Flight behaviour of birds around a solitary wind turbine in a Swiss alpine valley

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Abstract

1. As the number of wind turbines in operation is rising, it becomes ever clearer that wind turbines can have adverse effects on birds, and that research in this area is needed. What is consistent throughout previous studies is that flight behaviour is investigated but usually not linked to weather conditions such as wind speed or wind speed variability. Additionally, flight behaviour is usually assessed using visual estimations.
2. We investigated bird flight behaviour around a solitary wind turbine in the Swiss Alps using a laser rangefinder to obtain data on bird flight behaviour in three dimensions. Species identity of birds was assessed visually and environmental data was provided by Callandawind AG. To analyse bird flight behaviour and the effect of wind conditions on bird flight, we used GLMMs. Data were analysed stepwise by including more and more data of an increasing spatial scale (radius) around the wind turbine.
3. Birds avoided approaching the nacelle of the wind turbine closer than 100 m although they do not avoid crossing anthropogenic areas including the wind turbine in general. This is a sign of macro-avoidance.
4. The effects of wind speed, wind speed variability and rotor speed on approaching distances depend on the spatial scale of data included in the analyses.
5. We found that birds get generally closer to the wind turbine with increasing wind speed. This effect gets weaker when more and more distant data are included into the analysis. It seems that birds passively allow wind current to carry them closer to the wind turbine when wind speed is high. However, in a close radius (< 150 m), there

is an indication of an opposite effect: Approaching distances increased with increasing wind speed variability and increasing speed of the rotor of the wind turbine. This might show that close to the wind turbine birds actively keep distance when wind is turbulent and rotor speed is high. But further away, approaching distances decreased with increasing wind speed variability/rotor speed which is again a sign for passive wind drift.

6. *Synthesis and applications*. In conclusion, we found evidence that birds do show macro-avoidance around a wind turbine. The closest approaching distance is depending on wind speed, wind speed variability and rotor speed in combination with the spatial scale. This stresses the need for more studies linking bird flight behaviour to weather conditions but also the need for weather-dependent mitigation measures, such as curtailments. We also propose that laser range finders could be used serially in assessing bird flight behaviour, especially in the context of studying the environmental impact of wind turbines.

Keywords: bird flight behaviour, laser range finder, macro-avoidance, micro-avoidance, wind energy impact on birds, wind turbine, wind turbine curtailments.

Introduction

Electricity production through wind energy use is associated with less carbon dioxide production than fossil electricity production and is thus ecologically preferable (Huntley *et al.* 2006). Combined with economically interesting developments and widespread governmental approval wind energy use has seen a rapid increase in production in recent years in 83 countries all over the world (Islam, Mekhilef & Saidur 2013). The number of wind farms and solitary wind turbines is increasing fast. Although reducing carbon dioxide production, an

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thus carbon dioxide related impacts on birds , wind turbines have a negative impact on birds offshore (Drewitt & Langston 2006; Hüppop *et al.* 2006), as well as onshore (de Lucas, Janss & Ferrer 2005; de Lucas *et al.* 2012; Douglas *et al.* 2012). Apart from indirect hazards like habitat loss, habitat fragmentation and acoustic intrusions (Leddy, Higgins & Naugle 1999; Larsen & Guillemette 2007; Devereux, Denny & Whittingham 2008; Carrete *et al.* 2009; Pruett, Patten & Wolfe 2009; Plonczkier & Simms 2012) direct effects such as fatal collisions with wind turbines have been shown repeatedly (Hoover & Morrison 2005; Hüppop *et al.* 2006; Drewitt & Langston 2008; Douglas *et al.* 2012; Bellebaum *et al.* 2013; Loss, Will & Marra 2013), but see (Stewart, Pullin & Coles 2007). While wind turbines and wind farms are likely to differ strongly regarding their threat to birds (Osborn *et al.* 1998; Barrios & Rodriguez 2004; de Lucas, Janss & Ferrer 2004; Garthe & Hüppop 2004; Chamberlain *et al.* 2006; Barclay, Baerwald & Gruver 2007; Pearce-Higgins *et al.* 2009; Johnston, Bradley & Otter 2014; Olea & Mateo-Tomás 2014) bird species differ in their susceptibility to wind turbine related fatal collisions (Smallwood, Rugge & Morrison 2009; Winder *et al.* 2014) as well. Fatal bird collisions, but also habitat loss (Farfán *et al.* 2009; Martínez *et al.* 2010; Dahl *et al.* 2012) , are especially problematic for long living species such as most raptors and other large birds (Barrios & Rodriguez 2004; Carrete *et al.* 2009; García-Ripollés & López-López 2011; Garvin *et al.* 2011; Dahl *et al.* 2012; de Lucas *et al.* 2012; López-López, Sarà & Di Vittorio 2012; Martínez-Abraín *et al.* 2012; Rushworth & Krüger 2014). Since studies have shown that there is a large discrepancy between pre-construction assessments and actual post-construction fatal collision rates (de Lucas *et al.* 2008; Carrete *et al.* 2012; Ferrer *et al.* 2012) it is important to investigate bird flight behaviour in the vicinity of wind turbines (Kunz *et al.* 2007) and to develop methods to prevent birds from colliding with wind turbines (Elphick 2008), especially as considerably few studies have investigated bird flight behaviour changes linked to weather conditions such as visibility, temperature or wind conditions (Marques *et al.* 2014), but there are studies that show an impact of wind speed on bird flight behaviour around wind turbines (Barrios & Rodriguez 2004; Garvin *et al.* 2011).Of those, even fewer, such as Garvin *et al.* (2011), analysed on what spatial scale wind speed had an effect on bird flight behaviour. To investigate the effect of wind turbines on the flight behaviour of birds a reliable determination of flight trajectories of birds in three dimensions is essential. In most studies performing environmental impact assessments bird flight behaviour is only estimated visually without any measurement equipment. However, a qualitative comparison of flight heights estimated by visual observers with flight heights measured using a three dimensional tracking-radar showed that the visual estimation of flight heights is highly prone to false estimations with increasing height and distance of a bird (Swiss Ornithological Institute, unpublished). While there are different methods to protect birds from collisions such as visual markings on wind turbines, acoustic signals and turbine shutdown, visual approaches are likely to be ineffective to reduce fatal collisions (Drewitt & Langston 2008; Martin & Shaw 2010) and repeated acoustic warning signals are likely to lead to habituation (Drewitt & Langston 2008). On the other hand, wind turbine shutdown based on direct visual observations conducted by humans to detect birds approaching a wind turbine has proved to be an effective way to reduce bird mortality within wind farms (de Lucas *et al.* 2012). But these observations are time intensive and economically not realistic.

In this study we recorded flight behaviour of birds in the surroundings of a solitary wind turbine in a Swiss alpine valley using a military laser rangefinder to measure the three-dimensional position of birds in the airspace. Based on the data we investigated whether birds are actively avoiding close proximity of the wind turbine, what effect wind related environmental factors have on this, possibly active, avoidance behaviour and on what spatial scale those factors play a role.

Material and Methods

Study site

Our study site was located in the Chur Rhine Valley in Haldenstein, Switzerland, around the solitary wind turbine “Calandawind” (Vestas V-112-3.0 MW, nave height 119 m, rotor radius

56m) of Calandawind AG. Data collection occurred in an area within 1 km radius around the wind turbine.

Study species

In our study we focused on midsized to large soaring birds because these are most sensitive to wind turbines due to their flight behaviour and often slow reproduction cycle. Furthermore, our measurement method cannot be applied to small birds (see below). The main species or species groups in our study, in order of descending abundance, were Corvids (*Corvus corax*, Linnaeus, 1758; *Corvus frugilegus*, Linnaeus, 1758; and *Corvus corone*, Linnaeus, 1758), Buzzards (*Buteo buteo*, Linnaeus, 1758 and *Pernis apivorus* Linnaeus, 1758), Common Kestrels (*Falco tinnunculus*, Linnaeus, 1758), Red Kites (*Milvus milvus*, Linnaeus, 1758), Golden Eagles (*Aquila chrysaetos*, Linnaeus, 1758), Hawks (*Accipiter gentilis*, Linnaeus, 1758), Sparrow Hawks (*Accipiter nisus*, Linnaeus, 1758) and Black Kites (*Milvus migrans*, Boddaert, 1783). All other observed species were pooled together into the category “others”.

Data collection

Data supplied by Calandawind AG, Haldenstein

Calandawind AG provided us with data, recorded by sensors integrated into the wind turbine, on wind speed, wind speed standard deviation, as a measure of wind speed variability, wind direction and wind turbine rotor speed, all measured over 10 minutes intervals for the entire study period.

Manual data collection

Bird flight trajectories were recorded in times of no precipitation from mid-August to October 2014 using laser powered rangefinder binoculars (Vector 21 Aero, Vectronix, (Desholm *et al.* 2006; Aschwanden, Wanner & Liechti 2015). Small objects (for example birds smaller than a trush) cannot easily be measured using the Vector Aero 21 because it is difficult to strike a small object with the laser beam properly. Vector 21 Aero records and saves time, azimuth, elevation angle and distance to the observer. For statistical analysis and graphical display, data from Vector 21 Aero were converted to global positioning system (GPS) coordinates and synchronised to a satellite map of the Haldenstein area using software developed by the Swiss Ornithological Institute. For every bird sighting species identity was recorded by the observer.

Analysis

General remarks

For model selection in statistical analyses we included the factors that made sense from a biological point of view (Zuur *et al.* 2009). Where necessary we obtained p-values using Markov-Chain-Monte-Carlo simulations and all significance tests use $\alpha = 0.05$. We therefore considered p-values < 0.05 as statistically significant and $0.05 <$ p-value < 0.1 as a trend towards statistical significance. All analyses were carried out using R, version 3.2.2 (R Development Core Team 2013).

Flight trajectories, closest points and direction change

To analyse bird flight behaviour for every observed bird we compiled individual position measurements into a flight trajectory, assuming straight flight between two position measurements. For analysis we only included flight trajectories with at least two position measurements and calculated the point where the flight trajectory came closest to the wind turbine (closest point) for each flight trajectory. For trajectories consisting of three or more position measurements, where the position measured closest to the wind turbine was neither the first nor the last measurement of a track, we calculated whether birds turned towards the wind turbine or away from the wind turbine when they were at the position measured closest to the wind turbine (direction change). To investigate that effect we calculated the difference between the approaching angle from the position measurement before the closest position measurement to the closest position measurement and the leaving angle from the closest position measurement to the next position measurement.

Relative detection probability

To analyse whether flight trajectories were evenly distributed within the study site we had to define the detection probability first. We computed the distribution of distance to the observer for all closest points and approximated the density distribution using a lognormal function. This density distribution represents the relative detection probability in relation to the distance to the observer, assuming detection probability decreases with increasing distance to the observer.

GIS site mapping and habitat association

To investigate whether birds prefer to fly over certain types of habitat we used the geographical information system (GIS) program ArcGIS to define the habitat within a 1 km radius around the wind turbine. Based on aerial photographs we distinguished between wooded areas, agricultural areas, lakes, rivers and anthropogenic areas (roads, building, railway tracks and the wind turbine). We used a Chi^2-test to test whether the position measurements over a given habitat are distributed randomly according to that habitats proportion within the 1 km radius around the turbine. Pearson residuals (P) of $2 < P < -2$ were regarded as contributing extraordinarily to the violation of the assumption of randomness. We also incorporated the relative detection probability by weighing each measured position according to its relative detection probability.

Closest point and direction change modelling

We not only wanted to analyse what environmental factors determine how close birds fly to the wind turbine but also within which distance to the wind turbine those factors have a significant effect. We used closest point as our response variable and calculated three models (1) with wind speed (m/s, continuous, scaled) and wind direction (binomial), (2) with wind speed standard deviation (m/s, scaled) and wind direction (binomial), (3) with rotor speed (m/s, continuous, scaled) and wind direction (binomial) as explanatory variables, respectively. We incorporated Julian day (d, discrete, scaled), time (min, continuous, scaled) and species identity as random factors and performed a linear mixed model.

Secondly, we were interested in what environmental factors influence whether direction changes close to a wind turbine lead birds closer to a wind turbine or further away from it. Direction Change was used as response variable in three different models (1) with wind speed (m/s, continuous, scaled)and wind direction (binomial), (2) wind speed standard deviation (m/s, continuous, scaled) and wind direction (binomial), (3) with rotor speed (m/s, continuous, scaled) and wind direction (binomial) as explanatory variables, respectively. We incorporated Julian day (d, discrete, scaled) and species identity as random factors and performed a generalised linear mixed model using a binomial distribution. Time was not included as random factor because if included the models failed to converge due to the sample size which was smaller than in the analysis of the closest point.

The fixed factors were chosen based on findings of previous studies (Barrios & Rodriguez 2004) and the possibility to use them to predict effective curtailments. In order to address the question about the distance within which factors have a significant effect, we repeated each model 40 times with different radii. The first model contained just data from the first 25 meters around the wind turbine and every further model contained data from 25 meters more, up to model 40 which contained data from the entire 1 km radius. For every model we reported mean and standard errors of the effect estimates, the significance level, marginal R^2 (proportion of the variability explained by the fixed effects), conditional R^2 (proportion of the variability explained by the fixed and random effects) and the number of observations included.

Results

Flight height, relative detection probability and observation density

We recorded 272 flight tracks consisting of 1680 position recordings within a 1 km radius around the wind turbine (table 1). A big portion consisted of only two species groups, Corvids and Buzzards, with 113 tracks with 529 position recordings and 63 tracks with 450 position recordings, respectively. For all species, we compared the average flight height with the height of the rotor swept zone which is 63 m to 175 m. We found that all focus species fly at heights of the rotor swept zone and are therefore in danger of a collision (Figure 1). Relative detection probability pooled over all species followed a log-normal distribution and detection probability was highest 100 m away from the observer (Figure 3).

Distances of closest points and habitat association

Closest points were rarely closer than 100 m to the nacelle of the wind turbine and flight tracks with closest points further than 1000 m away from the nacelle were not included in the analysis (Figure 4).The position recordings were not randomly distributed among the different habitat types (i.e. not according to their area proportion). This was the case for all species pooled (Chi^2-test, p-value < 0.01) and individual species (Chi^2-test, p-value < 0.01, figures 5 and 6) as well. Hawks and the group “others” were positively associated with anthropogenic areas (preference) while Buzzards and Golden Eagles were negatively associated with anthropogenic areas (avoidance).

Influence of external factors on closest point and flight direction change

Because birds only rarely approached the wind turbine closer than 100 m the analysis of the influence of external factors was possible only when data of radii further away than 100 m were included into the models.

The model relating the closest point to wind speed and wind direction showed that there was a statistically significant influence of wind speed. The estimated effect of wind speed was negative for all the radii up to 500 m. This means that in all data sets the distance of the closest point increased with decreasing wind speed. This effect got weaker when more and more data of radii further away were included. Wind direction had no significant influence on the distance of the closest point. The small R^2 showed that only a small part of the variability in the data was explained by the factors included in the model (figure 7).

The model relating the closest point to wind speed standard deviation and wind direction showed that wind speed standard deviation had a statistically significant influence. The estimated effect of wind speed standard deviation was slightly positive for the data of the radii 100 m and 125 m and turned negative for all the other radii up to 500 m. This means that the distance of the closest point increased with increasing wind speed standard deviation close to the wind turbine (≤ 125 m) and decreased with increasing wind speed standard deviation more distant to the wind turbine (> 125 m). The negative effect got weaker when more and more data of radii further away were included. Wind direction had no significant influence on the distance of the closest point. The small R^2 showed that only a small part of the variability in the data was explained by the factors included in the model (figure 8).

The model relating the closest point to rotor speed and wind direction showed that rotor speed had a statistically significant effect. The estimated effect of rotor speed was positive for the radius 100 m and turned negative for all the other radii up to 500 m. This means that the distance of the closest point increased with increasing rotor speed close to the wind turbine (= 100 m) and decreased with increasing rotor speed more distant to the wind turbine (> 100 m). The negative effect got weaker after 300 m when more and more data of radii further away were included. Wind direction had no significant influence on the distance of the closest point. The small R^2 showed that only a small part of the variability in the data was explained by the factors included in the model (figure 9). Wind speed and rotor speed were positively correlated (Kendall’s T = 0.43, p-value > 0.01). Causally, rotor speed is dependent on wind speed but the rotor does not turn at very low wind speed or at wind speed exceeding 12 m/s.

Meanwhile, wind speed, wind speed standard deviation, rotor speed and wind direction did not have any statistically significant influence on flight direction change in all models over all analysed radii. Because not all observed bird flight tracks could be included our sample size for these models (N = 115) was considerably smaller than for the models investigating how close birds came to the wind turbine (N = 272).

Discussion

We found that exceptionally few birds were found within a radius of 100 m around the wind turbine but we did not find that fewer birds than expected were in close proximity of anthropogenic structures in general. Our findings that birds were less often observed in close proximity of wind turbines than expected (figure 3) falls in line with other studies, performed over a wide range of taxa (Larsen & Guillemette 2007; Garvin *et al.* 2011; Dahl *et al.* 2012; Plonczkier & Simms 2012; May *et al.* 2015). Birds not flying in close proximity to a wind turbine have a reduced potential collision risk and May (2015) calls this behaviour avoidance (Nathan 2008; Nathan *et al.* 2008). May distinguishes three categories, macro-, meso- and micro-avoidance. Macro-avoidance describes birds avoiding an entire wind farm, meso-avoidance avoiding a single wind turbine within a wind farm and micro-avoidance last-second avoiding of wind turbine rotor blades. Since macro- and meso-avoidance cannot be distinguished for a solitary wind turbine we classify the bird flight behaviour shown in our study as macro-avoidance. Our finding that birds are not found less often in close proximity to anthropogenic structures like roads, railway lines, buildings, including the wind turbine, in general (figure 6) indicates that birds actively avoided the wind turbine in particular. On the species level we did find that certain species, in our case Buzzards and Golden Eagles, are found less often than expected in close proximity to anthropogenic structures in general which has been shown in previous studies (e.g. Johnston *et al.* 2013; Johnston, Bradley & Otter 2014). Wang, Wang and Smith (2015) hypothesised that not just species identity but also environmental factors such as wind speed influence how close birds fly to wind turbines and wind speed is also included as a factor in some collision risk models, such as McAdam's or, Holmstrom *et al's.* (Masden & Cook 2016). In this study, we found that wind speed and two other wind related factors, wind speed variability and wind turbine rotor speed, can have significant effects on the approaching distance of birds around a wind turbine. We also found that the effects of wind speed, wind speed variability and wind turbine rotor speed depend on the spatial scale (figures 7-9), a fact that has not been shown often before (but see Garvin *et al.* 2011). Close to the wind turbine, approaching distances were increasing with increasing variability of the wind and with increasing speed of the rotor. Further away, the effect turned around and approaching distances decreased with increasing variability of the wind and increasing speed of the rotor. It seems that birds passively allow wind to carry them closer to the wind turbine when wind speed is high. But at a certain distance birds are actively avoiding proximity of the wind turbine: The approaching distance gets larger when wind speed is more and more variable (turbulent) or the rotor is turning faster and faster.

The influence of wind speed and wind speed variability on approaching distances weakens with increasing radius. This is consistent with the findings of Garvin et al. (2011) that while 31 % of the birds observed in a 100 m radius around the wind turbine showed avoidance behaviour, only 4 % of the birds observed within 500 m around the wind turbine showed avoidance behaviour. Higher wind speed leading to smaller approaching distances seems to contradict Barrios and Rodriguez (2004), who found that collision risk decreased with higher wind speed. But the study by Barrios and Rodriguez covered a broader range of wind speed than the data we discuss here. Furthermore, we have no data on closest approaching distances during strong wind speed conditions as defined by Barrios and Rodriguez (wind speed > 12 m/s). In fact, they found the collision risk to be highest at moderate wind speed (wind speed 8.6 m/s – 12.5 m/s), a range that corresponds to the highest wind speed that occurred in our data. Wind speed most likely affects the ability of birds to steer their flight direction (Longcore *et al.* 2013; Marques *et al.* 2014) and therefore flight behaviour becomes more random at higher wind speed. Carr and Lima (2010) experimentally showed that birds reactions to moving objects is weaker at higher wind speeds which helps explain our findings, although the study was performed using passerines. The effect of wind speed variability on approaching distances might have similar reasons. It is plausible that high wind speed variability also impacts the ability of birds to steer their flight direction or their reactiveness to moving objects, but experimental proof is surely needed. Since wind turbine rotor speed is highly correlated with wind speed and, based on the R^2, wind speed explains changes in macro-avoidance better than wind turbine rotor speed, we assume that wind speed influences both wind turbine rotor speed and macro-avoidance behaviour and that the wind turbine itself has a minor effect on macro-avoidance, although further studies that look explicitly into additive effects and interactions between these factors are needed.

One possible confounding factor could be that the proportion of migrating birds among all observed birds is higher during times of higher wind speed (Johnston, Bradley & Otter 2014) and this could lead to a weaker average macro-avoidance behaviour, assuming macro-avoidance is more developed in resident birds. Since we do not have any information about the migratory status of the observed birds we cannot draw any conclusion about the importance of this factor. In contrast to Johnston *et al.* (2013) wind direction had no influence on the approaching distance. This could be due to a weaker, and therefore harder to detect, effect, the fact that there are basically just two wind directions around the observed wind turbine, or the effect of wind direction could be mostly site specific. As a second proxy for macro-avoidance, additionally to the approaching distance to the wind turbine, we investigated flight direction change close to the wind turbine. The fact that none of the factors we investigated had an effect on flight direction change might stem from a smaller sample size or data not accurate enough. In a review of Schuster, Bulling and Koppel (2015) discussing the issue they also found that there cannot be drawn any conclusions about that issue yet. Perhaps a more comprehensive method to assess direction change, such as flight tortuosity as discussed in Dahl *et al.* (2012), which takes into account multiple direction changes instead of just one, would be better suited to address the issue. Other limitations of our study are that we focused on certain species only and the methodology used is not very suitable for investigating smaller birds such as passerines. Like every optical approach the use of laser rangefinders is mostly restricted to daylight use and decreases in accuracy during bad weather. Therefore, nightly flight activity and bird distance to the turbine at night cannot be measured this way. Furthermore, the data discussed here stems from one single fall migration season and long-term effects can therefore not be addressed, although they have been shown in other studies (for example Carr & Lima 2010). Relative detection probability was highest 100 m away from the observer and not around the wind turbine. To address this, further studies should be carried out in a way that the relative detection probability is highest in the area around the wind turbine or even with the use of multiple observers to improve overall detection. It is also important to stress that our findings stem from observations at a single site and should not be overly generalised. On the other hand, the methods we applied here can easily be used at other sites or in larger-scale projects.

Conservation implications and conclusion

In this study we found that birds show macro-avoidance around the solitary wind turbine "Calanda Wind". There is an indication that in a close radius approaching distances are increasing with increasing wind speed variability and increasing rotor speed. Nevertheless, approaching distances get generally smaller during times of higher wind speed which increases the collision risk. Considering that weather conditions do not often feature in studies on assessing wind turbine impacts on local wildlife (Marques *et al.* 2014), our findings point towards the need of weather dependant mitigation measures, such as curtailments (Marques *et al.* 2014), which have worked well for other taxa like bats (Arnett *et al.* 2011). Based on existing studies (de Lucas, Ferrer & Janss 2012), curtailment parameters have to be investigated to find ecologically desirable and economically applicable methods (Singh, Baker & Lackner 2015).

On the method side, by using a laser rangefinder bird flight trajectories can be measured reliably and reproducibly and no reliance on observer biased visual flight trajectory estimations is needed. We also propose that laser rangefinders could be regularly used for environmental impact assessments pre- and post-construction of wind turbines.

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Tables

Table 1. *Shown is if a species group is considered raptors, the number of recorded positions per species group, the number of tracks per species group, the average flight height thereof, the variability of the flight height (standard deviation of the average flight height) and if a species group was recorded as flying at heights of the wind turbine rotor swept zone.*

Species group	Raptor	Number of tracks	Number of positions	Average flight height [m]	Flight height std. dev. [m]	Within rotor swept height
Golden Eagle	Yes	9	79	455	182	Yes
Buzzard	Yes	63	450	288	208	Yes
Red Kite	Yes	24	205	244	161	Yes
Black Kite	Yes	2	16	241	45	Yes
Hawk	Yes	4	28	81	24	Yes
Common Kestrel	Yes	31	232	166	122	Yes
Sparrow Hawk	Yes	5	22	169	166	Yes
Corvid	No	113	529	231	180	Yes
Others	No	21	119	169	170	Yes
Total		**272**	**1680**	**227**	**105**	

Figures

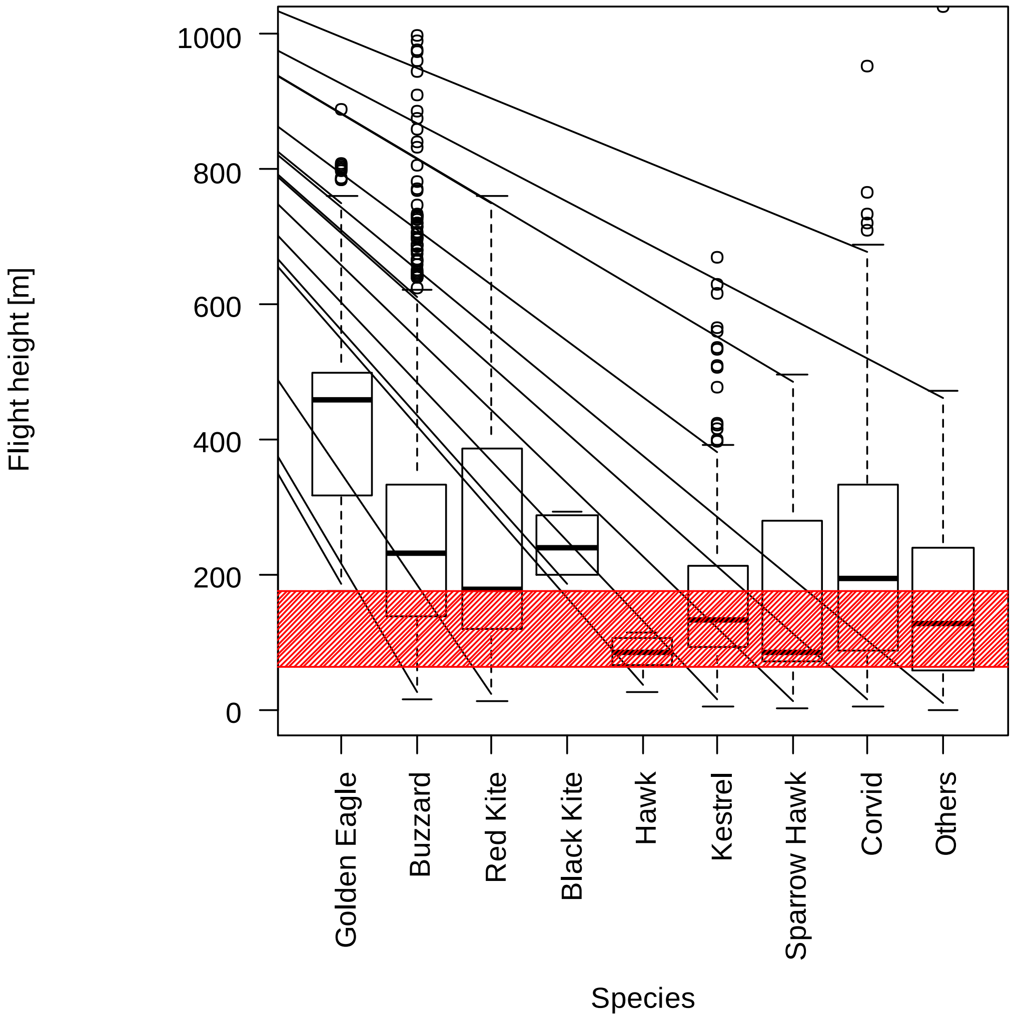

Figure 1*. Measured flight height above observer level per species group. Shown in red is the wind turbine rotor swept zone. The number of tracks (N) is given in table 1.*

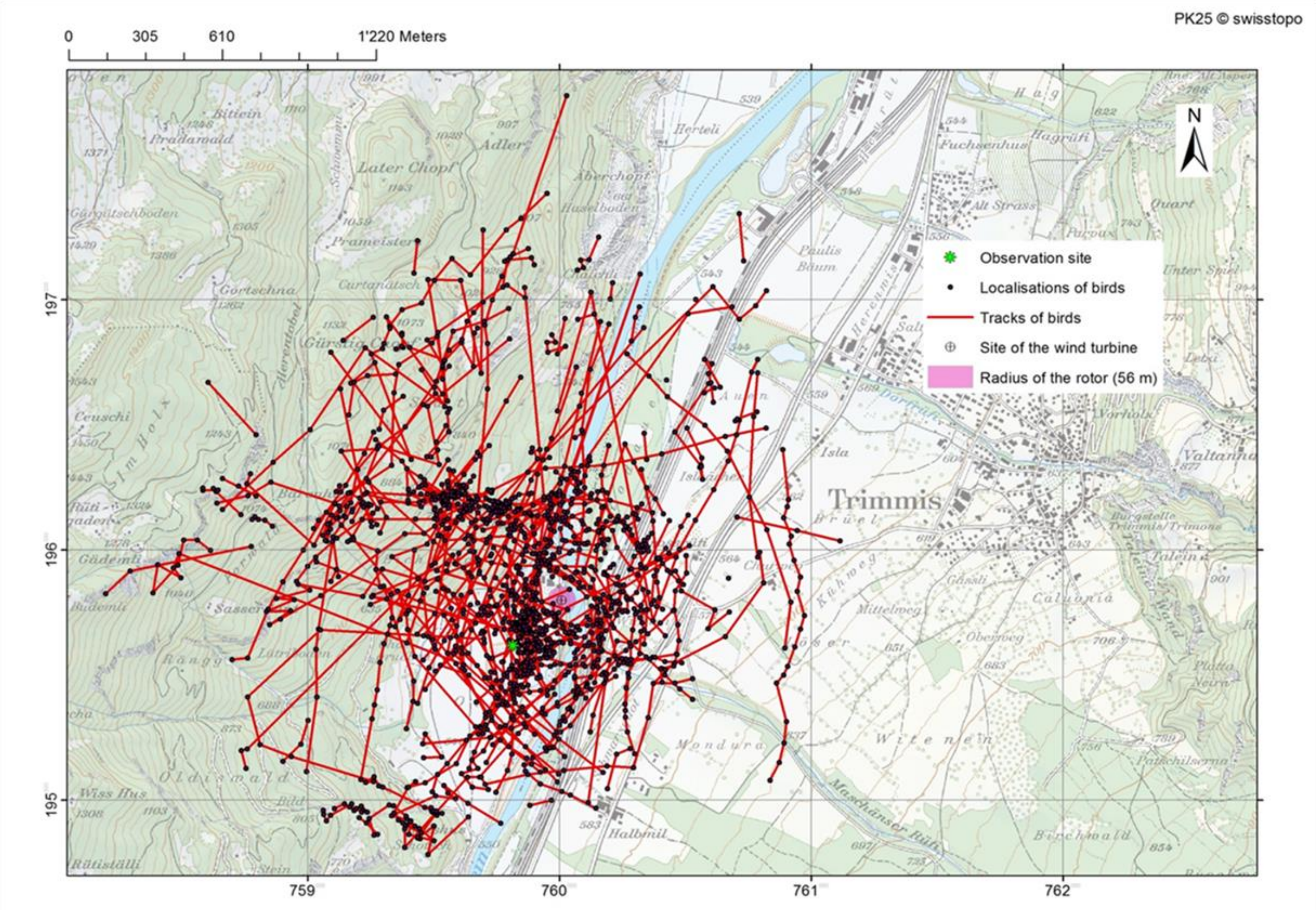

***Figure 2**. Map of the study area. Black dots represent recorded positions. The red lines connect the recorded positions to bird flight tracks. Shown in pink is the wind turbine rotor swept zone. The green point marks the location from where the birds where observed.*

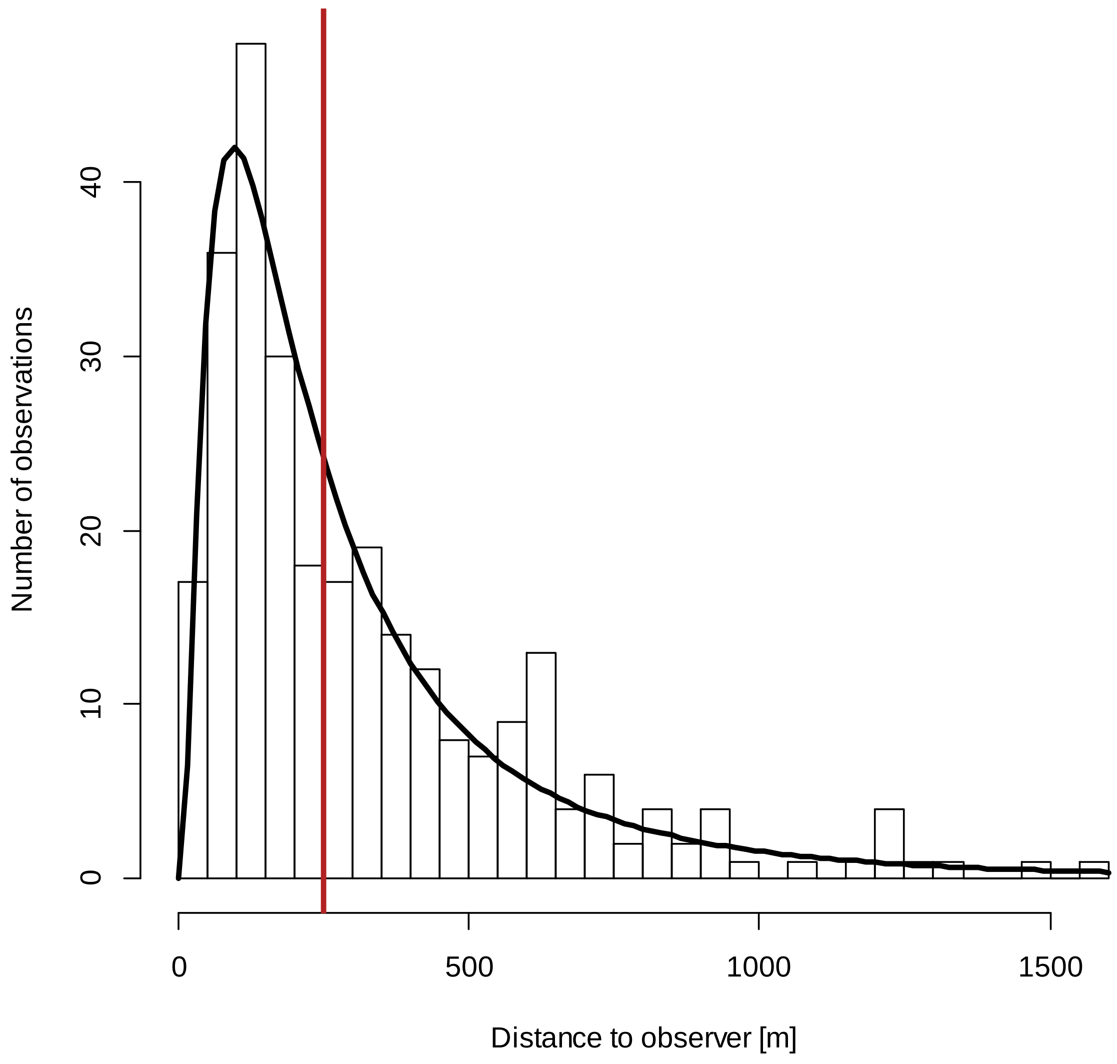

Figure 3. *Distribution of the distance of closest points to the observer. The black curve is based on the approximated distribution (lognormal, meanlog = 5.4, sdlog = 0.92). The red line indicates the distance of the wind turbine to the observer*.

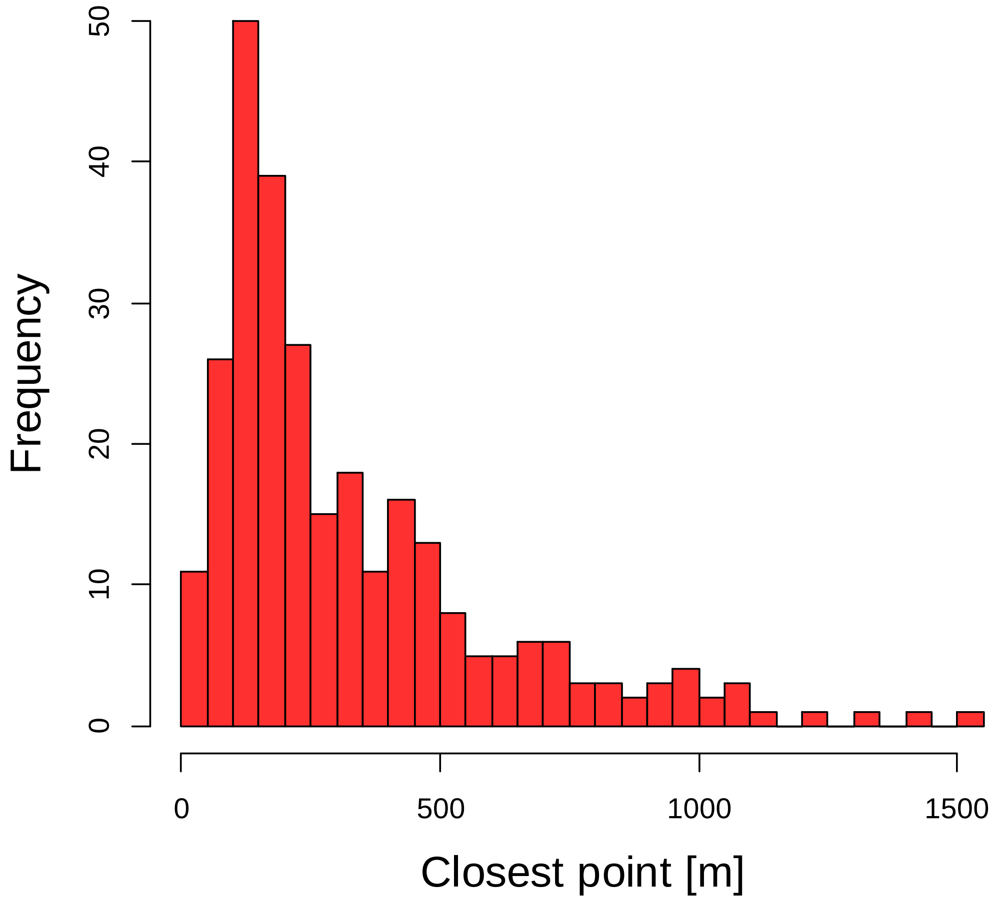

Figure 4: *Distribution of the distance of closest points to the nacelle of the wind turbine.*

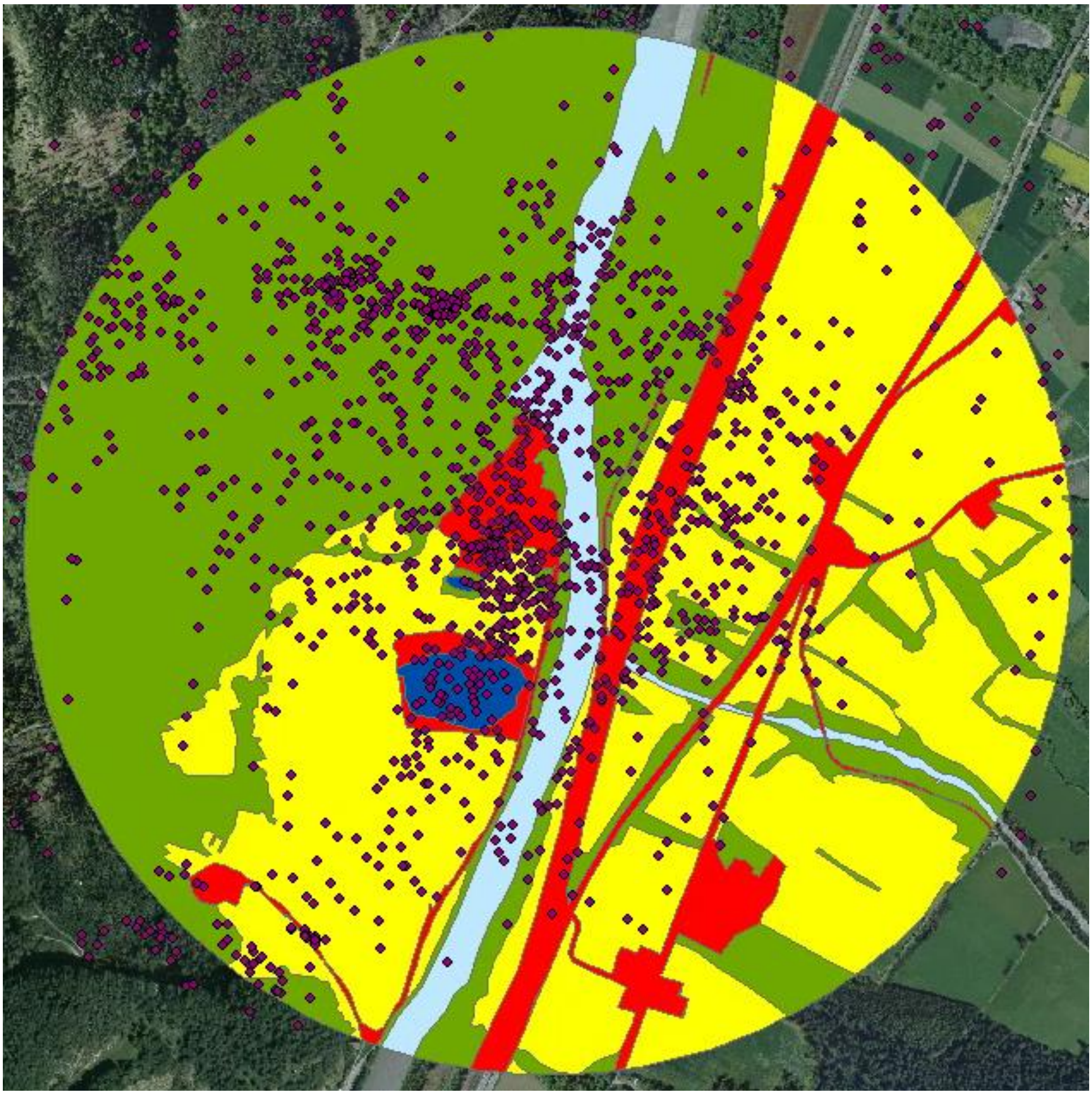

Figure 5*. The study site. The area within 1 km radius of the wind turbine was assigned to different habitat types, based on aerial photographs. Red: anthropogenic areas, Yellow: agricultural land, Green: wooded areas, Dark blue: lakes, Light blue: rivers.*

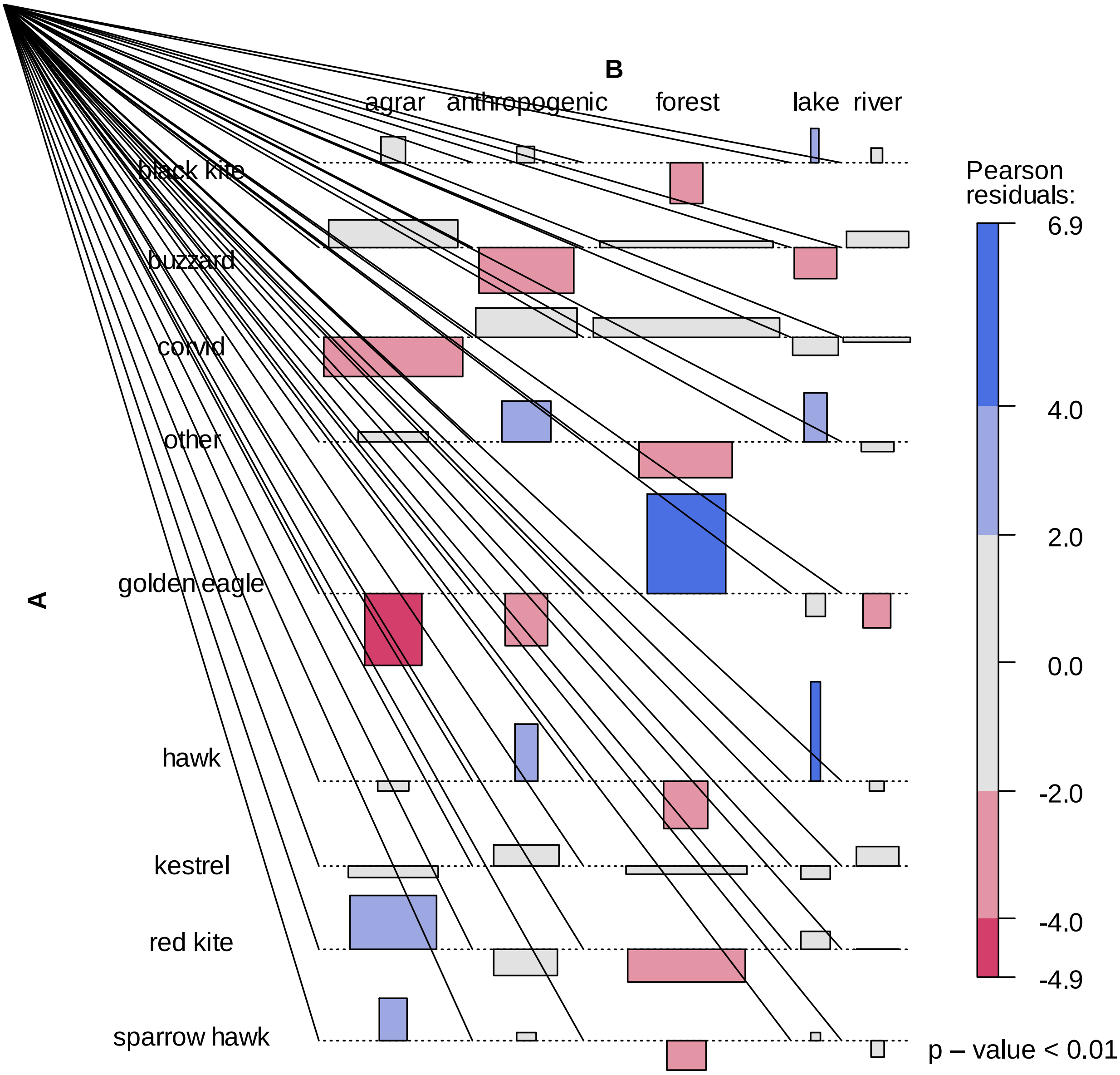

Figure 6. *Association table between species identity (**A**) and habitat type (**B**). The width of each bar represents the sample size and the height the difference between expected and measured association. Blue bars indicate a statistically significant positive association while red bars indicate statistically significant negative associations. Each data point was weighted according to the relative detection probability.*

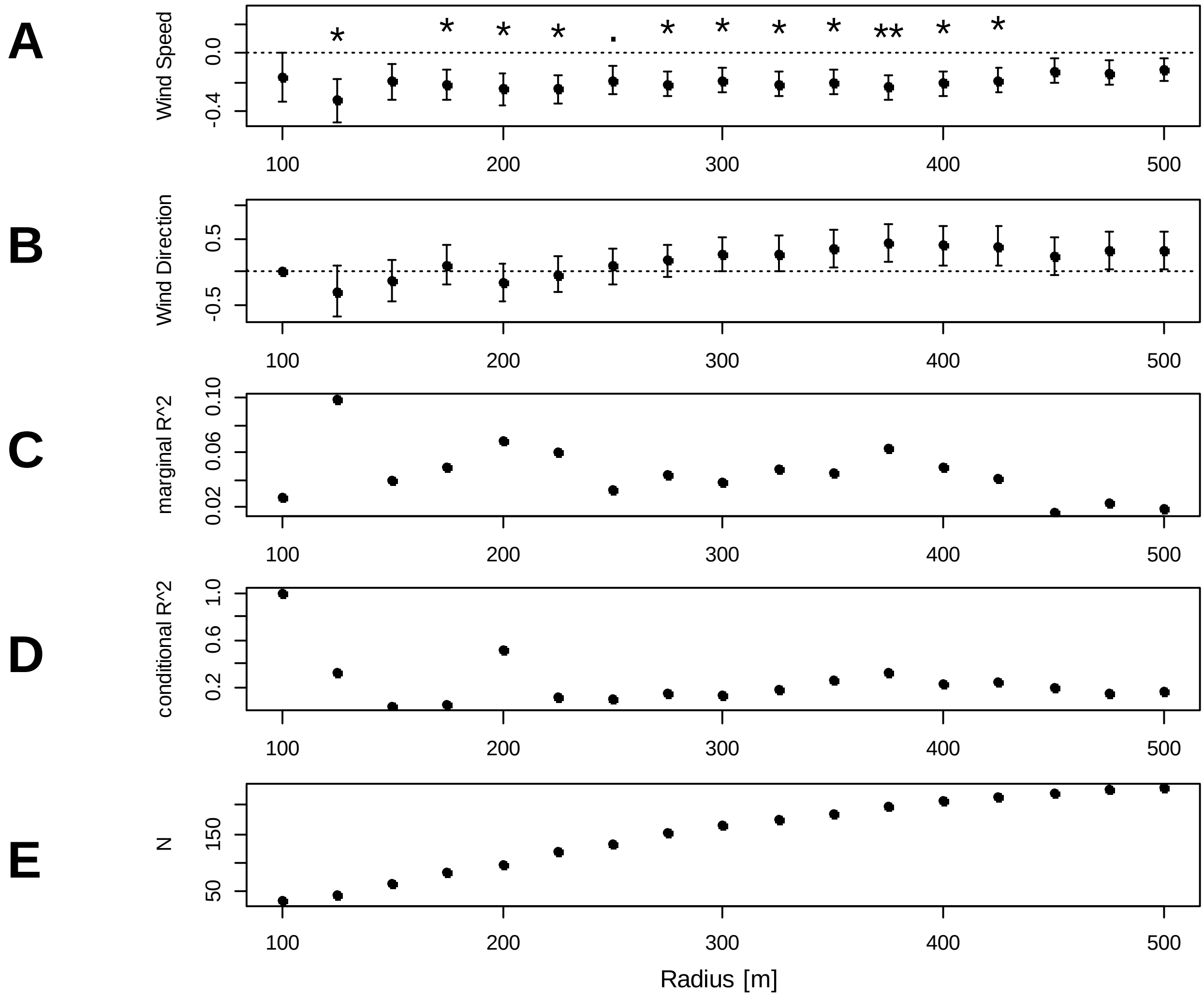

Figure 7. *Results of the GLMM analysing the effect of wind speed and wind direction on how close birds get to the wind turbine.* ***A:*** *Wind speed effect estimates, including error bars.* ***B****: Wind direction effect estimates, including error bars.* ***C****: GLMM marginal* R^2 *value.* ***D****: GLMM conditional* R^2 *value.* ***E****: Sample size. Only the results of the models with radii up to 500 m are shown. Statistically significant effects are labelled within the graphs.*

$^{\cdot}\ 0.1 \geq p - value > 0.05; * 0.05 \geq \text{p} - \text{value} > 0.01; ** 0.01 \geq \text{p} - \text{value};$

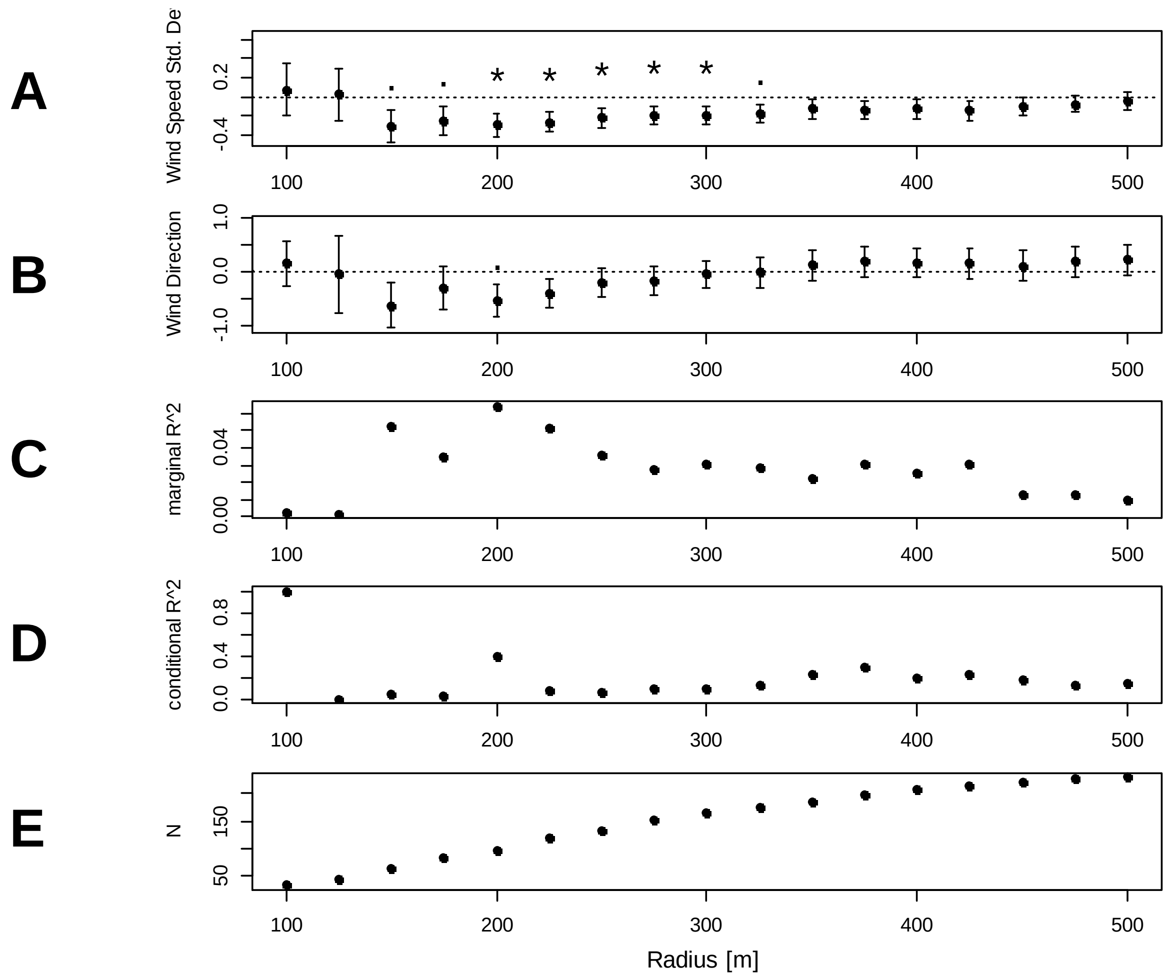

Figure 8. *Results of the GLMM analysing the effect of wind speed variability and wind direction on how close birds get to the wind turbine.* ***A****: Wind speed variability effect estimates, including error bars. For further legends see Figure 7.*

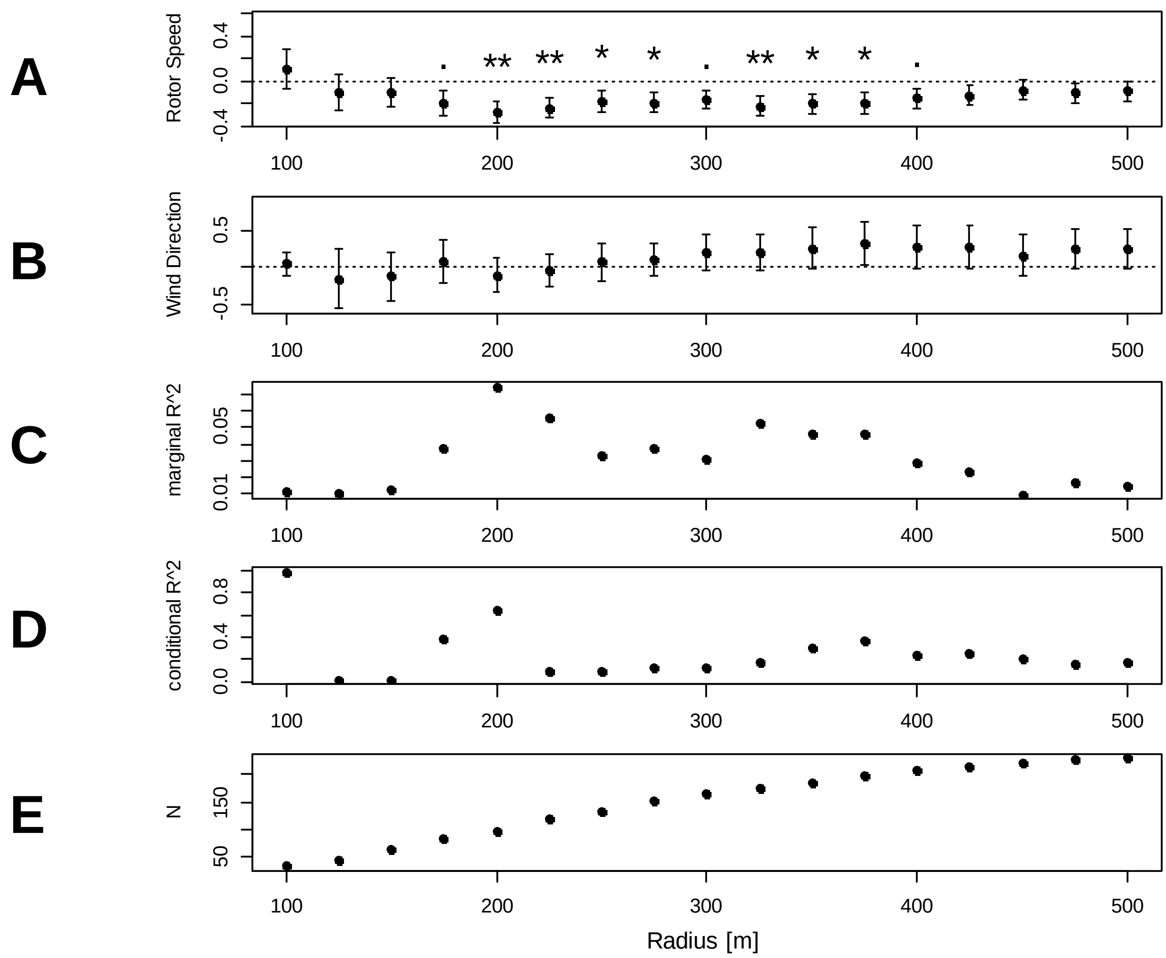

Figure 9. *Results of the GLMM analysing the effect of wind turbine rotor speed and wind direction on how close birds get to the wind turbine.* ***A****: Wind turbine rotor speed effect estimates, including error bars. For further legends see Figure 7.*

Declaration of consent

on the basis of Article 28 para. 2 of the RSL05 phil.-nat.

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Matriculation Number: 09-133-380

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Bachelor ☐ Master ☑ Dissertation ☐

Title of the thesis: Flight behaviour of birds around a solitary wind turbine in a swiss alpine vallley

Supervisor: Prof. Dr. R. Arlettaz

I declare herewith that this thesis is my own work and that I have not used any sources other than those stated. I have indicated the adoption of quotations as well as thoughts taken from other authors as such in the thesis. I am aware that the Senate pursuant to Article 36 para. 1 lit. r of the University Act of 5 September, 1996 is authorised to revoke the title awarded on the basis of this thesis. I allow herewith inspection in this thesis.

Place/Date
Sempach, 02.07.17

Signature