão da Costa et al., 2018; Passoni et al., 2017).

So far, research on the effects of wind power development on wolves has mainly been focussing on reproduction and choice of denning sites (Álvares et al., 2011, 2017). Studies conducted in Portugal reported home range shifts away from wind power plants, a decrease in reproductive success, change in den site selection and relocation of rendezvous sites (Álvares et al., 2011, 2017). But these changes were often only temporary (Ferrão da Costa et al., 2018). Furthermore, Passoni et al. (2017) found that wind power plants are often built in high quality areas for wolf reproduction in Croatia.

My study investigates how wolves might be impacted by wind power development on the Scandinavian Peninsula. The shared wolf population of Norway and Sweden, hereafter the Scandinavian wolf population, has its distribution in an area of wind power development, where the development has been taking place since the late 1990s (Pettersson et al., 2010). Wind power development sites are constrained by several criteria. A study by Ryberg et al. (2020) defined those by evaluating land eligibility constraints for onshore wind power. Some of those constraints were slope (> 17°), elevation (> 2000 m), distance to features like water bodies (< 400 m), all settlements (< 800 m), urban settlements (< 1.2 km), primary roads (< 300 m), secondary roads (< 200 m) and natural monuments (< 500 m) (Ryberg et al., 2020). Additionally, they are usually built in wind-rich places (Ryberg et al., 2020), and since wind speed increases with altitude, they are often placed on top of mountains and hills.

The wolf is a generalist species with regards to habitat requirements and is highly adaptable (Mech & Boitani, 2003). This is reflected in the wolves' widespread distribution occupying a variety of different habitats. Their movement and activity especially in winter is mainly driven by prey availability (Fuller, 1991). Wolves usually avoid areas with high human activity which is connected to e.g. roads and human settlements (Carricondo-Sanchez et al., 2020; Hebblewhite et al., 2005; Kaartinen et al., 2005; Karlsson et al., 2007; Ordiz et al., 2015). But the strength of the effects depends on the time of the year and it seems like wolves are most vulnerable to disturbance during the denning and rendezvous season (Houle et al., 2010). Those seasons can also impact habitat choice of young wolves after dispersal (Milleret et al., 2019; Sanz-Pérez et al., 2018). For example, wolves in Scandinavia chose natal-like habitat when dispersing short distances (Sanz-Pérez et al., 2018).

There are various negative influences of anthropogenic impacts on wolves, but for example logging can be a beneficial disturbance as it leads to a higher abundance of young forest stands and attracts species such as moose (Lindenmayer & Franklin, 2003; Potvin et al., 2005), which are the main prey of wolves in Scandinavia (Zimmermann et al., 2015). Another example are gravel roads, which are used by wolves for travelling to ease their travel (Zimmermann et al., 2014). Wolves avoid high altitudes in winter (Ordiz et al., 2020), which is most likely connected to the change in moose distribution (Allen & Singh, 2016), and they select for habitat in forested areas with rugged terrain (May et al., 2008; Milleret et al., 2018; Sanz-Pérez et al., 2018). Furthermore, Scandinavian wolves are also choosing mountainous terrain when establishing new territories, with low slopes and low human accessibility (Sanz-Pérez et al., 2018). Wolves have their activity peak at dawn whereas moose at dusk (Eriksen et al., 2011; Theuerkauf et al., 2003). Besides, wolves in Scandinavia choose resting sites during the day at intermediate distances to gravel roads and human settlements, large distances to main roads, and they avoid open habitat (Zimmermann et al., 2014). During the night distance to gravel road does not affect their choice of resting sites, though they still avoid main roads, but not as strongly, and avoid open habitat (Zimmermann et al., 2014). Therefore, it can be expected that habitat preferred by wolves may overlap with wind power development sites in certain situations.

Environmental Impact Assessments (EIA) are used to assess potential impact of projects or developments on the environment, and they can be part of the permitting process of wind power development. Though possible impacts of wind power development on terrestrial mammals are often not included in EIAs (Lundberg, 2011 cited in Helldin et al., 2012), most likely because there is a lack of knowledge.

The aim of this study was to investigate if areas selected for wind power development coincide with important wolf habitat, and thus the potential of wind turbines influencing wolf area use. I did this by analysing the overlap between proposed and developed wind power plants and high usage areas within wolf territories on the landscape level and on a finer scale in the immediate surroundings of the wind turbines, using wolf GPS and VHF positions from before the wind power plant construction. The aim is to answer the following questions:

1. Do wolf territories overlap with sites selected for wind power development?
2. Do high usage areas of undisturbed wolves overlap in space with sites selected for wind power development? And does the time of year and day as well as sex and reproductive status influence the amount of overlap?
3. What is the probability of individual wind turbines being placed in the activity centre of wolves?
4. What determines the areal overlap between wind power plants and the wolf activity centre?

Testing the following hypotheses, based on general knowledge on wolf habitat choice and behaviour as well as previous studies on effects of wind power development on wolves:

I. High usage areas of wolves overlap with wind power development sites.
II. Wind power development sites will overlap more with diurnal than nocturnal high usage areas of wolves.
III. There will be more overlap between high usage areas of wolves and planned wind power development sites during the denning and rendezvous seasons compared to early and late winter.
IV. There will be a difference in overlap between females and males during the denning season.
V. There will be a difference in overlap depending on the reproductive status (breeding wolves versus wolves without offspring) during the denning season.

The analysis of animal movement data prior to wind power development could be a more time- and cost-effective way to predict potential impacts of planned wind power development on wildlife. To my knowledge this thesis is the first to study the area use of sites chosen for wind power development using GPS and VHF positions of wolves from before the construction. This method could also be applied to other terrestrial mammals that are suspected to be impacted by wind power development.

2 Materials and methods

2.1 Study area

This study focused mainly on wolves located in south-central Scandinavia (Norway and Sweden, hereafter Scandinavia) except for a few individuals in northern Sweden (Figure 1). All together, the study area has an approximate size of 83 290 km^2 (south: 77 111 km^2; north: 6 179 km^2) and is partly located in Norway, but the major part is in Sweden. The southern part of the study area had a mean elevation of 273 m (range: 0 – 1738 m) and the northern part 174 m above sea level (range: 0 – 451 m). The southern part of the study area is dominated by boreal coniferous forest with Norway spruce (*Picea abies*) and Scots pine (*Pinus silvestris*) mixed with birch (*Betula spp.*), and to a lesser extent with rowan (*Sorbus aucuparia*), aspen (*Populus tremula*) and willow (*Salix spp.*). The density of secondary roads is high (avg.: 8.5 km/km^2) due to forestry, whereas primary road density is lower (avg.: 2.7 km/km^2) (Loosen et al., 2021). Generally road density is higher in the south (Loosen et al., 2021). The climate is continental in most of the study area, with snow cover between December to March (Mattisson et al., 2013).

The wolf was functionally extinct in Scandinavia in 1966 (Wabakken et al., 2001). Today's Scandinavian wolf population was founded by two wolves from the Finnish-Russian source population in 1983 (Wabakken et al., 2001). In 2021/2022 the Scandinavian wolf population has been estimated to be 540 (95% CI = 364-598) individuals in 55 family groups and 28 pairs (Wabakken et al., 2022). Besides wolves, three other large and medium-sized carnivores are present in the study area, i.e. wolverine (*Gulo gulo*), brown bear (*Ursus arctos*), and lynx (*Lynx lynx*). Wolves' main prey in this area is moose (Zimmermann et al., 2015).

2.2 Wind power development sites

A wind power plant is defined as a group of wind turbines that are used for electricity production. The placement of individual turbines within a wind power plant are dependent on various conditions, such as the terrain, wind speed and direction, turbine size, but there are ongoing developments on how to place individual turbines in an optimized way (Emami & Noghreh, 2010). The process of receiving a permit to build wind power plants differs between Norway and Sweden. In Norway all wind power plants that exceed an installed output of 10 MW have to go through an application process to the Norwegian Water Resources and Energy Directorate (NVE) (NVE, 2022b). The first step is an impact assessment, where NVE describes what aspects need to be investigated in more detail (NVE, 2022b). This assessment can also include possible effects on flora and fauna, e.g., shifts in wildlife's movement in the landscape throughout different seasons (Helland et al., 2015). Based on the assessment and application, the NVE then makes a decision, which can be appealed (NVE, 2022b).

In Sweden, regulations differ between medium- and large-sized power plants and there are differences in the process of getting the permission to establish a wind power plant (Energimyndigheten, 2019). Medium-sized power plants need to be applied for according to the Swedish Environmental Code and a building permit is required, which is examined by the municipality (Energimyndigheten, 2022a). The Swedish Environmental Code is a framework legislation containing the general provisions on environmental protection and has the purpose to promote sustainable development (The Swedish Environmental Protection Agency, 2022). A large-sized power plant needs a permit and municipal approval according to the Swedish Environmental Code and will be examined by the environmental review delegation of the county administrative board (Energimyndigheten, 2022b).

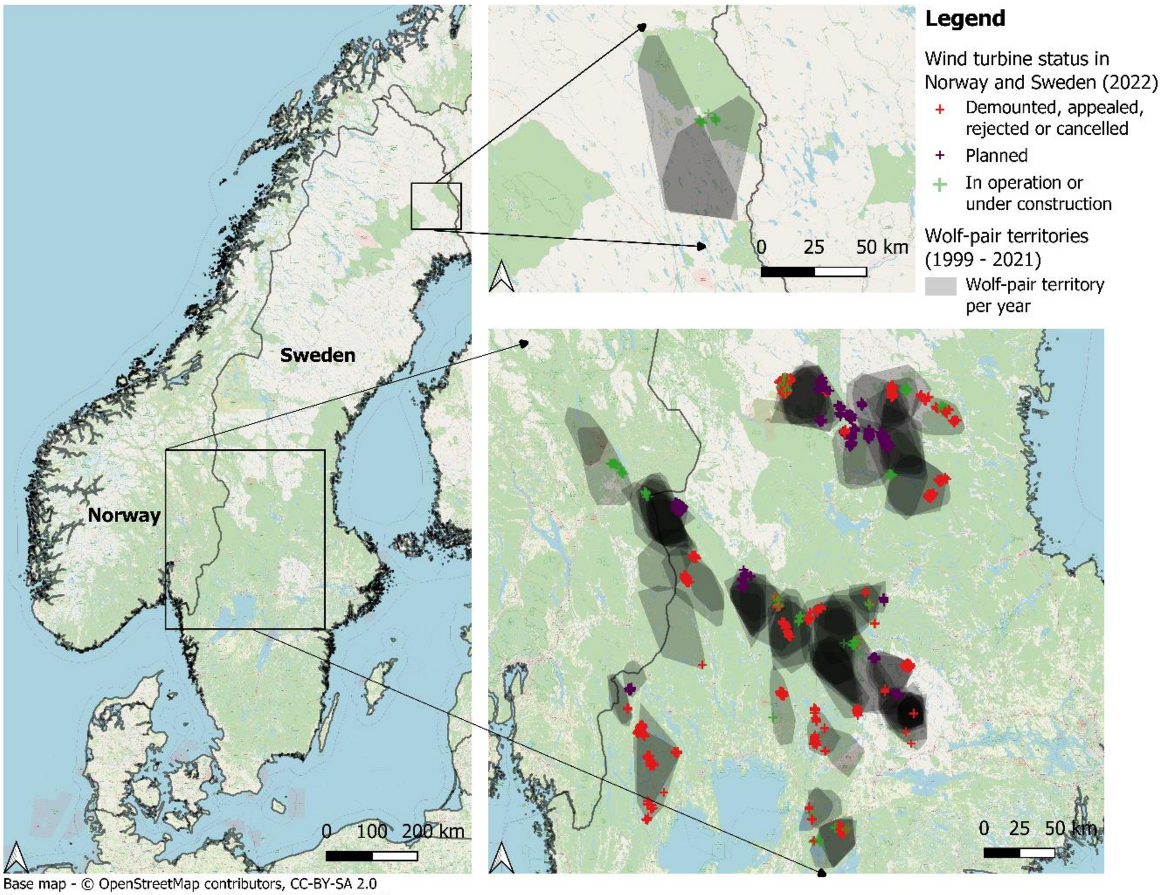
In Norway, there are currently 1 333 wind turbines in 61 wind power plants in operation (1998 – 2021) (NVE, 2022a). Furthermore, there are 3 wind power plants under construction, 85 have been approved, 47 rejected, 29 are under processing and for 107 the planning has been completed, a description of those categories can be found in Appendix A1: Table A1 (NVE, 2022c). In Sweden there are 4 754 wind turbines (1982 – 2021) in operation (Energimyndigheten & Statistikdatabas, 2022). In total, there are 21 900 wind turbines in additional categories, a description of those categories can be found in Appendix A1: Table A1 (Länsstyrelserna & Energimyndigheten, 2022b).

In the study area a total of 1 240 wind turbines overlapped in space with wolf territories. Of those 270 are now in operation/built, 1 is demounted, 386 are no longer relevant for construction, 185 have been rejected, 209 approved, 6 appealed and 183 processed. In Norway wolves only had overlap with wind power plants in operation. Of the wind turbines in operation in my study area 124 had a total height (measured from the ground to the top wing tip pointing straight up) between 100 – 150m, 84 between 151 – 200 m, 18 > 200m and 44 had no information available regarding their total height (see Appendix A1: Table A2 for an overview of the wind turbines).

For the data analysis, wind turbine placements for Norway were retrieved from NVEs' geographical thematic data website (NVE, 2022a). The wind turbine placements for Sweden were retrieved from the County administrative boards' website Vindbrukskollen (Länsstyrelserna & Energimyndigheten, 2022a).

2.3 Study animals and data collection

Over two decades (1999-2022) of GPS and VHF-data is available from wolves captured by the SKANDULV and GRENSEVILT research projects. Individuals were darted and immobilised from a helicopter, and equipped with a VHF (Telonics Inc, Mesa, Arizona, USA) or GPS collar (Followit Sweden AB, and VECTRONIC Aerospace GmbH, Germany) following the methods described in Arnemo & Evans (2017). All captures were evaluated and approved by the Swedish Agency of Animal Welfare and the Norwegian Agency of Animal Welfare. A more detailed description of the capturing procedure can be found in Sand et al. (2006). Data from a total of 166 captured adult territorial wolves in the years 1999-2021, were considered for this study.



Base map - © OpenStreetMap contributors, CC-BY-SA 2.0
European country outlines: @EuroGeographics and UN-FAO
Sources for data for wind turbine placements - Norway: NVE Norge, Norwegian Licence for Open Government Data (NLOD); Sweden: Vindbrukskollen, Länsstyrelserna, CC0 1.0

Figure 1: *Overview of the study area in Norway and Sweden (1999 – 2021), showing only wind power development sites that overlap with wolf territories from this study. Wolf territory (per wolf pair) per year is displayed.*

2.4 Data analysis

The analysis was carried out in RStudio (RStudio Team, 2022) in R 4.2.0 (R Core Team, 2022), except of the overlap on the landscape level between wolf territories and the turbine sites, which was carried out in QGIS Desktop 3.16.15 (QGIS Development Team, 2022).

To exclude the periods of hourly positions and obtain comparable data from all territories and seasons, I down sampled all GPS and VHF positions to a positioning interval of 4-hours or more. I split them into four three-month seasons within a typical wolf year: Denning (May 1 – July 31), followed by rendezvous (August 1 to October 31), early winter (November 1 – January 31), and late winter (February 1 – April 30). To have a sufficient number of positions for the home range and area use analyses, I only included seasons with minimum 60 days of positions. Since wolf pairs travel together most of the year (Nordli, 2018), except during the denning season, I analysed observations on two levels: as individuals during the denning season and in wolf pairs for the remainder of the year. When data of both the adult male and female were available for a given time stamp, I picked the position of the individual that was acquired first. I categorised the position data by time of day, where daytime was defined to be in the time period between 08:00 to 19:59 and night between 20:00 to 07:59. If turbines lacked an accurate construction start date, I set this as two years before the operational start. Since there was not enough data available to do a before-during-after comparison, I only used wolf positions from before the construction for this analysis, to analyse the area use of not yet by wind power development influenced wolves. For this process of cleaning my data, I used functions from the packages “tidyr” (Wickham & Girlich, 2022), “dplyr” (Wickham et al., 2022) and “lubridate” (Grolemund & Wickham, 2011). After those criteria, a total of 56 335 positions of 58 wolves were used for the analysis on the wolf pair level. On the individual level it was a total of 17 859 positions of 38 wolves.

I followed the protocol established by Zuur et al. (2010) for general data exploration. I expected that model fit would be generally low because I did not include any environmental variables that might explain wolf habitat selection and area use. The reason for this was that I have the assumption that wolves use areas that are most suitable for them within a territory, while the factors that influence this choice were not of interest for me. Where necessary I tried to adjust the models, by incorporating different variables (see 2.4.1 & 2.4.2), random effects, and distribution to improve model fit as much as possible. To plot figures, I used the package “ggplot2” (Wickham, 2016).

2.4.1 Wolf pair level

2.4.1.1 High usage area overlap

I only used wolf positions from before the construction for this analysis, because I assumed that these wolves were not yet influenced by wind power development and I did not have enough data to do a before-during-after comparison. This assumption allowed me to investigate if areas selected for wind power development, when placed in wolf territories, tend to overlap with high wolf usage areas. If the wolf territory was overlapping with wind turbines in operation, and there were several wind turbines within a wolf territory, I used the positions from before the start of construction of the first wind turbine. I included wind turbines of all statuses except “demounted”, as it was not possible to get information on when the wind turbines were actually disassembled. I included all other project status categories because I assumed that all of these turbine sites corresponded to places of high interest for wind power development.

First, I created individual home ranges using the 100% minimum convex polygon (MCP) method for each wolf pair, year, and season using the packages “adehabitatHR” (Calenge, 2006) and “sp” (Bivand et al., 2013; Pebesam & Bivand, 2005). I then conducted a simple spatial overlay analysis to find which individual home ranges overlapped with wind power development. Although this allowed me to examine overlap at the landscape level, I also wanted to narrow the focus to examine wolf use of the immediate area around the planned placement of the turbines, which sees the most development and activity during construction. To achieve this, I calculated a kernel utilisation distribution for each wolf pair, year, season, and time of day with the function “kernelUD” from the “adehabitatHR” package (Calenge, 2006) choosing the “href” bandwidth method and a grid size of 250. The “getvolumeUD” function allowed me to extract the utilisation distribution (UD) values. I extracted the UD values at the turbine sites by transforming the volume into a raster file and clipping this raster kernel UD file with the individual home range of the wolf pair season using the “raster” package (Hijmans, 2022). Then I used the function “extract” from the “raster” package (Hijmans, 2022) to extract the UD values at the grid location for each turbine site.

To be able to model the UD values in a generalized linear mixed model (GLMM) I transformed it to a proportion with the formula:

$$Wolf\ Usage\ Index = \frac{1 - UD\ value}{100}$$

This transformation results in values ranging from 0 to 1, where higher values correspond to higher probability of wolf use and lower values to lower probabilities of wolf use. I defined a high usage area of a wolf as lying within the activity centre which corresponds to the 50% kernel UD, i.e., areas with a wolf usage index > 0.5. The proportion of the home range that is covered by the activity centre is expected to differ between seasons, e.g., during denning, the activity centre area is probably much smaller than during other seasons. Therefore, I calculated the “relative activity centre area” by dividing the area of the activity centre with the total area of the individual home ranges for each combination of wolf pair, season, and time of day. To model what influences the variation of the wolf usage index at the turbine sites, I used a generalised linear mixed model (GLMM) with the function “glmmTMB” from the package “glmmTMB” (Brooks et al., 2017) with a beta distribution and logit link function. I included the wolf usage index at the turbine sites as the response variable, the season and time of day as explanatory variables into the candidate models (Table 1). Additionally, I included the relative activity centre area as fixed effect (Table 1) to correct for changing probabilities of overlap due to seasonally changing utilisation distributions. I included two-way interactions between the season and the relative activity centre area, as the relative activity centre area varies throughout the different seasons, and this can lead to a variation in the wolf usage index at the turbine sites. I also included the interaction between season and time of day, as their area use might be different during the seasons and time of day, and therefore can influence the wolf usage index at the turbine sites. Furthermore, I incorporated wolf territory and wind power plant ID into the random error structure of the model to account for both individual wolf territory differences and spatial autocorrelation. I did so because in some cases there were several planned wind power plants within a territory and the same power plant covered several territories.

I used the Akaike's Information Criterion corrected for small sample size (AIC_C; Hurvich & Tsai, 1991; Sugiura, 1978) to compare models, considering models with the lowest AIC_C the best ones and with a $\Delta AIC_C < 2$ as equally good. I used the AIC_C irrespective if sample size was small or not, as it is though that with large sample size the correction factor will be 0 and therefore the difference between AIC and AIC_C gets negligible. I assessed the model fit using tools provided in the "DHARMa" package (Hartig, 2022). To generate predictions, I used the function "ggpredict" from the package "ggeffects" (Lüdecke, 2018). I applied the same procedures for the probability of individual wind turbines being placed in the activity centre.

2.4.1.2 Probability of individual wind turbine placed in activity centre

In the next step I estimated the probability of individual wind turbines being placed in a wolf pair activity centre. I obtained the 50% kernel outlines with the "getverticeshr" function from the package "adehabitatHR" (Calenge, 2006). I then cropped the activity centre (50% kernel utilisation distribution) with the individual home range using the "raster" package (Hijmans, 2022). I then counted the number of individual wind turbines within the resulting polygon with the function "st_intersection" from the package "sf" (Pebesma, 2018). Using the same function, I did this additionally for the total number of individual wind turbines within the individual home range.

To model this, I used a GLMM with a binomial distribution and logit link function (Brooks et al., 2017). Since the number of trials was > 1, I expressed the response variable as proportion of individual wind turbines in the activity centre, compared to all wind turbines in the individual home range. I included the random error structure wolf territory ID, and the explanatory variables season and time of day, and the relative activity centre area to correct for the variation in activity centre area throughout the seasons. I included two-way interactions between the season and the relative activity centre area and the season and time of day for the same reasoning as for the wolf usage index at the turbine sites. Candidate models are listed in Table 1.

2.4.1.3 Area overlap

To estimate the extent of the overlap between the activity centres with the wind power plants I calculated the wind power plant areas by creating a 100% MCP of the wind turbines with the same power plant ID. To find the size of the area overlap, I used the function "st_intersection" of the package "sf" (Pebesma, 2018). I then calculated the proportion of areal overlap between wind power plants and the wolf activity centre to use as the response variable.

I used a Bayesian generalized linear multivariate multilevel model with a zero inflated beta distribution (function "brm" from the package "brms") (Bürkner, 2017, 2018, 2021). I chose this model because the response variable was continuous but included zeroes. Since a beta distribution cannot handle zeroes, I had to use a zero-inflated model. I included the wolf territory ID in the random error structure of the models and the explanatory variables included were the season and time of day, and the relative activity centre area to correct for the variation in activity centre area throughout the seasons (Table 1). I included two-way interactions between the season and the relative activity centre area and the season and time of day for the same reasoning as for the wolf usage index at the turbine sites.

I ran the Markov Chain Monte Carlo (MCMC) sampling in the model with 4 chains and 10 000 iterations. I used the default priors since there was not enough prior knowledge available to define informed priors. I used the efficient approximate leave-one-out cross-validation (LOO) to compare the models, where low values for the leave-one-out cross-validation information criterion (LOOIC) and high values for the expected log predictive density (ELPD) indicate a better model fit (Vehtari et al., 2017, 2022). To reduce high Pareto k values I included moment matching into the LOO (Paananen et al., 2021). To assess the convergence of the model and model fit I used posterior and prior predictive checks, density- and trace-plots of the MCMC chains, R-hat values, effective number of parameters, number of effective samples, quantile residual plots, and I checked for autocorrelation in the chains. R-hat values should be below 1.05 (Vehtari et al., 2021), Pareto k values should be below 0.7 (Vehtari et al., 2015, 2017), the effective number of parameters should be smaller than the total number of parameters in the model (Vehtari et al., 2017), and the ratio of the number of effective samples should be high (Gelman et al., 2013). I used the function "fitted" from the package "brms" (Bürkner, 2017, 2018, 2021) to generate predictions.

Table 1: *Candidate models on the wolf pair level with only the fixed effects displayed for the overlap between high wolf usage area and subsequent wind power development, with the response variable being the wolf usage index at the turbine sites (random effects: wolf territory and power plant ID), the probability of individual wind turbines being placed in the activity centre with the response variable of the proportion of individual wind turbines in the activity centre in relation to all wind turbines in the seasonal MCP (random effect: wolf territory ID), and the proportion of areal overlap between wind power plants and the wolf activity centre (random effect: wolf territory ID)*

Model ID	Model structure
Model 0	1
Model 1	Rel. activity centre area
Model 2	Season + Rel. activity centre area
Model 3	Time of day + Rel. activity centre area
Model 4	Season + Time of day + Rel. activity centre area
Model 5	Season * Rel. activity centre area
Model 6	Season * Time of day + Rel. activity centre area
Model 7	Season * Rel. activity centre area + Time of day

2.4.2 Individual level

I used the same procedure as for the wolf pair level on the individual level but with the difference of using only the data of the denning season and for all individuals instead of wolf pairs. I included the explanatory variables time of day, sex and reproductive status (breeding/ non-breeding), and the relative activity centre area to correct for the variation in activity centre area throughout the seasons, in all three sets of models. Since wolves are not travelling together during the denning season I included the variable sex, as there could be sex-differences. Furthermore, I included the variable reproductive status, to account for potential differences in movement or behaviour during the denning season based on reproductive status. I retrieved the information on reproductive status from the annual status reports (Rovdata). Furthermore, I included the random error structure of the wolf territory ID. Since the sex and reproductive status can affect behaviour and movement and therefore also the response variables, I included the two-way interactions between sex and reproductive status. Furthermore, I included an interaction term between sex and relative activity centre area since the sex can influence the relative activity centre area, which in turn can affect the response variable values. For the same reasoning I included the interaction between reproductive status and the relative activity centre area. I included the three-way interaction between sex, reproductive status, and the relative activity centre area as well. The candidate models for all sets of models can be found in Table 2.

Table 2: *Candidate models on the individual level with only the fixed effects displayed for the overlap between high wolf usage area and subsequent wind power development, with the response variable being the wolf usage index at the turbine sites (random effects: wolf territory and power plant ID), the probability of individual wind turbines being placed in the activity centre with the response variable of the proportion of individual wind turbines in the activity centre in relation to all wind turbines in the seasonal MCP (random effect: wolf territory ID), and the proportion areal overlap between wind power plants and the wolf activity centre (random effect: wolf territory ID)*

Model ID	**Model structure**
Model 0	1
Model 1	Rel. activity centre area
Model 2	Sex + Rel. activity centre area
Model 3	Reproductive status + Rel. activity centre area
Model 4	Time of day + Reproductive status
Model 5	Sex + Reproductive status + Rel. activity centre area
Model 6	Sex + Time of day + Rel. activity centre area
Model 7	Reproductive status + Time of day + Rel. activity centre area
Model 8	Sex + Reproductive status + Time of day + Rel. activity centre area
Model 9	Sex * Rel. activity centre area
Model 10	Reproductive status * Rel. activity centre area
Model 11	Sex * Reproductive status + Rel. activity centre area
Model 12	Sex * Rel. activity centre area + Reproductive status
Model 13	Sex * Rel. activity centre area + Time of day
Model 14	Reproductive status * Rel. activity centre area + Sex
Model 15	Reproductive status * Rel. activity centre area + Time of day
Model 16	Sex * Reproductive status + Time of day + Rel. activity centre area
Model 17	Sex * Rel. activity centre area + Reproductive status + Time of day
Model 18	Sex * Reproductive status * Rel. activity centre area
Model 19	Sex * Reproductive status * Rel. activity centre area + Time of day

3 Results

3.1 Data overview

I found spatial overlap between a total of 1 240 wind turbines from before the construction with wolf territories in the study area. Those territories were of a total of 48 wolf pairs which made up 56 335 positions (one synchronous position per pair) from 32 males and 26 females. On the individual level during the denning season, I analysed a total of 38 wolves with 18 117 positions, of which 18 were from males and 20 from females. The number of recorded GPS and VHF positions varied among individuals (see Appendix A1: Table A3). The relative activity centre area varied between seasons on the wolf pair level, with the lowest values during denning and highest during early winter (Figure 2). The differences in mean of the relative activity centre area between seasons was significant (one-way ANOVA; F = 89.962, p < 2.2e16***). A post-hoc test confirmed a significant difference (Tukey's HSD test; p<0.01**) between all groups, except between the rendezvous and late winter season (Tukey's HSD test; p > 0.05). On the individual level non-breeding wolves had a higher relative activity centre area compared to breeding wolves (Figure 2). The differences in mean of the relative activity centre area between the reproductive status was significant (one-way ANOVA; F = 124.83, p < 2.2e16***).

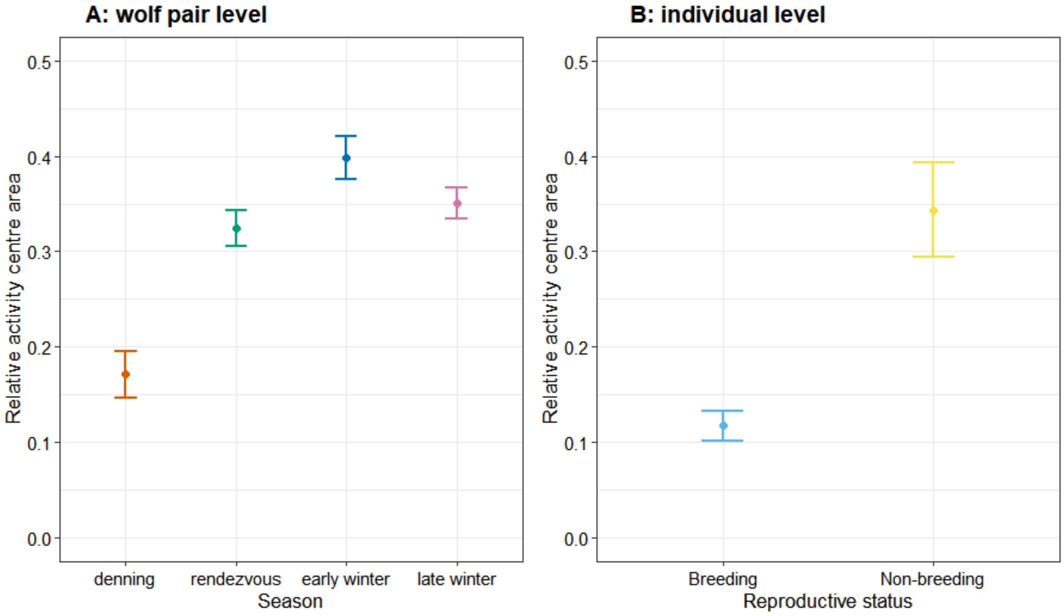


Figure 2: *Overview of the relative activity centre area of wolves (area of the activity centre in relation to the total area of the home range) (y-axis) in south-central Scandinavia (Norway and Sweden) during the years 1999-2021, that overlap with wind power development sites during* ***(A)*** *the different seasons (denning (May 1 – July 31), rendezvous (August 1 to October 31), early winter (November 1 – January 31), and late winter (February 1 – April 30)) (x-axis) on the wolf pair level, and* ***(B)*** *the reproductive status (breeding or non-breeding wolves) during the denning season on the individual level.*

3.2 High usage area overlap

3.2.1 Wolf pair level

The wolf usage index values at the planned turbine sites (n = 13 641 observations of wolf usage index, calculated for all combinations of wind turbine, territory, year, and time of day) had an average value of 0.31 (range: 0.00 - 0.99; 95% CI [0.30; 0.31]). According to the AIC_C, model 7 was the best to explain the observed variation in the wolf usage index at the turbine sites (see Appendix A2: Table A1). It included the time of day and interaction between the season and relative activity centre area. The wolf usage index was highest during the denning season, followed by the rendezvous season, early and late winter (Figure 3A & Appendix A2: Table A3). It increased with increasing relative activity centre area (Figure 3A & Appendix A2: Table A3). The late winter season was the only one not having overlap between high usage areas of wolves and turbine sites (Figure 3A). The relative activity centre area was lowest during denning and highest during early winter, with the largest ranges during denning and early winter, whereas rendezvous and late winter were found at intermediate relative activity centre areas (Figure 3A). Furthermore, the wolf usage index was slightly higher during day than night (Figure 3B & Appendix A2: Table A3).

The model fit was low. The residual diagnostics revealed that there was a deviation from the expected distribution and that there was no homogeneity of variance. Furthermore, it detected outliers. Attempts of refitting to improve model fit were unsuccessful. The model had a marginal R^2 of 0.243 and a conditional R^2 of 0.900 (Appendix A2: Table A3).

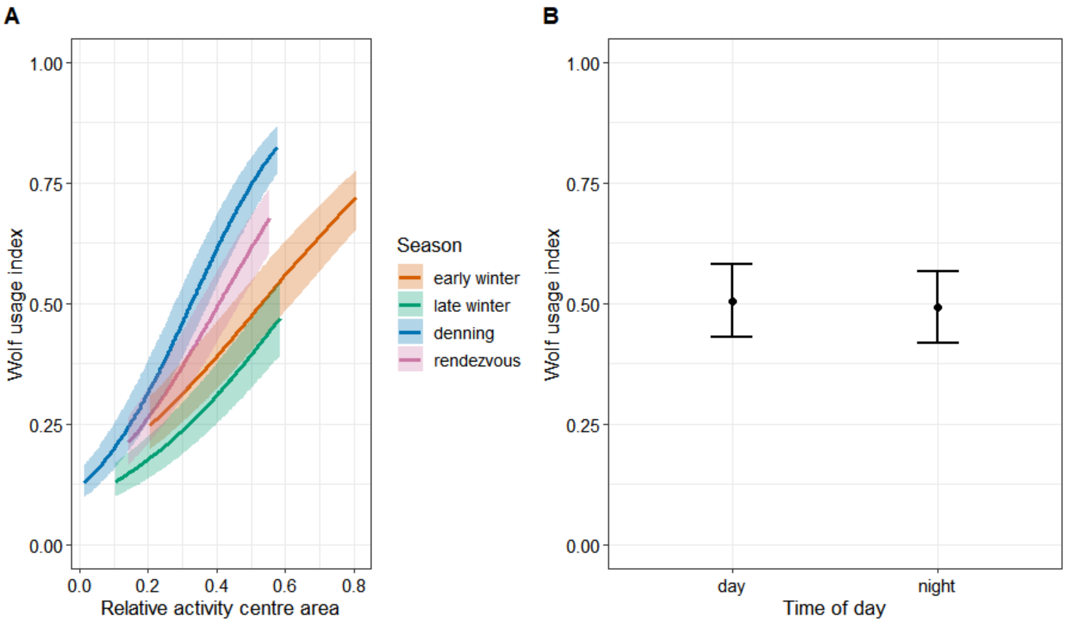


Figure 3: *Prediction plots for the wolf usage index with a 95% confidence interval (CI) (y-axis) at the turbine sites on the wolf pair level in relation to* ***(A)*** *relative activity centre area (area of the activity centre in relation to the total area of the home range) (x-axis) during the different seasons (denning, rendezvous, early winter, and late winter), and* ***(B)*** *during different times of day (day and night) (x-axis).*

3.2.2 Individual level

The wolf usage index values at the turbine sites (n = 3 650 observations of wolf usage index, calculated for all combinations of wolf, year, and time of day) during the denning season for breeding wolves, averaged 0.21 (range: 0.00 - 0.99; 95% CI [0.19, 0.21]). Non-breeding wolves had an average wolf usage index at turbines sites of 0.31 (range: 0.00 - 0.99; 95% CI [0.29, 0.33]). According to the AIC$_C$ model 19 was the best to explain the observed variation in the wolf usage index at the turbine sites (see Appendix A2: Table A1). It included the time of day and the three-way interaction of the sex, reproductive status, and relative activity centre area. Non-breeding females and non-breeding males had the highest wolf usage index at turbine sites (Figure 4A & Appendix A2: Table A4). Breeding females and males only had low wolf usage index values at turbine sites and small relative activity centre areas (Figure 4A & Appendix A2: Table A4). Furthermore, for females and breeding males, the wolf usage index at turbine sites increased with increasing relative activity centre area (Figure 4A & Appendix A2: Table A4). The opposite pattern was found for non-breeding males (Figure 4A & Appendix A2: Table A4). Breeding females had slightly higher wolf usage index values at turbine sites compared to males (Figure 4A & Appendix A2: Table A4). The relative activity centre area was lowest for breeding wolves with males reaching into slightly higher areas than females (Figure 4A). The biggest ranges were found for non-breeding wolves (Figure 4A). Additionally, the wolf usage index at turbine sites was slightly higher during the night compared to day (Figure 4B & Appendix A2: Table A4).

The model fit was low. The residual diagnostics revealed that there was a deviation from the expected distribution and that there was no homogeneity of variance. Furthermore, it detected outliers. Attempts of refitting to improve model fit were unsuccessful. The model had a marginal R^2 of 0.192 and a conditional R^2 of 0.855 (Appendix A2: Table A4).

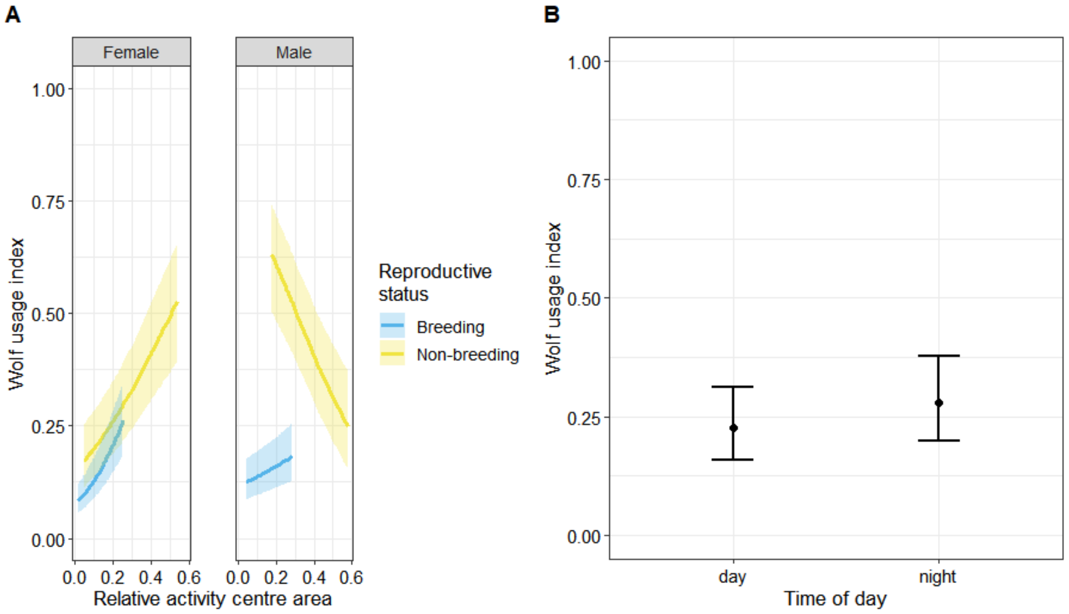


Figure 4: *Prediction plots for the wolf usage index at turbine sites with a 95% confidence interval (CI) (y-axis) on the wolf pair level in relation to* ***(A)*** *the relative activity centre area (area of the activity centre in relation to the total area of the home range) (x-axis), the reproductive status (breeding and non-breeding), and the sex (female and male), and* ***(B)*** *during different times of day (day and night) (x-axis).*

3.3 Probability of individual wind turbines placed in activity centre

3.3.1 Wolf pair level

Out of 325 combinations of wolf pair, year, season, and time of day, 46% (n = 148) of all seasonal home ranges had no planned wind turbines in their activity centre and 54 % (n = 177) did. According to the AIC_C, model 7 was the best to explain the observed variation in the probability of individual wind turbines being placed in the activity centre (see Appendix A2: Table A1). It included the explanatory variables time of day and the interaction between the season and the relative activity centre area. According to the model the probability of individual wind turbines being placed in the activity centre is highest during the denning season, followed by the rendezvous season, early and then late winter, and increased with increasing relative activity centre area (Figure 5A & Appendix A2: Table A5). The relative activity centre area was lowest during denning and highest during early winter, with the biggest ranges during denning and early winter, whereas rendezvous and late winter were found at intermediate relative activity centre areas (Figure 5A). The probability of individual wind turbines being placed in the activity centre was slightly higher during the day than during the night (Figure 5B & Appendix A2: Table A5).

The model fit was low. The residual diagnostics revealed that there was a deviation from the expected distribution and that there was no homogeneity of variance in some groups. Attempts of refitting to improve model fit were unsuccessful. The model had a marginal R^2 of 0.135 and a conditional R^2 of 0.570 (Appendix A2: Table A5).

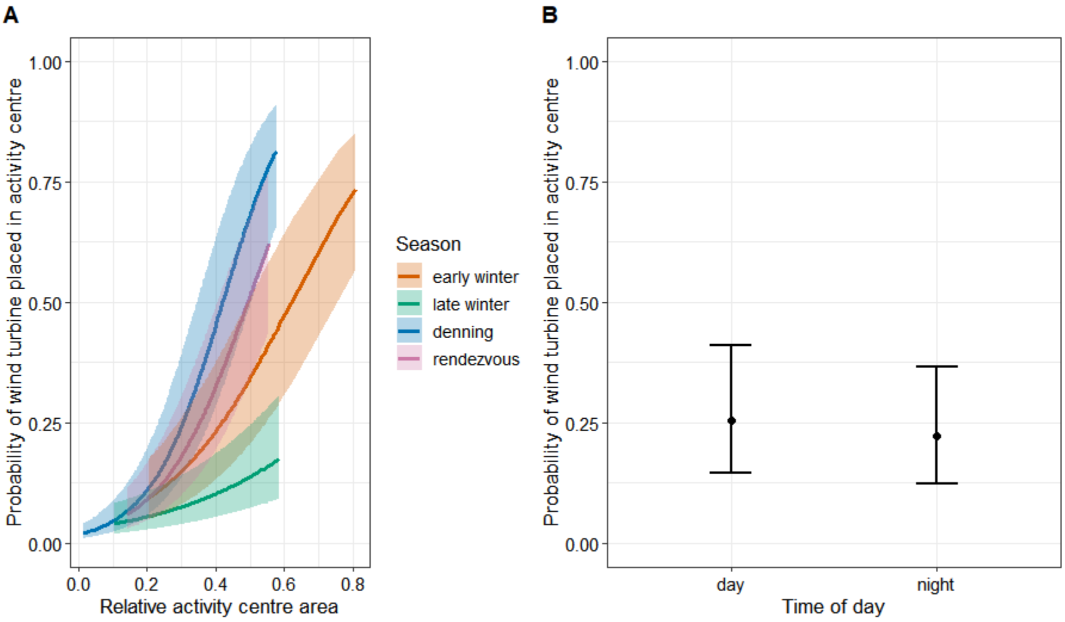


Figure 5: *Prediction plots for the probability of individual wind turbines being placed in the activity centre with a 95% confidence interval (CI) (y-axis) on the wolf pair level in relation to* ***(A)*** *relative activity centre area (area of the activity centre in relation to the total area of the home range) (x-axis) during the different seasons (denning, rendezvous, early winter, and late winter), and* ***(B)*** *during different times of day (day and night) (x-axis).*

3.3.1 Individual level

Out of the 111 combinations of wolf, year, season, and time of day , 58% (n = 62) had no planned wind turbines in their activity centre of which 12% (n = 13) were non-breeding wolves and 46% (n = 49) were breeding wolves. 42% (n = 45) of the data included wind turbines in the wolf activity centre of which 19% (n = 20) were non-breeding wolves and 23% (n = 25) were breeding wolves. According to the AIC_C, model 18 was the best one to explain the observed variation in the probability of individual wind turbines being placed in the activity centre. It included the three-way interaction between sex, reproductive status, and the relative activity centre area (see Appendix A2: Table A1). The probability of individual wind turbines being placed in the activity centre of wolves increased for females irrespective of the reproductive status and increased slightly with increasing relative activity centre area (Figure 6 & Appendix A2: Table A6). Non-breeding males showed the opposite trend whereas the probability for breeding males stayed nearly constant (Figure 6 & Appendix A2: Table A6). Breeding females had a slightly higher probability than males (Figure 6 & Appendix A2: Table A6). The relative activity centre area was lowest for breeding wolves with males reaching into slightly higher areas than females (Figure 6). The biggest ranges were found for non-breeding wolves (Figure 6). Model 19 was within $\Delta AIC_C < 2$ (Appendix A2: Table A1). It included the explanatory variable of the time of day and the three-way interaction between sex, reproductive status and the relative activity centre area and showed the same trends as model 18 and had higher values during the night compared to day (Appendix A2: Table A7).

The model fit was low. The residual diagnostics revealed that there was no homogeneity of variance in some groups. Attempts of refitting to improve model fit were unsuccessful. The model had a marginal R^2 of 0.040 and a conditional R^2 of 0.895 (Appendix A2: Table A6).

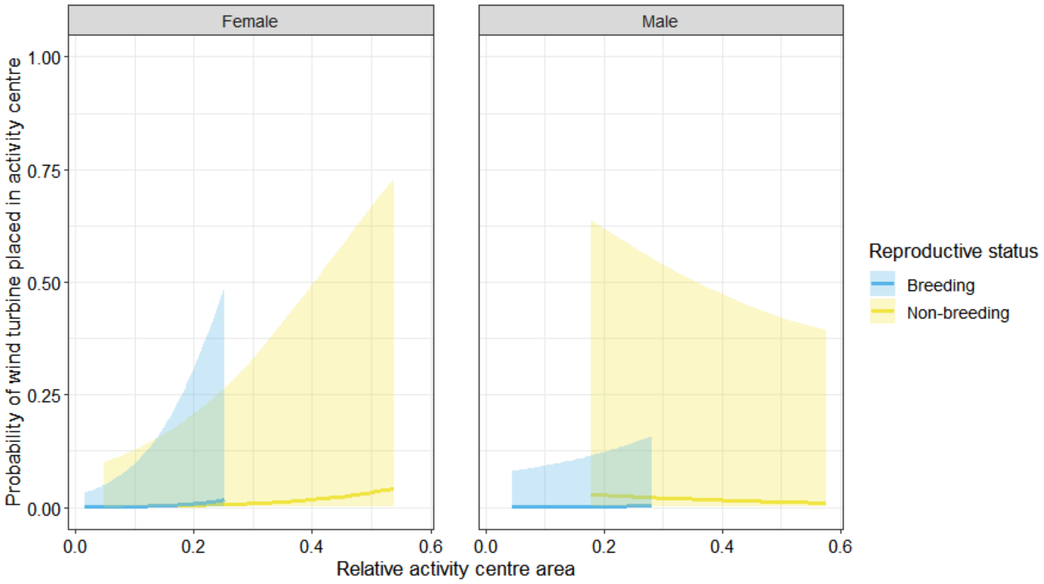


Figure 6: *Prediction plots for the probability of individual wind turbines being placed in the activity centre with a 95% confidence interval (CI) (y-axis) on the individual level in relation to the relative activity centre area (area of the activity centre in relation to the total area of the home range) (x-axis), the reproductive status (breeding and non-breeding), and the sex (female and male).*

3.4 Area overlap

3.4.1 Wolf pair level

The proportion of areal overlap between wind power plants and the wolf activity centre (n = 432 observations of the proportion of areal overlap, calculated for all combinations of wolf, year, and time of day) had an average value of 0.02 (range: 0.00 - 0.56; 95% CI [0.01; 0.02]). According to the LOO model 5 was the best one to explain the observed variation in the proportion of areal overlap between wind power plants and the wolf activity centre (Appendix A2: Table A2). It included the interaction between the relative activity centre area and the season. According to the model the proportion of areal overlap between wind power plants and the wolf activity centre was highest during denning, followed by late winter, early winter, and rendezvous at low proportions of the relative activity centre area (Figure 7 & Appendix A2: Table A8). The proportion was decreasing for the denning and late winter season, whereas for early winter and rendezvous it was increasing slightly (Figure 7 & Appendix A2: Table A8). The relative activity centre area was lowest during denning and highest during early winter, with the biggest ranges during denning and early winter, whereas rendezvous and late winter were found at intermediate relative activity centre areas (Figure 7).

All R-hat values were below 1.05, and all Pareto k values were below 0.7, which indicates that the model converged. Furthermore, the trace plots showed a good mix of the chains, the prior predictive check did not show any large deviations and the ratio of effective number of samples was not below the threshold. Though the effective number of parameters was higher than the number of parameters in the model (Appendix A2: Table A2), and the posterior predictive checks indicated that the model fit was low. Attempts to improve the model failed. The posterior distribution can be found in Appendix A2: Figure A1. The model had a marginal R^2 of 0.085 and a conditional R^2 of 0.164 (Appendix A2: Table A8).

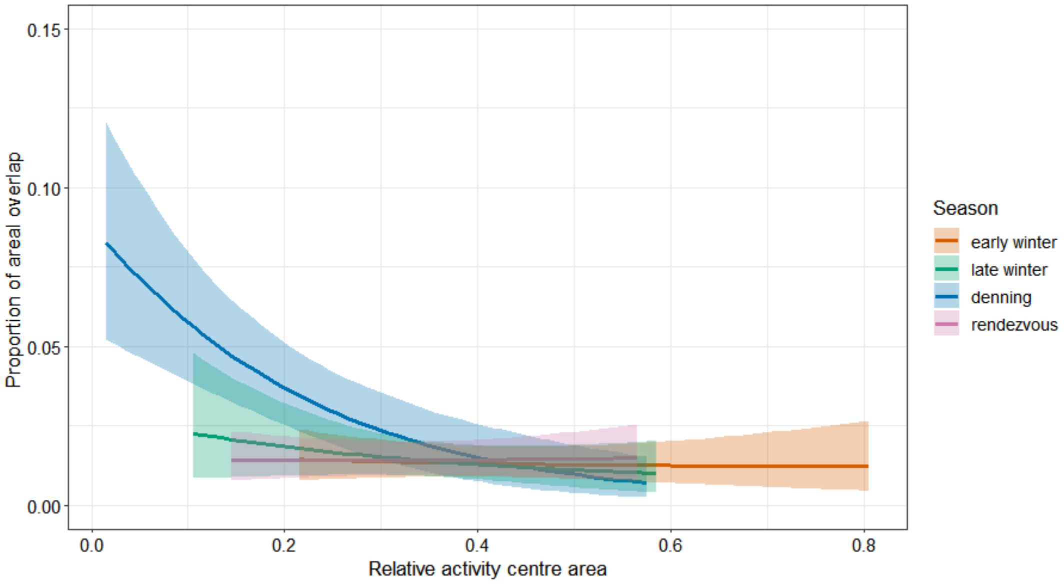


Figure 7: *Prediction plots for the proportion of areal overlap between wind power plants and the wolf activity centre with a 95% confidence interval (CI) (y-axis) on the wolf pair level in relation to the relative activity centre area (area of the activity centre in relation to the total area of the home range) (x-axis) during the different seasons (denning, rendezvous, early winter, and late winter).*

3.4.2 Individual level

The proportion of areal overlap between wind power plants and the wolf activity centre (n = 110 observations of the proportion of areal overlap, calculated for all combinations of wolf, year, and time of day) had a mean value of 0.05 (range: 0.00 - 0.61; 95% CI [0.01; 0.08]) for breeding wolves. Non-breeding wolves had a mean value of 0.03 (range: 0.00 - 0.37; 95% CI [0.0; 0.06]). According to the LOO model 1 was the best one to explain the observed variation in the proportion of areal overlap between wind power plants and the wolf activity centre (Appendix A2: Table A2). It included only the explanatory variable relative activity centre area. According to the model the proportion of areal overlap between wind power plants and the wolf activity centre decreases slightly with increasing relative activity centre area (Figure 8 & Appendix A2: Table A9).

All R-hat values were below 1.05, and all Pareto k values were below 0.7, which indicates that the model converged. Furthermore, the trace plots showed a good mix of the chains, the prior predictive check did not show any large deviations, and the ratio of effective number of samples was not below the threshold. Though the effective number of parameters was higher than the number of parameters in the model (Appendix A2: Table A2) and the posterior predictive checks indicated that the model fit was low. Attempts to improve the model failed.

The posterior distribution can be found in Appendix A2: Figure A2. The model had a marginal R^2 of 0.011 and a conditional R^2 of 0.226 (Appendix A2: Table A9).

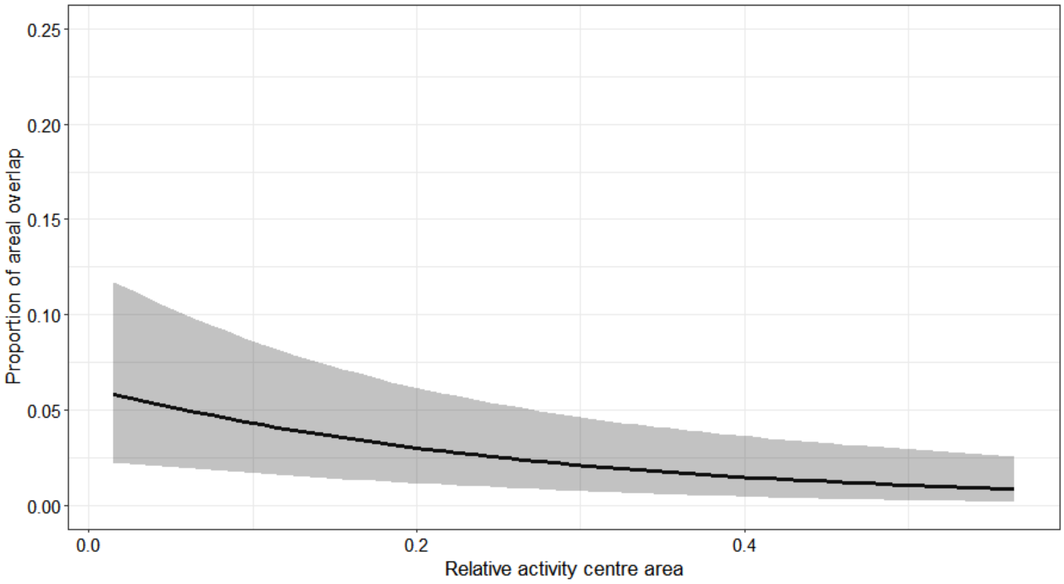


Figure 8: *Prediction plot for the proportion of areal overlap between wind power plants and the wolf activity centre with a 95% confidence interval (CI) (y-axis) on the individual level in relation to relative activity centre area (area of the activity centre in relation to the total area of the home range) (x-axis).*

4 Discussion

The mean wolf usage index at the turbine sites did not reflect high usage areas, though it had a very large range, and my further analysis did indeed confirm that sites chosen for wind power development can coincide with high wolf usage areas under certain conditions. This stands in accordance with my predictions. Furthermore, the denning and rendezvous seasons were the ones with the generally highest wolf usage index at the turbine sites, which stands in accordance with my predictions. The probability of individual wind turbines being placed in the activity centre was high during denning and rendezvous seasons when activity centres were relatively large. However, the proportion of areal overlap between wind power plants and the wolf activity centre were rather low. On the individual level, sex, reproductive status, and time of day were affecting both the wolf usage index and probability of individual wind turbines being placed in the wolf activity centre, with breeding females having higher values compared to males. That there are differences between reproductive statuses and sexes stands in accordance with my predictions as well.

During the denning season, movements of breeding wolves, especially of females, are restricted to the denning site (Jedrzejewski et al., 2001; Packard, 2003), which can lead to smaller home ranges for breeding compared to non-breeding wolves (Roffler & Gregovich, 2018). This might explain the rather low wolf usage index values at turbine sites for wolf pairs during the denning season at relatively small activity centre areas. Reasoning for this being that smaller activity centre areas could lead to lower probabilities of overlap with high usage areas because the probability of a wind turbine falling into a small area are lower compared to when areas are large. Furthermore, this difference in area uses and home ranges between reproductive statuses means that non-breeding wolves occupy a larger area of the territory, which leads to a higher probability of overlap with high usage areas as well as probabilities of individual wind turbines being placed in the activity centre. This could explain the higher values for non-breeding compared to breeding wolves of wolf usage index and probability of individual wind turbines being placed in the activity centre. The findings of restricted movement of breeding wolves imply that non-breeding wolves have a more widespread movement, which could lead to higher probabilities of overlap with wind turbines in their high usage areas, as they occupy larger areas. This could explain the findings that only high usage areas of non-breeding wolves overlap with turbine sites during the denning season.

During the rendezvous season, space use patterns are concentrated around the homesites (Demma & Mech, 2009; Jedrzejewski et al., 2001). As movement is restricted but they occupy larger areas compared to the denning season, this could explain the relatively high wolf usage index values at turbine sites as well as probabilities of individual wind turbines being placed in the activity centre during the rendezvous season.

Ahmadi et al. (2013) and Roffler et al. (2018) found that wolves placed dens in rather elevated areas and rugged terrain. As wind power plants are often placed in elevated areas and this might coincide with habitat selected for den sites, this could be an explanation for the high wolf usage index values at turbine sites during the denning season. Though it is to mention that other studies have found that wolf dens are being placed in lower elevations as well as flat terrain (Matteson, 1992; Norris et al., 2002; Person & Russell, 2009). Furthermore, some studies have found rendezvous sites being located in high elevations, steep slopes and rough terrain in order to avoid humans (Ahmadi et al., 2013; Capitani et al., 2006; Sazatornil et al., 2016). Choosing higher elevations could again explain high wolf usage index values at turbine sites as well as probabilities of individual wind turbines being placed in the activity centre during the rendezvous season, as the habitat remains the same, but the activity centre might cover a larger area. Though steep slopes are not preferential for wind power development sites (Ryberg et al., 2020). Other studies have reported rendezvous sites being placed in less rough terrain because of higher energetic costs of movement in those areas (Ausband et al., 2010; Person & Russell, 2009) and lower slopes (Houle et al., 2010). This could as well explain the higher wolf usage index as well as probabilities of individual wind turbines being placed in the activity centre during the rendezvous season.

The winter season is usually characterised by wolves utilising more areas within the territories because by this time, the pups can follow the adult wolves (Mech & Boitani, 2003). As the wolves might follow their preys' migration into winter ranges at lower elevations (Allen & Singh, 2016; Ordiz et al., 2020), the probability of overlap with wind turbines might decrease as those areas are not preferential for wind power development sites. The even lower overlap during late winter could be connected to the wolf movement being restricted by high snow accumulation (Houle et al., 2010), which can result in smaller areal use. Furthermore, wolves have been found to avoid human-made features at a lower extent during winter (Carricondo-Sanchez et al., 2020). This could contribute to lower wolf usage values at turbine sites during winter, because the placement of wind power plants can be restricted by the distance to human-made features, e.g. at a certain safety distance to roads (Ryberg et al., 2020). The fact that the late winter season was the only season without overlap between high usage areas and the turbine sites, might be explained with the highest snow accumulation in that season, which forces wolves and their prey to lower elevations.

The wolf usage index at turbine sites and the probability of individual wind turbines being placed in the activity centre were slightly higher for the daytime activity centres compared to night-time activity centres, when analysed at the wolf pair level, which stands in accordance with my predictions. In general, it is thought that wolves have a bimodal diel activity pattern in Scandinavia following the one of their main prey, the moose (Theuerkauf, 2009). Though, Eriksen et al. (2011) found that wolves had their activity peak at dawn whereas moose had it at dusk. Furthermore, wolves might choose their day beds in areas with low human disturbance (Zimmermann et al., 2014), which could mean choosing resting sites at higher elevations. This might coincide with sites chosen for wind power development, which could lead to slightly higher overlap with high usage areas during the day. But since the differences were very low, it might be irrelevant.

On the individual level, the probability of individual wind turbines being placed in the activity centre differed only slightly between breeding and non-breeding wolves, and 95% confidence intervals were large, especially for non-breeding wolves. This might be a sample size issue. Therefore, we cannot draw strong conclusions from this. Furthermore, the negative relationship between wolf usage index and relative activity centre area for non-breeding males is contra-intuitive and might be a consequence of a relatively low sample size of this wolf category.

For the proportion of areal overlap between wind power plants and the wolf activity centre, the relationship between the activity centre and the overlap can be described as – the larger the activity centre the lower the proportion of overlap. This could be an explanation for the observed decrease in proportion of areal overlap between wind power plants and the wolf activity centre with increasing relative activity centre area on the individual level. Furthermore, this could as well explain the decrease in the denning and late winter season with increasing relative activity centre area. Wolves are restricted in their movement during the denning (Jedrzejewski et al., 2001; Packard, 2003), wherefore they might have the smallest activity centre area in that season, but it might make up a large part of their individual home ranges. Therefore, high overlap at small relative activity centre areas is observed because the proportion of overlap is higher at smaller activity centre areas. This might as well be an explanation for the lower values of early winter, late winter and rendezvous season compared to the denning.

A study in Portugal has found that the denning season is the most vulnerable season for wolves and that they moved their dens further from the wind power development site during the construction phase if dens were located within 3 km of the construction site and that rendezvous sites were as well relocated (Álvares et al., 2011, 2017; Ferrão da Costa et al., 2018). This avoidance during the construction phase has also been shown for other species like for example for black bears (*Ursus americanus*) (Wallin, 1998 cited in Ferrão da Costa et al., 2018). My findings show the highest wolf usage index at turbine sites during the denning and rendezvous season which coincides with those findings.

In general, I have observed a very high range in wolf usage values at turbine sites both at the individual and wolf pair level. This reflects the possibility of high variation among individuals and could explain why a relatively high amount of the variation is explained by the random effect in the models. I intentionally did not include any environmental variables as explanatory variables, as I was not interested in effects of those on space use. As expected, this most likely was the cause for observing a relatively low model fit. Other causes could have been that the distribution of the wolf usage index had a lot of values close to zero and a long tail. This makes it relatively difficult to model and the distribution chosen might not have been the most appropriate one. Though I have tried modelling with different distributions to improve model fit, but without success. Another reason for the apparent low model fit could have been the relatively large number of observations for the wolf usage index on both the wolf pair and individual level. This can make the tests performed for model fit assessment very sensitive for deviations and could detect them falsely.

Furthermore, I have found very high 95% CIs for both the individual level of the probability of individual wind turbines being placed in the activity centre as well as the proportion of areal overlap between wind power plants and the wolf activity centre. This could have been caused by the high variation of values and possibly a small number of observations for those parts of the analysis, as well as the low model fit. Because of the low model fit and relatively low R^2 values, my results should be interpreted with caution.

The rather low model fit for the Bayesian models was most likely caused by not including environmental variables as well as a not very well-fitting distribution chosen for the model. The data included many zeroes, small values and had a tail, which makes it relatively difficult to model. Even after trying different distributions model fit did not improve. The results of my analysis should therefore as well be interpreted with caution.

Furthermore, the results should be verified with quasi-experimental studies with a before-during-after design on radio-collared wolves, to know if the results are in fact reliable and might be an alternative approach to a Before-After-Control-Impact BACI design. Though my findings standing in accordance with a study on wolves and wind power development in Portugal could already be an indication that this way of analysing the data, might be adequate to answer my questions and to be used to find potential of conflict. It might be as well beneficial to additionally perform the analysis for the wolf usage index and probability of individual wind turbines being placed in the activity centre on the level of wind power plants and not only turbines sites. The turbine sites are just accounting for the immediate surroundings, which can give valuable information on potential effects close to the turbine sites but does not account for the effects that might be to a spatially larger extent. Whereas when taking the wind power plants into account one includes the whole area of a power plant. This might give information on a larger extent. Since wind power plants can occupy a large area as distances between turbines can be high, this could come at the cost that areas that might not be relevant to include for investigating effects of wind power on wolf area use are included. Therefore, to be able to use the wind power plants, one would need more information on the distance at which wind power development can influence wolves.

5 Conclusion

In general, this study indicates that there is overlap between high usage areas of wolves with wind power development. The results stand in accordance with a previous study that has found wolves to be most vulnerable during the denning season. Possible impacts of wind power development on terrestrial mammals are often not included in EIAs (Lundberg, 2011 cited in Helldin et al., 2012). One of the reasons could be a lack of knowledge of effects of wind power development on various terrestrial mammals and the necessity for data over a long period to be able to use a BACI design. Such a design can be used to investigate for example how wind power influences a species by comparing parameter before the construction of the wind power plant with the same ones after. However, sample size requirements can make such studies time consuming and expensive. If the results of this thesis could be verified by quasi-experimental studies with a before-during-after design, it would verify that this approach is providing equally good information. Therefore, it could give useful information as a basis for EIAs for wind power development in a more time and cost-effective way. This approach could then be a valuable alternative to a BACI design when such a design is not feasible. This method could as well be applied to other terrestrial mammals that are suspected to be impacted by wind power development.

However, there is still a big lack of knowledge on for example the spatial extent to which wolves can be affected by wind power development, which should be investigated in the future to make analyses more accurate. Furthermore, since wolves might follow their prey's distribution, which they are thought to do in winter (Allen & Singh, 2016; Ordiz et al., 2020), it would be important to gain more knowledge on effects of wind power development on their prey species, such as moose in this area.

Acknowledgments

First and foremost, I would like to thank my supervisors Barbara Zimmermann, Ane Eriksen, and Camilla Wikenros for their guidance, help, and feedback throughout writing my thesis. I would as well like to thank the Skandulv and GRENSEVILT project for providing me with the data and everyone that was included in the captures and data collection. Furthermore, I would like to thank Olivier Devineau with his advice and help on my analysis.

I would like to thank all my classmates and fellow students in the master's room for good discussions and support throughout our studies and process of writing our theses. In particular, I would like to thank Paige Hellbaum Eikeland for her feedback and language checks and Erik Versluijs for some help with R.

Furthermore, I would like to thank my friends for their support. I would like to thank my family and boyfriend especially for supporting me throughout the process of writing my thesis and always motivating me to follow my goals.

References

Ahmadi, M., Kaboli, M., Nourani, E., Alizadeh Shabani, A., & Ashrafi, S. (2013). A predictive spatial model for gray wolf (Canis lupus) denning sites in a human-dominated landscape in western Iran. *Ecological Research*, *28*, 513–521. https://doi.org/10.1007/s11284-013-1040-2

Allen, A. M., & Singh, N. J. (2016). Linking Movement Ecology with Wildlife Management and Conservation. *Frontiers in Ecology and Evolution*, *3*(155). https://doi.org/10.3389/fevo.2015.00155

Álvares, F., Rio-Maior, H., Roque, S., Nakamura, M., Cadete, D., Pinto, S., & Petrucci-Fonseca, F. (2011). *Assessing ecological responses of wolves to wind power plants in Portugal: Methodological constrains and conservation implications* [Presentation].

Álvares, F., Rio-Maior, H., Roque, S., Nakamura, M., & Petrucci-Fonseca, F. (2017). Ecological response of breeding wolves to windfarms: Insights from two case studies in Portugal. In *Wildlife and wind farms: Conflicts and solutions* (pp. 225–227).

Andersen, R., Linnell, J. D. C., & Langvatn, R. (1996). Short term behavioural and physiological response of moose Alces alces to military disturbance in Norway. *Biological Conservation*, *77*(2–3), 169–176. https://doi.org/10.1016/0006-3207(96)00004-3

Arnemo, J. M., & Evans, A. L. (2017). *Biomedical Protocols for Free-ranging Brown Bears, Wolves, Wolverines and Lynx*. Inland Norway University of Applied Sciences.

Arnett, E. B., Inkley, D. B., Johnson, D. H., Larkin, R. P., Manes, S., Manville, A. M., Mason, J., Morrison, M., Strickland, M. D., & Thresher, R. (2007). Impacts of wind energy facilities on wildlife and wildlife habitat. *Wildlife Society Technical Review*, *7*(2).

Ausband, D. E., Mitchell, M. S., Doherty, K., Zager, P., Mack, C. M., & Holyan, J. (2010). Surveying Predicted Rendezvous Sites to Monitor Gray Wolf Populations. *The Journal of Wildlife Management*, *74*(5), 1043–1049. https://doi.org/10.2193/2009-303

Bivand, R. S., Pebesma, E. J., & Gómez-Rubio, V. (2013). *Applied spatial data analysis with R* (2nd ed.). Springer. https://asdar-book.org/

Brooks, M. E., Kristensen, K., van Benthem, K. J., Magnusson, A., Berg, C. W., Nielsen, A., Skaug, H. J., Maechler, M., & Bolker, B. M. (2017). GlmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling. *The R Journal*, *9*(2), 378–400. https://doi.org/10.3929/ethz-b-000240890

Bürkner, P.-C. (2017). brms: An R Package for Bayesian Multilevel Models Using Stan. *Journal of Statistical Software*, *80*(1), 1–28. https://doi.org/10.18637/jss.v080.i01

Bürkner, P.-C. (2018). Advanced Bayesian Multilevel Modeling with the R Package brms. *The R Journal*, *10*(1), 395–411. https://doi.org/10.32614/RJ-2018-017

Bürkner, P.-C. (2021). Bayesian Item Response Modeling in R with brms and Stan. *Journal of Statistical Software*, *100*(5), 1–54. https://doi.org/10.18637/jss.v100.i05

Calenge, C. (2006). The package “adehabitat” for the R software: A tool for the analysis of space and habitat use by animals. *Ecological Modelling*, *197*(3–4), 516–519. https://doi.org/10.1016/j.ecolmodel.2006.03.017

Capitani, C., Mattioli, L., Avanzinelli, E., Gazzola, A., Lamberti, P., Mauri, L., Scandura, M., Viviani, A., & Apollonio, M. (2006). Selection of rendezvous sites and reuse of pup raising areas among wolves Canis lupus of north-eastern Apennines, Italy. *Acta Theriologica*, *51*(4), 395–404. https://doi.org/10.1007/BF03195186

Carricondo-Sanchez, D., Zimmermann, B., Wabakken, P., Eriksen, A., Milleret, C., Ordiz, A., Sanz-Pérez, A., & Wikenros, C. (2020). Wolves at the door? Factors influencing the individual behavior of wolves in relation to anthropogenic features. *Biological Conservation*, *244*, 108514. https://doi.org/10.1016/j.biocon.2020.108514

Demma, D. J., & Mech, L. D. (2009). Wolf Use of Summer Territory in Northeastern Minnesota. *The Journal of Wildlife Management*, *73*(3), 380–384. https://doi.org/10.2193/2008-114

Emami, A., & Noghreh, P. (2010). New approach on optimization in placement of wind turbines within wind farm by genetic algorithms. *Renewable Energy*, *35*(7), 1559–1564. https://doi.org/10.1016/j.renene.2009.11.026

Energimyndigheten. (2019, August 21). *Planering och tillstånd*. Planering och tillstånd. https://www.energimyndigheten.se/fornybart/vindkraft/vindlov/planering-och-tillstand/

Energimyndigheten. (2022a, June 20). *Medelstora anläggningar*. Medelstora anläggningar. https://www.energimyndigheten.se/fornybart/vindkraft/vindlov/planering-och-tillstand/medelstora-anlaggningar/

Energimyndigheten. (2022b, June 20). *Stora anläggningar*. Stora anläggningar. https://www.energimyndigheten.se/fornybart/vindkraft/vindlov/planering-och-tillstand/stora-anlaggningar/

Energimyndigheten, & Statistikdatabas. (2022, April 21). *Vindkraftsstatistik*. Antal verk, installerad effekt och elproduktion, hela landet, 1982 -. https://pxexternal.energimyndigheten.se/pxweb/sv/Vindkraftsstatistik/Vindkraftsstatistik/EN0105_1.px/table/tableViewLayout2/

Eriksen, A., Wabakken, P., Zimmermann, B., Andreassen, H. P., Arnemo, J. M., Gundersen, H., Liberg, O., Linnell, J., Milner, J. M., & Pedersen, H. C. (2011). Activity patterns of predator and prey: A simultaneous study of GPS-collared wolves and moose. *Animal Behaviour*, *81*(2), 423–431. https://doi.org/10.1016/j.anbehav.2010.11.011

Ferrão da Costa, G., Paula, J., Petrucci-Fonseca, F., & Álvares, F. (2018). The Indirect Impacts of Wind Farms on Terrestrial Mammals: Insights from the Disturbance and Exclusion Effects on Wolves (Canis lupus). In *Biodiversity and Wind Farms in Portugal* (pp. 111–134). Springer.

Frair, J. L., Merrill, E. H., Beyer, H. L., & Morales, J. M. (2008). Thresholds in landscape connectivity and mortality risks in response to growing road networks. *Journal of Applied Ecology*, *45*(5), 1504–1513. https://doi.org/10.1111/j.1365-2664.2008.01526.x

Fuller, T. K. (1991). Effect of snow depth on wolf activity and prey selection in north central Minnesota. *Canadian Journal of Zoology*, *69*(2), 283–287. https://doi.org/10.1139/z91-044

Gelman, A., Carlin, J. B., Stern, H. S., & Rubin, D. B. (2013). *Bayesian Data Analysis, Chapman & Hall/CRC Texts in Statistical Science Vol. 3*.

Gill, J. A., Norris, K., & Sutherland, W. J. (2001). Why behavioural responses may not reflect the population consequences of human disturbance. *Biological Conservation*, *97*(2), 265–268. https://doi.org/10.1016/S0006-3207(00)00002-1

Global Wind Energy Council. (2021). Global wind report 2021. *Global Wind Energy Council: Brussels, Belgium*. https://gwec.net/global-wind-report-2021/

Grolemund, G., & Wickham, H. (2011). Dates and Times Made Easy with lubridate. *Journal of Statistical Software*, *40*(3), 1–25.

Hartig, F. (2022). DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models. *R Package Version 0.4.5*. https://CRAN.R-project.org/package=DHARMa

Hebblewhite, M., White, C. A., Nietvelt, C. G., McKenzie, J. A., Hurd, T. E., Fryxell, J. M., Bayley, S. E., & Paquet, P. C. (2005). Human activity mediates a trophic cascade caused by wolves. *Ecology*, *86*(8), 2135–2144. https://doi.org/R package version 0.4.5

Helland, M. L., Anker, M., Belgen Jakobsen, S., Sjong, M. L., Grønningsæter, T., Simensen, T., Vindedal, K., & Gaukstad, E. (2015). *Veileder for vurdering av landskapsvirkninger ved utbygging av vindkraftverk* (No. 1/2015). Norges vassdrags- og energidirektorat (NVE).

Helldin, J. O., Jung, J., Neumann, W., Olsson, M., Skarin, A., & Widemo, F. (2012). *The impacts of wind power on terrestrial mammals* (No. 6510). Swedish Environmental Protection Agency.

Hijmans, R. (2022). *raster: Geographic Data Analysis and Modeling*. https://CRAN.R-project.org/package=raster

Houle, M., Fortin, D., Dussault, C., Courtois, R., & Ouellet, J.-P. (2010). Cumulative effects of forestry on habitat use by gray wolf (Canis lupus) in the boreal forest. *Landscape Ecology*, *25*, 419–433. https://doi.org/10.1007/s10980-009-9420-2

Hurvich, C. M., & Tsai, C.-L. (1991). Bias of the corrected AIC criterion for underfitted regression and time series models. *Biometrika*, *78*(3), 499–509. https://doi.org/10.1093/biomet/78.3.499

Jedrzejewski, W., Schmidt, K., Theuerkauf, J., Jedrzejewska, B., & Okarma, H. (2001). Daily movements and territory use by radio-collared wolves (Canis lupus) in Bialowieza Primeval Forest in Poland. *Canadian Journal of Zoology*, *79*(11), 1993–2004. https://doi.org/10.1139/z01-147

Kaartinen, S., Kojola, I., & Colpaert, A. (2005). Finnish wolves avoid roads and settlements. *Annales Zoologici Fennici*, *42*(5), 523–532. https://www.jstor.org/stable/23736885

Karlsson, J., Brøseth, H., Sand, H., & Andrén, H. (2007). Predicting occurrence of wolf territories in Scandinavia. *Journal of Zoology*, *272*(3), 276–283. https://doi.org/10.1111/j.1469-7998.2006.00267.x

Klich, D., Łopucki, R., Ścibior, A., Gołębiowska, D., & Wojciechowska, M. (2020). Roe deer stress response to a wind farms: Methodological and practical implications. *Ecological Indicators*, *117*, 106658. https://doi.org/10.1016/j.ecolind.2020.106658

Koschinski, S., Culik, B. M., Henriksen, O. D., Tregenza, N., Ellis, G., Jansen, C., & Kathe, G. (2003). Behavioural reactions of free-ranging porpoises and seals to the noise of a simulated 2 MW windpower generator. *Marine Ecology Progress Series*, *265*, 263–273. https://doi.org/10.3354/meps265263

Kuvlesky Jr, W. P., Brennan, L. A., Morrison, M. L., Boydston, K. K., Ballard, B. M., & Bryant, F. C. (2007). Wind Energy Development and Wildlife Conservation: Challenges and Opportunities. *The Journal of Wildlife Management*, *71*(8), 2487–2498. https://doi.org/10.2193/2007-248

Länsstyrelserna, & Energimyndigheten. (2022a). *LST Vindbrukskollen Vindkraftverk, CC0 1.0*. https://vbk.lansstyrelsen.se/sv

Länsstyrelserna, & Energimyndigheten. (2022b). *Vindbrukskollen Användarhandbok*. https://www.energimyndigheten.se/fornybart/vindkraft/vindlov/vindbrukskollen/anvandarhandbok/

Lindenmayer, D., & Franklin, J. (2003). *Towards forest sustainability*. CSIRO PUBLISHING. ISBN: 0-643-06832-5

Loosen, A. E., Devineau, O., Zimmermann, B., Cromsigt, J. P., Pfeffer, S. E., Skarpe, C., & Marie Mathisen, K. (2021). Roads, forestry, and wolves interact to drive moose browsing behavior in Scandinavia. *Ecosphere*, *12*(1), e03358. https://doi.org/10.1002/ecs2.3358

Lovich, J. E., & Ennen, J. R. (2013). Assessing the state of knowledge of utility-scale wind energy development and operation on non-volant terrestrial and marine wildlife. *Applied Energy*, *103*, 52–60. https://doi.org/10.1016/j.apenergy.2012.10.001

Lüdecke, D. (2018). ggeffects: Tidy Data Frames of Marginal Effects from Regression Models. *Journal of Open Source Software*, *3*(26), 772. https://doi.org/10.21105/joss.00772

Lundberg, P. (2011). *Vindkraften och landlevande däggdjur – blir det effekter och hur påvisar vi dem?* [Projektarbete]. Department of Wildlife, Fish, and Environmental Studies, SLU.

Matteson, M. Y. (1992). *Denning ecology of wolves in Northwest Montana and southern Canadian Rockies* [Master thesis]. University of Montana.

Mattisson, J., Sand, H., Wabakken, P., Gervasi, V., Liberg, O., Linnell, J. D., Rauset, G. R., & Pedersen, H. C. (2013). Home range size variation in a recovering wolf population: Evaluating the effect of environmental, demographic, and social factors. *Oecologia*, *173*, 813–825. https://doi.org/10.1007/s00442-013-2668-x

May, R., Van Dijk, J., Wabakken, P., Swenson, J. E., Linnell, J. D., Zimmermann, B., Odden, J., Pedersen, H. C., Andersen, R., & Landa, A. (2008). Habitat differentiation within the large-carnivore community of Norway's multiple-use landscapes. *Journal of Applied Ecology*, *45*(5), 1382–1391. https://doi.org/10.1111/j.1365-2664.2008.01527.x

Mech, L. D., & Boitani, L. (2003). Wolf Social Ecology. In *Wolves: Behavior, Ecology, and Conservation* (pp. 1–34). The University of Chicago Press.

Milleret, C., Ordiz, A., Chapron, G., Andreassen, H. P., Kindberg, J., Månsson, J., Tallian, A., Wabakken, P., Wikenros, C., & Zimmermann, B. (2018). Habitat segregation between brown bears and gray wolves in a human-dominated landscape. *Ecology and Evolution*, *8*(23), 11450–11466. https://doi.org/10.1002/ece3.4572

Milleret, C., Ordiz, A., Sanz-Perez, A., Uzal, A., Carricondo-Sanchez, D., Eriksen, A., Sand, H., Wabakken, P., Wikenros, C., & Åkesson, M. (2019). Testing the influence of habitat experienced during the natal phase on habitat selection later in life in Scandinavian wolves. *Scientific Reports*, *9*(6526), 1–11. https://doi.org/10.1038/s41598-019-42835-1

Naylor, L. M., Wisdom, M. J., & Anthony, R. G. (2009). Behavioral responses of North American elk to recreational activity. *The Journal of Wildlife Management*, *73*(3), 328–338. https://doi.org/10.2193/2008-102

Nordli, K. T. (2018). *On the way to independence: Ebbing cohesion in Scandinavian wolf family groups* [Master thesis]. Inland Norway University of Applied Sciences.

Norges vassdrags- og energidirektorat (NVE). (2022a). *Vindkraftverk, Norsk lisens for offentlige data (NLOD)*. http://nedlasting.nve.no/gis/

Norges vassdrags- og energidirektorat (NVE). (2022b, August 18). *Oversikt kraftverk*. Data for utbygde vindkraftverk i Norge. https://www.nve.no/energi/energisystem/vindkraft/data-for-utbygde-vindkraftverk-i-norge/

Norges vassdrags- og energidirektorat (NVE). (2022c, October 4). *Saksgang for konsesjonsbehandling av vindkraft*. Konsesjonsbehandling av vindkraftverk på land. https://www.nve.no/konsesjon/konsesjonsbehandling-og-oppfoelging-av-vindkraft-paa-land/konsesjonsbehandling-av-vindkraftverk-paa-land/

Norges vassdrags- og energidirektorat (NVE). (2022d, October 20). *NVE Temakart*. NVE Vindkraft. https://temakart.nve.no/tema/vindkraftverk

Norris, D. R., Theberge, M. T., & Theberge, J. B. (2002). Forest composition around wolf (Canis lupus) dens in eastern Algonquin Provincial Park, Ontario. *Canadian Journal of Zoology*, *80*(5), 866–872. https://doi.org/10.1139/z02-067

Olsson, M., Cox, J., Larkin, J., Maehr, D., Widen, P., & Wichrowski, M. (2007). Movement and activity patterns of translocated elk (Cervus elaphus nelsoni) on an active coal mine in Kentucky. *Wildlife Biology in Practice*, *3*(1), 1–8. https://doi.org/10.2461/wbp.2007.3.1

Ordiz, A., Milleret, C., Kindberg, J., Månsson, J., Wabakken, P., Swenson, J. E., & Sand, H. (2015). Wolves, people, and brown bears influence the expansion of the recolonizing wolf population in Scandinavia. *Ecosphere*, *6*(12), 1–14. https://doi.org/10.1890/ES15-00243.1

Ordiz, A., Uzal, A., Milleret, C., Sanz-Pérez, A., Zimmermann, B., Wikenros, C., Wabakken, P., Kindberg, J., Swenson, J. E., & Sand, H. (2020). Wolf habitat selection when sympatric or allopatric with brown bears in Scandinavia. *Scientific Reports*, *10*(9941), 1–11. https://doi.org/10.1038/s41598-020-66626-1

Paananen, T., Piironen, J., Bürkner, P.-C., & Vehtari, A. (2021). Implicitly adaptive importance sampling. *Statistics and Computing*, *31*(16). https://doi.org/10.1007/s11222-020-09982-2

Packard, J. M. (2003). Wolf Behavior: Reproductive, Social and Intelligent. In *Wolves: Behavior, Ecology, and Conservation* (pp. 35–65). The University of Chicago Press.

Passoni, G., Rowcliffe, J. M., Whiteman, A., Huber, D., & Kusak, J. (2017). Framework for strategic wind farm site prioritisation based on modelled wolf reproduction habitat in Croatia. *European Journal of Wildlife Research*, *63*(38), 1–16. https://doi.org/10.1007/s10344-017-1092-7

Pebesam, E. J., & Bivand, R. S. (2005). Classes and methods for spatial data in R. *R News*, *5*(2). https://cran.r-project.org/doc/Rnews/

Pebesma, E. (2018). Simple Features for R: Standardized Support for Spatial Vector Data. *The R Journal*, *10*(1), 439–446. https://doi.org/10.32614/RJ-2018-009

Person, D. K., & Russell, A. L. (2009). Reproduction and Den Site Selection by Wolves in a Disturbed Landscape. *Northwest Science*, *83*(3), 211–224. https://doi.org/10.3955/046.083.0305

Pettersson, M., Ek, K., Söderholm, K., & Söderholm, P. (2010). Wind power planning and permitting: Comparative perspectives from the Nordic countries. *Renewable and Sustainable Energy Reviews*, *14*(9), 3116–3123. https://doi.org/10.1016/j.rser.2010.07.008

Potvin, F., Breton, L., & Courtois, R. (2005). Response of beaver, moose, and snowshoe hare to clear-cutting in a Quebec boreal forest: A reassessment 10 years after cut. *Canadian Journal of Forest Research*, *35*(1), 151–160. https://doi.org/10.1139/x04-151

QGIS Development Team. (2022). *QGIS Geographic Information System*. QGIS Association. https://www.qgis.org

R Core Team. (2022). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. https://www.R-project.org/

REN21. (2021). *Renewables 2021 Global Status Report*. REN21 Secretariat.

Roffler, G. H., & Gregovich, D. P. (2018). Wolf space use during denning season on Prince of Wales Island, Alaska. *Wildlife Biology*, *2018*(1), 1–11. https://doi.org/10.2981/wlb.00468

Roffler, G. H., Gregovich, D. P., & Larson, K. R. (2018). Resource selection by coastal wolves reveals the seasonal importance of seral forest and suitable prey habitat. *Forest Ecology and Management*, *409*, 190–201. https://doi.org/10.1016/j.foreco.2017.11.025

Rovdata. (1998, 2022). *Overvåkingsresultater/ Rapporter Ulv*. Ulv. https://rovdata.no/Ulv/Rapporter.aspx

RStudio Team. (2022). *RStudio: Integrated Development Environment for R*. RStudio, PBC. http://www.rstudio.com/

Ryberg, D. S., Tulemat, Z., Stolten, D., & Robinius, M. (2020). Uniformly constrained land eligibility for onshore European wind power. *Renewable Energy*, *146*, 921–931. https://doi.org/10.1016/j.renene.2019.06.127

Rydell, J., Engström, H., Hedenström, A., Kyed Larsen, J., Pettersson, J., & Green, M. (2012). *The effect of wind power on birds and bats:–A synthesis* (No. 6511). Swedish Environmental Protection Agency.

Sand, H., Wikenros, C., Wabakken, P., & Liberg, O. (2006). Effects of hunting group size, snow depth and age on the success of wolves hunting moose. *Animal Behaviour*, *72*(4), 781–789. https://doi.org/10.1016/j.anbehav.2005.11.030

Sanz-Pérez, A., Ordiz, A., Sand, H., Swenson, J. E., Wabakken, P., Wikenros, C., Zimmermann, B., Åkesson, M., & Milleret, C. (2018). No place like home? A test of the natal habitat-biased dispersal hypothesis in Scandinavian wolves. *Royal Society Open Science*, *5*(12), 181379. https://doi.org/10.1098/rsos.181379

Sazatornil, V., Rodríguez, A., Klaczek, M., Ahmadi, M., Álvares, F., Arthur, S., Blanco, J. C., Borg, B. L., Cluff, D., & Cortes, Y. (2016). The role of human-related risk in breeding site selection by wolves. *Biological Conservation*, *201*, 103–110. https://doi.org/10.1016/j.biocon.2016.06.022

Skarin, A., Sandström, P., & Alam, M. (2018). Out of sight of wind turbines—Reindeer response to wind farms in operation. *Ecology and Evolution*, *8*(19), 9906–9919. https://doi.org/10.1002/ece3.4476

Sugiura, N. (1978). Further analysts of the data by akaike's information criterion and the finite corrections: Further analysts of the data by akaike's. *Communications in Statistics-Theory and Methods*, *7*(1), 13–26. https://doi.org/10.1080/03610927808827599

The Swedish Environmental Protection Agency. (2022). *The Swedish Environmental Code*. Naturvårdsverket. https://www.naturvardsverket.se/en/laws-and-regulations/the-swedish-environmental-code/

Theuerkauf, J. (2009). What Drives Wolves: Fear or Hunger? Humans, Diet, Climate and Wolf Activity Patterns. *Ethology*, *115*(7), 649–657. https://doi.org/10.1111/j.1439-0310.2009.01653.x

Theuerkauf, J., Jędrzejewski, W., Schmidt, K., Okarma, H., Ruczyński, I., Śniezko, S., & Gula, R. (2003). Daily Patterns and Duration of Wolf Activity in the Białowieza Forest, Poland. *Journal of Mammalogy*, *84*(1), 243–253. https://doi.org/10.1644/1545-1542(2003)084<0243:DPADOW>2.0.CO;2

Vehtari, A., Gabry, J., Magnusson, M., Yao, Y., Bürkner, P., Paananen, T., & Gelman, A. (2022). loo: Efficient leave-one-out cross validation and WAIC for Bayesian models. *R Package Version 2.5.1*. https://mc-stan.org/loo/

Vehtari, A., Gelman, A., & Gabry, J. (2017). Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC. *Statistics and Computing*, *27*, 1413–1432. https://doi.org/10.1007/s11222-016-9696-4

Vehtari, A., Gelman, A., Simpson, D., Carpenter, B., & Bürkner, P.-C. (2021). Rank-normalization, folding, and localization: An improved R for assessing convergence of MCMC (with discussion). *Bayesian Analysis*, *16*(2), 667–718. https://doi.org/10.1214/20-BA1221

Vehtari, A., Simpson, D., Gelman, A., Yao, Y., & Gabry, J. (2015). Pareto smoothed importance sampling. *ArXiv*. https://doi.org/10.48550/ARXIV.1507.02646

Wabakken, P., Sand, H., Liberg, O., & Bjärvall, A. (2001). The recovery, distribution, and population dynamics of wolves on the Scandinavian peninsula, 1978-1998. *Canadian Journal of Zoology*, *79*(4), 710–725. https://doi.org/10.1139/z01-029

Wabakken, P., Svensson, L., Maartmann, E., Nordli, K., Flagstad, Ø., & Åkesson, M. (2022). *Bestandsovervåking av ulv vinteren 2021-2022. Inventering av varg vintern 2021-2022* (No. 1–2022; Bestandsstatus for store rovdyr i Skandinavia, p. 59). Rovdata og SLU Viltskadecenter. https://hdl.handle.net/11250/2997123

Wallin, J. A. (1998). *A movement study of black bears in the vicinity of a wind turbine project, Searsburg, Vermont*. Report for Green Mountain Power Corporation.

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York. https://ggplot2.tidyverse.org

Wickham, H., François, R., Henry, L., & Müller, K. (2022). dplyr: A Grammar of Data Manipulation. *R Package Version 1.0.9*. https://CRAN.R-project.org/package=dplyr

Wickham, H., & Girlich, M. (2022). tidyr: Tidy Messy Data. *R Package Version 1.2.0*. https://CRAN.R-project.org/package=tidyr

Zimmermann, B., Nelson, L., Wabakken, P., Sand, H., & Liberg, O. (2014). Behavioral responses of wolves to roads: Scale-dependent ambivalence. *Behavioral Ecology*, *25*(6), 1353–1364. https://doi.org/10.1093/beheco/aru134

Zimmermann, B., Sand, H., Wabakken, P., Liberg, O., & Andreassen, H. P. (2015). Predator-dependent functional response in wolves: From food limitation to surplus killing. *Journal of Animal Ecology*, *84*(1), 102–112. https://doi.org/10.1111/1365-2656.12280

Zuur, A. F., Ieno, E. N., & Elphick, C. S. (2010). A protocol for data exploration to avoid common statistical problems. *Methods in Ecology and Evolution*, *1*(1), 3–14. https://doi.org/10.1111/j.2041-210X.2009.00001.x

Appendices

Appendix A1: Data Overview

Table A1: Explanations for the different wind power plant status in Norway and Sweden. Information retrieved from Länsstyrelserna & Energimyndigheten (2022b) and NVE (2022d)

Country	Category	Explanation
Norway	**In operation/built**	Wind turbines are built (and are in operation).
	Under construction	Wind turbines are under construction.
	Approved	The case has been granted a final licence.
	Rejected	The case has been finally rejected.
	Under processing	The case is being processed. There may be cases that have been appealed and are therefore pending in appeal processing.
	Planning completed	The case has been closed. They have been either withdrawn or put on hold. They are not expected to become active again.
Sweden	**In operation/built**	Wind turbines are built on site (and are in operation).
	Approved	The application for wind power establishment has been approved by the authorities but the wind turbines have not been built yet. The application could still be rejected by other authorities.
	Rejected	The authorities have rejected the proposed wind power establishment.
	Processed	The proposed wind power establishment is being processed but no decision has yet been made.
	Demounted	Wind turbines have been demounted.
	Appealed	An appeal has been filed and no final decision has been made yet.
	Information missing	There is no information available to assess the status.
	Not relevant or withdrawn	The proposed wind power establishment is no longer relevant for construction. For example, the project has been cancelled or the permit is not valid any longer.

Table A2: Overview of wind power plants with its' status, municipality, county and number of turbines. Data retrieved from NVE (2022a) and Länsstyrelserna & Energimyndigheten (2022a).

Project	**Status**	**Municipality**	**County**	**Number of turbines**
Aapua Vindpark	In operation	Övertorneå	Norrbottens län	7
Älgkullen	Approved	Smedjebacken	Dalarnas län	15
Åndberget	Rejected	Härjedalen	Jämtlands län	39
	no longer relevant for construction			9
	In operation			53
Årjäng Byn	Rejected	Årjäng	Värmlands län	15
Årjäng NO	Rejected	Årjäng	Värmlands län	29
	no longer relevant for construction			14
Bergvind Annefors	no longer relevant for construction	Bollnäs	Gävleborgs län	15
		Ovanåker		5
Björnetjärnsberget	Processed	Eda	Värmlands län	18
Broboberget	Approved	Rättvik	Dalarnas län	80
Edsleskogs Hult	no longer relevant for construction	Åmål	Västra Götalands län	6
Fageråsen	Approved	Malung-Sälen	Dalarnas län	20
Fjällberget	In operation	Ludvika	Dalarnas län	3
Fjällrämmen	no longer relevant for construction	Filipstad	Värmlands län	26
Gagnef Rosberget	no longer relevant for construction	Gagnef	Dalarnas län	6
Granåsen	no longer relevant for construction	Karlskoga	Örebro län	2
Granberget	no longer relevant for construction	Torsby	Värmlands län	16
Grävlingkullarna	no longer relevant for construction	Filipstad	Värmlands län	16
Gullberget	Processed	Borlänge	Dalarnas län	6
Gussjöberget	no longer relevant for construction	Ludvika	Dalarnas län	2
Häljebyn	no longer relevant for construction	Årjäng	Värmlands län	19
Hälsingeskogen	Rejected	Ovanåker	Gävleborgs län	40
Hedbodberget Etapp 1	In operation	Rättvik	Dalarnas län	15
Kajsberget 6	no longer relevant for construction	Vansbro	Dalarnas län	18
Kajsberget 7	no longer relevant for construction	Vansbro	Dalarnas län	10
Kedjeåsen	no longer relevant for construction	Karlskoga	Örebro län	17
Kjolberget	In operation			13

Korpfjället	no longer relevant for construction	Malung-Sälen	Dalarnas län	6
	In operation			9
Kungbergen	no longer relevant for construction	Filipstad	Värmlands län	18
Långholmsberget	no longer relevant for construction	Smedjebacken	Dalarnas län	26
Lannaberget	Approved	Rättvik	Dalarnas län	35
Laxåskogen	Rejected	Laxå	Örebro län	1
	no longer relevant for construction			14
	In operation			7
Lerviken	In operation	Ljusnarsberg	Örebro län	1
Maevaara vindkraftpark	In operation	Övertorneå	Norrbottens län	10
Mången	In operation	Karlstad	Värmlands län	2
Mangslidberget	no longer relevant for construction	Torsby	Värmlands län	34
Markebäck	no longer relevant for construction	Askersund	Örebro län	8
Mjöberget	no longer relevant for construction	Ljusdal	Gävleborgs län	8
	Appealed			6
Norra Hunna	Rejected	Askersund	Örebro län	1
	In operation			4
Norrmogen	Processed	Lindesberg	Örebro län	11
Öby gård	no longer relevant for construction	Lindesberg	Örebro län	1
Orrberget/Stensvedberget	no longer relevant for construction	Ludvika	Dalarnas län	1
	In operation			9
Orrmosshöjden	Rejected	Hällefors	Örebro län	2
Orsa Norr	Processed	Orsa	Dalarnas län	92
Paljakoberget	In operation	Ludvika	Dalarnas län	1
Ramsberg Syd	no longer relevant for construction	Lindesberg	Örebro län	3
Rämsberget	no longer relevant for construction	Malung-Sälen	Dalarnas län	4
	In operation			7
Ramsnäs	In operation	Laxå	Örebro län	7
Raskiftet	In operation			31
Röbergsfjället	In operation	Vansbro	Dalarnas län	8
Röknölen	Processed	Torsby	Värmlands län	56
Ryttersfjäll	no longer relevant for construction	Eda	Värmlands län	6
Saxberget	no longer relevant for construction	Ludvika	Dalarnas län	6
	In operation			17
Silkomhöjden	In operation	Ludvika	Dalarnas län	2
		Vansbro		4
Skaftåsen	Approved	Härjedalen	Jämtlands län	35

Skäftberget	no longer relevant for construction	Orsa	Dalarnas län	8
Skinnerud	no longer relevant for construction	Sunne	Värmlands län	1
Slottsbol	Rejected	Laxå	Örebro län	2
	In operation			3
Sörbyparken	no longer relevant for construction	Ljusdal	Gävleborgs län	7
	In operation			37
Stöllsäterberget	Approved	Torsby	Värmlands län	15
Stömne	no longer relevant for construction	Arvika	Värmlands län	8
Stubberud	no longer relevant for construction	Säffle	Värmlands län	1
Torpaskoga	no longer relevant for construction	Laxå	Örebro län	5
Tretjärnsberget	no longer relevant for construction	Köping	Västmanlands län	1
Vårbo	no longer relevant for construction	Degerfors	Örebro län	1
Värnebo	no longer relevant for construction	Bengtsfors	Västra Götalands län	5
Vassland Eolus	no longer relevant for construction	Nora	Örebro län	15
Vindkraftanläggning Grannäs Eka	no longer relevant for construction	Degerfors	Örebro län	2
Vindkraftanläggning Norrboda	In operation	Degerfors	Örebro län	2
Vindkraftpark Blacksåsberget	no longer relevant for construction	Ljusdal	Gävleborgs län	9
Vindkraftpark Hemberget	Rejected	Ljusdal	Gävleborgs län	34
Vindpark Edsleskog	Rejected	Åmål	Västra Götalands län	6
		Bengtsfors		6
	no longer relevant for construction	Bengtsfors		1
Vindpark Hallbrån	Rejected	Bollnäs	Gävleborgs län	10
Vindpark Högkölen	In operation	Ljusdal	Gävleborgs län	18
Vindpark Tandsjö	Approved	Ljusdal	Gävleborgs län	9
	no longer relevant for construction			6

Table A3: Overview of wolf individuals with territory, sex, year, sampling interval, number of positions and reproductive status. Reproductive status is only displayed for individuals included in the analysis on the individual level.

Reproductive status = Breeding – wolves with pups; N = Non-breeding - wolves without pups

Wolf ID	Territory	Sex	Year	Number of positions	Reproductive status
M0609	Aamäck	F	2008	794	Breeding
			2009	603	Breeding
M0916	Aamäck	M	2009	14	Breeding
M1309	Aamäck	M	2013	331	Breeding
			2014	53	
M1310	Aamäck	F	2013	437	Breeding
			2014	7	
M0512	Amungen	F	2005	446	Breeding
			2006	469	Breeding
M1501	Aspafallet	F	2015	412	Non-breeding
			2016	34	
M1502	Aspafallet	M	2015	686	Non-breeding
M1711	Aspafallet	M	2018	1541	Breeding
M0009	Bograngen	M	2003	738	Non-breeding
M1901	Bograngen	F	2019	354	
M1904	Bograngen	M	2019	137	
M0209	Djurskog	F	2003	940	Breeding
			2004	292	Breeding
M0306	Djurskog	M	2004	781	Breeding
M0505	Forshytttan	M	2005	178	Non-breeding
M0903	Galven	M	2009	731	Breeding
M0914	Galven	F	2009	541	Breeding
M0212	Glaskogen	F	2002	58	
			2003	19	
M0213	Glaskogen	M	2002	321	
M0004	Grangärde	F	2000	6	
M9804	Grangärde	M	1999	36	
			2000	231	
			2001	233	
M0611	Gräsmark	M	2007	292	
			2008	154	
M0206	Halgån	F	2003	106	
			2004	650	
			2005	191	
			2006	607	Breeding
			2007	762	Breeding
			2008	71	
M0105	Hasselfors	M	2001	162	
			2003	393	

	Hedbyn		2010	77	
M1006	Hedbyn	F	2010	1619	Non-breeding
			2011	4	
M1106	Homna	M	2011	171	
M0305	Julussa	F	2009	952	Non-breeding
M1409	Julussa	F	2014	632	
M1410	Julussa	M	2014	311	
M0510	Juvberget	F	2006	250	Non-breeding
			2007	19	
			2011	785	Non-breeding
M0606	Juvberget	M	2007	293	Non-breeding
			2008	55	
M1113	Juvberget	M	2011	658	Non-breeding
			2012	257	
M1813	Juvberget	F	2018	344	
			2019	1041	
			2020	1207	Breeding
M1902	Juvberget	M	2019	583	
			2020	566	Breeding
M1903	Juvberget	M	2019	10	
M0504	Kilsbergen	M	2005	105	
			2006	59	
M0507	Kloten	F	2008	761	
			2009	451	Breeding
			2010	1113	Breeding
M0918	Kloten	M	2009	444	
			2010	364	Breeding
M1301	Kukumäki	F	2013	376	Breeding
			2014	486	Breeding
			2015	1100	Breeding
			2016	56	
M1302	Kukumäki	M	2013	682	Breeding
			2014	686	Breeding
M1009	Loka	F	2010	1426	Breeding
M1811	Magnor	M	2019	1614	Breeding
M1814	Norrsjön	M	2018	908	
			2019	549	
			2020	545	
			2021	186	
M0007	Nyskoga	M	2001	109	
			2002	124	
M0702	Pirtijärvi	M	2007	902	
			2008	62	
M0009	Rotna	M	2004	426	Non-breeding
M1204	Siljansringen	F	2012	763	Breeding

			2013	538	
M0909	Tandsjö	F	2009	323	
			2010	654	Non-breeding
			2012	588	Breeding
			2013	26	
			2014	475	Breeding
			2015	58	
M1103	Tandsjö	M	2011	1089	Breeding
			2012	493	
			2014	574	Breeding
M1104	Tansen	F	2011	358	
M1701	Tansen	M	2018	959	Breeding
M1001	Tenskog	F	2010	892	Non-breeding
			2011	536	Breeding
M1002	Tenskog	M	2010	111	
			2011	687	Breeding
M1311	Tiveden	F	2013	422	Breeding
			2014	676	Breeding
			2015	227	
M1312	Tiveden	M	2013	384	Breeding
			2014	9	
M0204	Tyngjsö	F	2002	894	Non-breeding
M0602	Ulriksberg	F	2006	806	
			2007	854	
			2008	513	
M9804	Ulriksberg	M	2004	506	
			2005	402	
			2006	97	
			2007	11	
M0506	Uttersberg	M	2005	736	Breeding
			2006	176	
			2007	623	Non-breeding
			2008	603	Breeding
			2009	369	Non-breeding
M0601	Uttersberg	F	2006	741	
			2007	288	Non-breeding
			2008	121	

Appendix A2: Results

Table A1: AIC$_C$ table for the wolf usage index and probability of individual wind turbines being placed in the activity centres of wolves models on the wolf pair and individual level.

The table shows model names, number of estimated parameters (K), difference in Akaike Information Criterion (corrected) (AICc) between model and best model (ΔAICc), Akaike weights (AICcWt), cumulative Akaike weight (Cum. Wt.), negative likelihood (LL).

			K	**ΔAICc**	**AICcWt**	**Cum. Wt**	**LL**
Wolf usage index	**wolf pair level**	Model 7	12	0	0.99	0.99	6675.58
		Model 5	11	9.3	0.01	1	6669.93
		Model 6	12	138.7	0	1	6606.23
		Model 4	9	167.26	0	1	6588.94
		Model 2	8	168.73	0	1	6587.21
		Model 1	5	884.56	0	1	6226.29
		Model 3	6	886.54	0	1	6226.3
		Model 0	4	3542.51	0	1	4896.32
	individual level	Model 19	12	0	1	1	3195.8
		Model 18	11	78.05	0	1	3155.77
		Model 17	9	129.18	0	1	3128.19
		Model 15	8	138.31	0	1	3122.62
		Model 16	9	143.13	0	1	3121.21
		Model 7	7	149.06	0	1	3116.24
		Model 8	8	151.05	0	1	3116.25
		Model 13	8	163.25	0	1	3110.15
		Model 6	7	187.85	0	1	3096.84
		Model 4	6	187.92	0	1	3095.81
		Model 12	8	201.73	0	1	3090.91
		Model 10	7	212.07	0	1	3084.74
		Model 9	7	213.45	0	1	3084.05
		Model 14	8	213.58	0	1	3084.99
		Model 11	8	218.23	0	1	3082.66
		Model 3	6	223.62	0	1	3077.96
		Model 5	7	225.2	0	1	3078.17
		Model 2	6	238.62	0	1	3070.46
		Model 1	5	239.23	0	1	3069.15
		Model 0	4	810.11	0	1	2782.71
Probability wind turbine in activity centre	**wolf pair level**	Model 7	10	0	0.99	0.99	-1751.21
		Model 5	9	9.81	0.01	1	-1757.18
		Model 4	7	59.92	0	1	-1784.34
		Model 6	10	59.95	0	1	-1781.18

		Model 2	6	65.1	0	1	-1787.97
		Model 3	4	308.95	0	1	-1911.97
		Model 1	3	311.16	0	1	-1914.1
		Model 0	2	1025.58	0	1	-2272.33
	individual level	Model 18	9	0	0.69	0.69	-175.76
		Model 19	10	1.63	0.31	1	-175.35
		Model 10	5	18.23	0	1	-189.5
		Model 15	6	18.98	0	1	-188.76
		Model 3	4	20.1	0	1	-191.54
		Model 12	6	20.3	0	1	-189.42
		Model 14	6	20.47	0	1	-189.5
		Model 17	7	20.66	0	1	-188.45
		Model 7	5	20.72	0	1	-190.75
		Model 1	3	21.43	0	1	-193.29
		Model 9	5	21.77	0	1	-191.27
		Model 5	5	22.15	0	1	-191.46
		Model 8	6	22.61	0	1	-190.57
		Model 4	4	23.06	0	1	-193.02
		Model 2	4	23.43	0	1	-193.2
		Model 13	6	23.46	0	1	-191
		Model 11	6	24.13	0	1	-191.33
		Model 16	7	24.7	0	1	-190.47
		Model 6	5	25.12	0	1	-192.95
		Model 0	2	76.16	0	1	-221.71

Table A2: Efficient approximate leave-one-out cross-validation (LOO) for model comparison for the proportion of areal overlap between wind power plants and the wolf activity centre on the wolf pair level and the individual level.

The table shows the difference of the Bayesian LOO estimated of the expected log pointwise predictive density between models (ELPD diff.), the standard error of the component-wise differences of ELPD LOO (SE diff.), the Bayesian LOO estimated of the expected log pointwise predictive density (ELPD LOO), the standard error of the expected log pointwise predictive density (SE ELPD LOO), the effective number of parameters (p LOO), the standard error of the effective number of parameters (SE p LOO), the leave one out cross validation information criterion (LOOIC) and the standard error of the LOO information criterion (SE LOOIC).

		ELPD diff.	**SE diff.**	**ELPD LOO**	**SE ELPD LOO**	**p LOO**	**SE p LOO**	**LOOIC**	**SE LOOIC**
Wolf pair level	**Model 5**	0.0000000	0.0000000	426.4408	43.38641	26.20944	3.927760	-852.8816	86.77281
	Model 7	-1.3640880	0.3944835	425.0767	43.35175	27.41023	4.069196	-850.1534	86.70351
	Model 2	-4.6253480	4.6857455	421.8155	43.77766	22.62547	4.054368	-843.6309	87.55532
	Model 4	-5.4830120	4.6999432	420.9578	43.75946	23.41139	4.104131	-841.9156	87.51892
	Model 6	-8.4009120	5.2581211	418.0399	43.85373	26.37944	4.591248	-836.0798	87.70747
	Model 1	-8.5558610	8.0011068	417.8849	44.34979	16.24963	3.056310	-835.7699	88.69958
	Model 3	-9.4679650	7.9890057	416.9728	44.31237	17.17428	3.161382	-833.9457	88.62474
	Model 0	-15.6187430	10.5742702	410.8221	45.23774	10.89648	2.162411	-821.6441	90.47549
individual level	**Model 1**	0.0000000	0.0000000	20.077421	17.32595	12.70389	5.664577	-40.15484	34.6519
	Model 2	-0.2533127	1.3487661	19.824109	17.23318	13.73121	5.697756	-39.64822	34.46635
	Model 3	-0.8362465	4.4419313	19.241175	18.07105	16.07165	7.028639	-38.48235	36.14209
	Model 10	-0.8513761	7.1972001	19.226045	18.59134	18.53781	8.729348	-38.45209	37.18267
	Model 4	-0.9113740	0.4963341	19.166048	17.10462	13.30729	5.548368	-38.33209	34.20924
	Model 15	-0.9211028	6.8037691	19.156319	18.24633	18.44006	8.273206	-38.31264	36.49265
	Model 9	-1.2072981	1.9284686	18.870123	17.04606	14.65629	5.730339	-37.74025	34.09213
	Model 6	-1.2735062	1.6941477	18.803915	17.06555	14.44836	5.683934	-37.60783	34.1311
	Model 5	-1.4102461	4.6222049	18.667175	17.97744	16.47044	7.031186	-37.33435	35.95487
	Model 7	-1.5686417	4.1016307	18.50878	17.87797	16.34181	6.815309	-37.01756	35.75595
	Model 0	-1.7572953	2.4630835	18.320126	17.5536	11.09132	5.264331	-36.64025	35.1072
	Model 13	-2.3977222	2.3260426	17.679699	16.93875	15.29818	5.784723	-35.35940	33.87749

	Model 8	-2.3988563	4.3692683	17.678565	17.7738	16.99462	6.893831	-35.35713	35.54759
	Model 11	-2.4884308	5.3135582	17.588991	17.99087	17.48135	7.324343	-35.17798	35.98173
	Model 12	-2.5538373	5.0247299	17.523584	17.78437	17.15199	7.066263	-35.04717	35.56875
	Model 16	-3.3785016	5.0599032	16.69892	17.78253	17.87101	7.154199	-33.39784	35.56506
	Model 17	-3.4186601	4.8758049	16.658761	17.61227	17.58197	6.962902	-33.31752	35.22455
	Model 14	-7.6086902	13.0577894	12.468731	21.7789	24.25961	13.272720	-24.93746	43.5578
	Model 18	-10.3133801	12.2992434	9.764041	21.10583	25.57081	12.787196	-19.52808	42.21166
	Model 19	-11.0455163	12.1094328	9.031905	20.85571	26.12014	12.554745	-18.06381	41.71141

Table A3: Back transformed estimates for the fixed and random effects of the top model for the wolf usage index at the turbine sites on the wolf pair level.

The table shows the estimates, 95% confidence interval and p-value for the fixed effects and its levels and variance of the error term (σ^2), between group variance (τ_{00}), intra-class correlation (ICC) and number of levels for the random effects. Number of observations and marginal and conditional R^2 are displayed as well.

Predictors	**Estimates**	**95% CI**	**p**
(Intercept)	0.12	0.09- 0.15	**<0.001**
Rel. activity centre area	1.00	1.00 – 1.00	**<0.001**
Season [Early winter]	0.55	0.52 - 0.58	**0.001**
Season [Late winter]	0.43	0.40 - 0.47	**0.001**
Season [Rendezvous]	0.50	0.46 - 0.53	0.759
Time of day [Night]	0.49	0.48 - 0.49	**0.001**
Rel. activity centre area : Season [Early winter]	0.06	0.04 - 0.09	**<0.001**
Rel. activity centre area : Season [Late winter]	0.08	0.05 - 0.13	**<0.001**
Rel. activity centre area : Season [Rendezvous]	0.23	0.16 – 0.33	**< 0.001**
Random Effects			
σ^2	0.16		
$\tau_{00\ Territory}$	0.37		
$\tau_{00\ Power\ plant\ ID}$	0.66		
ICC	0.87		
$N_{Territory}$	32		
$N_{Power\ plant\ ID}$	79		
Observations	13614		
Marginal R^2 / Conditional R^2	0.243 / 0.900		

Table A4: Back transformed estimates for the fixed and random effects of the top model for the wolf usage index at the turbine sites on the individual level.

The table shows the estimates, 95% confidence interval and p-value for the fixed effects and its levels and variance of the error term (σ^2), between group variance (τ_{00}), intra-class correlation (ICC) and number of levels for the random effects. Number of observations and marginal and conditional R^2 are displayed as well.

Predictors	**Estimates**	**95% CI**	**p**
(Intercept)	0.15	0.10 - 0.23	**<0.001**
Sex [Male]	0.95	0.91 - 0.98	**<0.001**
Reproductive status [Breeding]	0.32	0.25 - 0.40	**<0.001**
Rel. activity centre area	0.97	0.90 - 0.99	**<0.001**
Time of day [Night]	0.57	0.55 - 0.58	**<0.001**
Sex [Male] : Reproductive status [Breeding]	0.07	0.04 - 0.14	**<0.001**
Sex [Male] : Rel. activity centre area	0.00	0.00 - 0.00	**<0.001**
Reproductive status [Breeding] : Rel. activity centre area	0.92	0.74 – 0.98	**0.001**
Sex [Male] : Reproductive status [Breeding] : Rel. activity centre area	0.97	0.82 – 1.00	**0.001**
Random Effects			
σ^2	0.29		
$\tau_{00\ \text{Territory}}$	0.31		
$\tau_{00\ \text{Power plant ID}}$	1.03		
ICC	0.82		
$N_{\text{Territory}}$	22		
$N_{\text{Power plant ID}}$	42		
Observations	3650		
Marginal R^2 / Conditional R^2	0.192 / 0.855		

Table A5: Back transformed odd ratios for the fixed and random effects of the top model for the probability of individual wind turbines being placed in the activity centre of wolves on the wolf pair level.

The table shows the odds ratios, 95% confidence interval and p-value for the fixed effects and its levels and variance of the error term (σ^2), between group variance (τ_{00}), intra-class correlation (ICC) and number of levels for the random effects. Number of observations and marginal and conditional R^2 are displayed as well.

Predictors	**Odds ratio**	**95% CI**	**p**
(Intercept)	0.02	0.01- 0.04	**<0.001**
Rel. activity centre area	1.00	1.00 – 1.00	**<0.001**
Season [Early winter]	0.65	0.55 - 0.74	**0.005**
Season [Late winter]	0.62	0.50 - 0.72	0.056
Season [Rendezvous]	0.53	0.43 - 0.62	0.553
Time of day [Night]	0.45	0.43 - 0.48	**0.001**
Rel. activity centre area : Season [Early winter]	0.02	0.00 - 0.07	**<0.001**
Rel. activity centre area : Season [Late winter]	0.00	0.00 - 0.01	**<0.001**
Rel. activity centre area : Season [Rendezvous]	0.16	0.04 – 0.44	**0.023**
Random Effects			
σ^2	3.29		
$\tau_{00\ Territory}$	3.33		
ICC	0.50		
$N_{Territory}$	32		
Observations	325		
Marginal R^2 / Conditional R^2	0.135 / 0.570		

Table A6: Back transformed odd ratios for the fixed and random effects of the top model for the probability of individual wind turbines being placed in the wolf activity centre on the individual level.

The table shows the odd ratios, 95% confidence interval and p-value for the fixed effects and its levels and variance of the error term (σ^2*), between group variance (*τ_{00}*), intra-class correlation (ICC) and number of levels for the random effects. Number of observations and marginal and conditional* R^2 *are displayed as well.*

Predictors	**Odd ratios**	**95% CI**	**p**
(Intercept)	0.00	0.00 - 0.08	**0.002**
Sex [Male]	0.97	0.78 – 1.00	**0.003**
Reproductive status [Breeding]	0.28	0.11 - 0.55	0.108
Rel. activity centre area	1.00	0.90 – 1.00	**0.004**
Sex [Male] : Reproductive status [Breeding]	0.07	0.01 - 0.47	**0.041**
Sex [Male] : Rel. activity centre area	0.00	0.00 - 0.05	**0.004**
Reproductive status [Breeding] : Rel. activity centre area	1.00	0.79 – 1.00	**0.017**
Sex [Male] : Reproductive status [Breeding] : Rel. activity centre area	0.14	0.00 – 1.00	0.676
Random Effects			
σ^2	3.29		
$\tau_{00\ Territory}$	26.78		
ICC	0.89		
$N_{Territory}$	22		
Observations	107		
Marginal R^2 / Conditional R^2	0.040 / 0.895		

Table A7: Back transformed odd ratios for the fixed and random effects of the second-best model for the probability of individual wind turbines being placed in the activity centre of wolves on the individual level.

The table shows the odds ratios, 95% confidence interval and p-value for the fixed effects and its levels and variance of the error term (σ^2), between group variance (τ_{00}), intra-class correlation (ICC) and number of levels for the random effects. Number of observations and marginal and conditional R^2 are displayed as.

Predictors	**Odd ratios**	**95% CI**	**p**
(Intercept)	0.00	0.00 - 0.08	**0.002**
Sex [Male]	0.98	0.79 – 1.00	**0.002**
Reproductive status [Breeding]	0.27	0.10 - 0.54	0.091
Rel. activity centre area	1.00	0.84 – 1.00	**0.008**
Time of day [Night]	0.53	0.46 – 0.60	0.369
Sex [Male] : Reproductive status [Breeding]	0.06	0.01 - 0.46	**0.036**
Sex [Male] : Rel. activity centre area	0.00	0.00 - 0.04	**0.004**
Reproductive status [Breeding] : Rel. activity centre area	1.00	0.72 – 1.00	**0.024**
Sex [Male] : Reproductive status [Breeding] : Rel. activity centre area	0.21	0.00 – 1.00	0.760
Random Effects			
σ^2	3.29		
$\tau_{00\ Territory}$	26.76		
ICC	0.89		
$N_{Territory}$	22		
Observations	107		
Marginal R^2 / Conditional R^2	0.038 / 0.895		

Figure A1: Posterior distribution for the best model for the proportion of areal overlap between wind power plants and the wolf activity centre on the wolf pair level with estimates (x-axis) for the different model parameters (y-axis).

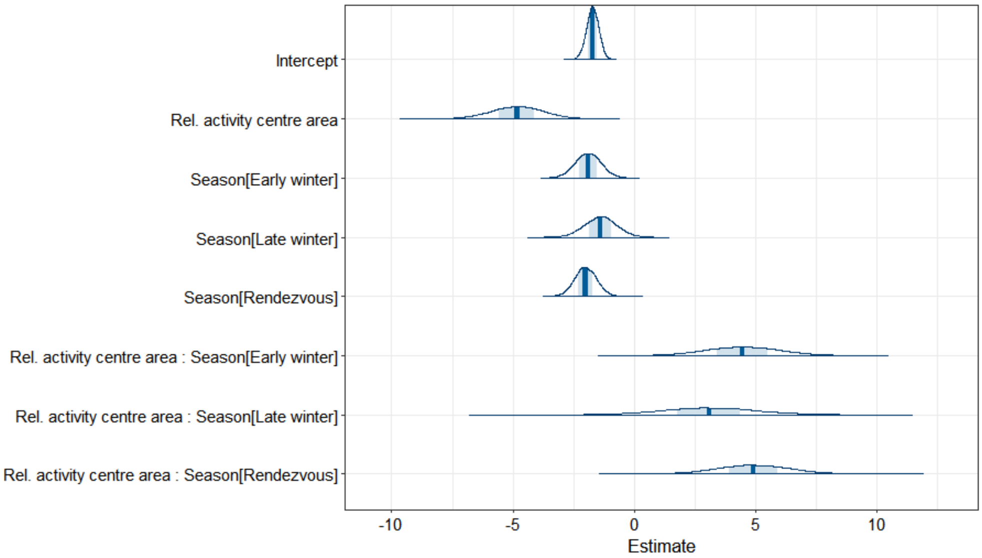


Table A8: Back transformed estimates for the fixed effects of the top model for the proportion of areal overlap between wind power plants and the wolf activity centre on the wolf pair level.

The table shows the estimates and 95% confidence interval for the fixed effects. Number of observations and marginal and conditional R^2 are displayed as.

Predictors	**Estimate**	**95% CI**
(Intercept)	0.15	0.10 - 0.23
Rel. activity centre area	0.01	0.00 - 0.06
Season [Early winter]	0.13	0.05 - 0.30
Season [Late winter]	0.20	0.06 - 0.48
Season [Rendezvous]	0.12	0.05 – 0.25
Rel. activity centre area : Season [Early winter]	0.99	0.81 – 1.00
Rel. activity centre area : Season [Late winter]	0.96	0.33 – 1.00
Rel. activity centre area : Season [Rendezvous]	0.99	0.88 – 1.00
$N_{Territory}$	32	
Observations	432	
Marginal R^2 / Conditional R^2	0.085 / 0.164	

Figure A2: Posterior distribution for the best model for the proportion of areal overlap between wind power plants and the wolf activity centre on the individual level, with estimates (x-axis) for the different model parameters (y-axis).

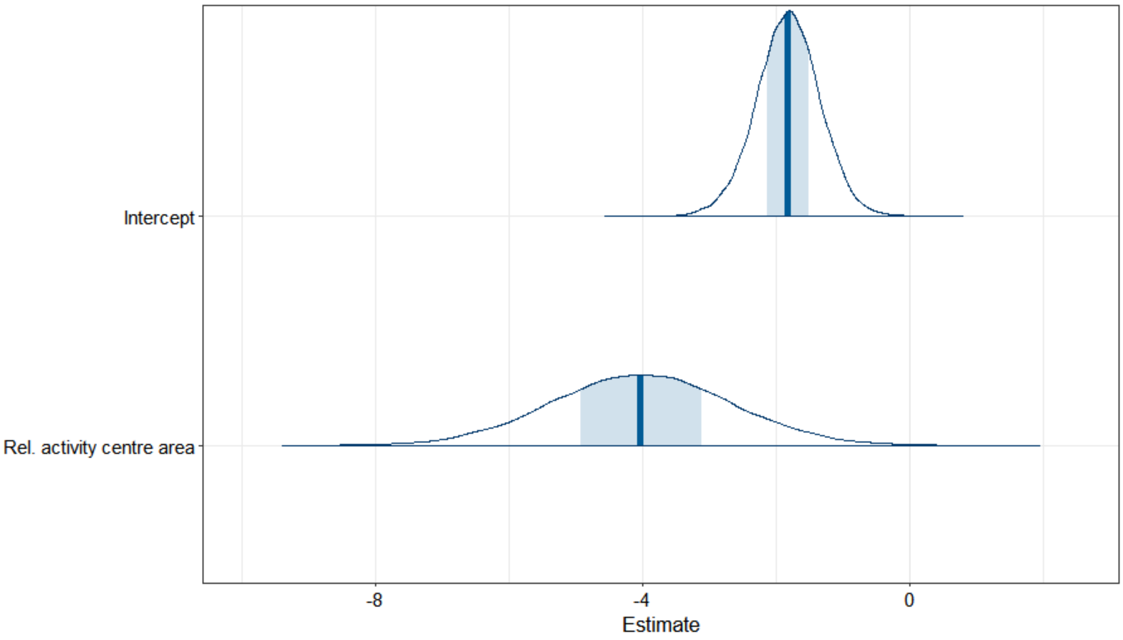


Table A9: Back transformed estimates for the fixed effects of the top model for the areal overlap between wind power plants and the wolf activity centre on the individual level.

The table shows the estimates and 95% confidence interval for the fixed effects. Number of observations and marginal and conditional R^2 are displayed as.

Predictors	Estimates	95% CI
(Intercept)	0.14	0.06 - 0.30
Rel. activity centre area	0.02	0.00 - 0.20
$N_{\text{Territory}}$	23	
Observations	110	
Marginal R^2 / Conditional R^2	0.011 / 0.226	