Mitigating the negative effects of tall wind turbines on bats: vertical activity profiles and relationships to wind speed

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Mitigating the negative effects of tall wind turbines on bats: vertical activity profiles and relationships to wind speed

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Summary

1. Wind turbines represent a source of hazard for bats, especially through collision with rotor blades. Tall wind turbines (rotor-swept area typically between 50 - 150 m above ground level) tend to become the rule, but we lack quantitative information about bat assemblages active at these elevations, which impedes proposing targeted mitigation measures. We investigated vertical habitat profiles and relationships to wind speed within a bat community inhabiting a major valley of the European Alps where tall wind turbines are being installed.

2. Bat activity was monitored with automatic recorders installed at various elevations, from ground level up to 70 m, with the goal to reconstruct vertical activity profiles extrapolated to 150 m elevation, and to link them with wind speed measurements taken with anemometers. Bat call sequences were scrutinized for species identification, with a particular emphasis on mouse-eared bats (*Myotis myotis* and *Myotis blythii*) and European free-tailed bats (*Tadarida teniotis*), three rare locally occurring species that might be negatively impacted by wind turbines.

3. Most bat species were little active at the dangerous elevations (> 50 m a.g.l.). The most often recorded bats were *Pipistrellus pipistrellus* and *Hypsugo savii*, two locally abundant species. Mouse-eared bats were rarely recorded, being mostly active at ground level: they seem to be out of risk of collision with the rotor blades. In contrast, the rare *T. teniotis* shows a more evenly distributed vertical activity profile, being often active at rotor level, which puts it at major collision risk. Bat activity dramatically declined with increasing wind speed, showing only residual activity above 4 m/s.

4. *Synthesis and applications*. Most risks of collision could be avoided if the wind turbines were operated with a cut-in-speed greater than 4 m/s. This speed restriction should also be implemented in winter when ambient temperature is above –0°C because *T. teniotis,* the species potentially most threatened by the wind turbines at the study site, remains largely active in winter. These simple measures could be applied at any wind park projected at low altitude within the main valleys of the European Alps, if not beyond.

Key-words: acoustic sampling, Batlogger, bat fatality, bat recorder, collision risk, cut-in speed, elevation, rotor-swept area, truck-mounted crane

Introduction

The continuous supply of fossil energy sources such as petrol seems to be compromised in the long run due to a steadily increasing consumption since the beginning of the 20th century. The global warming crisis furthermore calls for a decrease in carbon and other greenhouse gas emissions. Thus, many nations worldwide have started to seek new ways of generating more sustainable sources of energy for the future. Wind energy is such an alternative source of sustainable energy. At a first glance, wind energy appears to offer a perfect neutral solution for the environment, but it also has its drawbacks. Conservationists have early raised concerns about the impact of wind turbines on wildlife, especially flying vertebrates such as birds and bats. Conservation scientists launched several research projects about bird and bad fatalities at wind turbines, which established that wind turbines might be even more detrimental to bats than to birds (Kuvlesky *et al.* 2007; Rodrigues *et al.* 2008; Young *et al.* 2011). This is largely due to the fact that bats have a very slow life history strategy, having both long life spans (e.g. Arlettaz *et al.* 2002) and low reproductive rates (most species have an annual fecundity below 1, e.g. Schaub *et al.* 2007). This means that any new source of mortality, if additive, might have a tremendous impact on population dynamics. Casualties due to wind turbines may thus put at risk of extinction bat populations, especially those with small sizes (Kuvlesky *et al.* 2007). Actually, several North American and European studies have reported very high bat fatality rates at wind turbines (Arnett *et al.* 2008; Rydell *et al.* 2010, Johnson *et al.* 2004). Bats are injured or killed directly when striking turbine blades, or indirectly by decompression near blades, although the latter factor is contended (Baerwald *et al.* 2008; Grodsky *et al.* 2011, Rollins *et al.* 2012). There are several possible explanations why bats collide with wind turbines. First, they may fail to detect the moving, rapidly approaching blades because of the extremely high rotor speed (up to 83 m h^{-1} at blade extremity) due to the very focal character of bat sonar. Second, they may underestimate blade velocity when maneuvering in the rotor-swept area, failing to avoid collision (Arnett *et al.* 2005, Horn *et al.* 2008). Third, they might be attracted to wind turbine towers as these tall elements dominating the landscape might be perceived as potential roosts, e.g. vantage mating sites (Cryan 2008). Some authors have suggested that bats might be furthermore 1) disorientated by the complex electromagnetic fields prevailing around wind farms; 2) attracted by audible or ultrasonic sounds generated by operating wind turbines; 3) attracted by the nocturnally flying insects aggregating around nacelles due to the heat they generate (Cryan & Barclay 2009; Kunz *et al.* 2007). However, collision with rotor blades remains the major potential threat to bats (Bach 2001; Rodrigues *et al.* 2008).

Currently installed wind turbines tend to be much taller than in the past, being equipped with wider diameter rotors, which on the one hand increases the rotor-swept area, i.e. the probability of collision for bats. Barclay *et al.* (2007) have found a positive exponential relationship between number of bats killed and turbine tower height. On the other hand, however, tall turbines also tend to have their rotors situated higher up in the air than previous models, which might on the contrary contribute to decrease overall collision risks, at least in bat communities where low elevation flying species predominate. Yet, we still lack quantitative information about vertical bat activity profiles, which impedes specifying which species are particularly at risk, i.e. to propose appropriate mitigation measures. We investigated vertical bat activity profiles and their relationships to wind speed within bat communities occurring at low elevation (valley bottom) in a windy stretch of the Rhône valley in the European Alps. We also evaluated the potential threat of the foreseen wind turbines to locally rare bat species, notably the European free-tailed bat (*Tadarida teniotis*) and the lesser mouse-eared bat (*Myotis blythii*). Our main objective was to propose targeted evidence-based management measures for reducing the number of bat fatalities at the tall wind plants that are currently spreading in many areas, with a particular emphasis on the situation within the European Alps.

Materials and methods

Study area and its bat community

Fieldwork was conducted in the Upper Rhône valley (Valais, SW Switzerland) in an area where a wind park is planned. The valley bottom is situated at ca. 500 m elevation, with mountain ranges culminating over 4000 m a.s.l. on both sides of the valley. Audio recordings of vertical bat activity were taken up to 70 m above ground level (a.g.l.) at two sites situated close to the planned implantation area (Solverse, Fully, and Marais d'Ardon; Table S1) while bat activity at ground level was also recorded at the six projected wind turbines in order to better assess local bat assemblage.

Altogether, 27 bat species have been recorded in Valais (Arlettaz 1997), with two species of high conservation concern breeding within 8 km of the planned wind farm. The first species is the European free-tailed bat, a long-distance, high-elevation forager, with a mostly Mediterranean distribution, that remains partly active in winter down to –1°C ambient temperature, foraging mostly on flying tympanate insects such as moths (Rydell & Arlettaz 1994; Arlettaz *et al.* 2000; Marques *et al.* 2004). The second species, the lesser mouse-eared bat, is a substrate gleaner specialized on orthopterans captured from grass stalks. It breeds in the church attics in Fully, 2 km from the next planned wind turbine, forming a mixed colony with the less threatened sibling species *M. myotis* (Arlettaz 1996; Arlettaz *et al.* 1997b; Arlettaz 1999). In addition to general information about the vertical activity profile of an overall Alpine bat community, we thus put a special emphasis on these two species that are particularly at risk due to their conservation status within Switzerland. More information about the local bat community are presented in supplementary material (Appendix S1).

Bat recordings

Bat echolocation calls were automatically recorded from dusk to dawn with Batloggers® (Elekon AG and Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, Switzerland) equipped with an elongated wire microphone, extended rechargeable battery pack and protective box (OtterBox®). These recorders operate within the 10 – 150 kHz frequency range; the lower frequency sensitivity was important in this study because *T. teniotis* emits audible echolocation calls, which enables it to feed on flying tympanate insects (Rydell & Arlettaz 1994). Data are initially written into the Random Access Memory (RAM) of the device, with call sequences being automatically transferred onto a SDHC card. During data transfer, the device can temporarily not record new coming-in sequences. In the automatic mode, the Batlogger® constantly monitors the microphone signal and recording is triggered for at maximum 15 s in a row as long as an entering signal reaches a pre-set sensitivity threshold. By default, a time frame of 0.5 s before the first and 1 s after the last triggering signal is additionally recorded.

We avoided sampling on nights with very low bat activity, i.e. under windy conditions, when ambient temperature was below 8° C or during rainfall. Microphone sensitivity was checked and adjusted if necessary before any night recording session. The detection distance differs among bat species depending on call intensity, but this bias could not be accounted for.

Sampling

Vertical activity profiles

In order to investigate the vertical activity profiles of bats, a truck-mounted crane (LTM 1200 – 5.1) was hired. Two 2 cm thick metal cables were stretched from the ground level (fixed on two cement blocks, 2.5 t each) to a 4 m long horizontal bar fixed under the crane hook. The cables had to be kept under permanent high tension in order to avoid to whole system to twist. A distance of 4 m was maintained between the two vertical cables by horizontal aluminium bars (4.5 m each) positioned at 5 m, 20 m, 35 m, 50 m and 65 m a.g.l., respectively. These aluminium bars were equipped with C-shaped ends to accommodate the recorders and microphones, which were fixed on the structure with strong sticky tape. At 70 m there was a 4 m long iron bar (connection with crane cable) which was also used to fix recorders. There were thus two devices positioned at each end of the bar (i.e. 12 recorders in total), with microphones pointing out, a bit downwards (~30° angle) so as to avoid rain potentially entering the protective cylinder, facing NW and SE, respectively (Fig. S1).

Vertical bat activity data was collected during 9 nights from July to October 2011 (the former 4 nights at the site located within the projected wind park; the latter 5 nights at the second site situated ~10 km away from the wind park, where bat activity was slightly more intense due to the presence of a more diverse landscape). Additionally, two anemometers were fixed on the side of the metal cables, at 70 m and 10 m elevation, respectively. Wind speed was recorded every 10 min. The first author of this study had to stay overnight in proximity of the truck-mounted crane for checking wind speed, because full development of the crane arm is not allowed above 40 km/h (~ 11 m/s). In the morning, the crane arm was put down so that detectors could be taken off.

Activity at foreseen wind turbine sites

The same 12 bat detectors were used for an acoustic above ground-level survey of bat communities and activity at the six foreseen wind turbine sites. The surveys took place during 11 nights in July-October 2011 and eight nights in May - June 2012. The protective boxes, holding the detectors, were installed on sheep fence plastic poles fixed into the ground, with the microphone horizontally taped on the upper end of the pole at about 1 m elevation, but slightly tilted downwards to avoid rain flowing into the protective tube (Fig. S2).

A pair of two bat detectors per wind turbine site was installed within 150 m distance of the projected location, the former among fruit tree plantations, the latter in open fields. The intention was to record bats foraging in these two locally dominant habitat types, both in clutter and in more open space. The devices were again operated the whole night. Wind speed data was available from a nearby anemometer situated at 35 m elevation.

Data analysis

Data extraction and bat identification

The software BatScope® 2.0 was used to identify the recorded bat echolocation call sequences to species or group of species, based on a reference database containing 20,000 calls from 27 species, recorded mostly in Central Europe. As a sequence corresponds to one bat passing next to the microphone, we term it a bat pass hereafter. Only bat calls with a signal-to-noise ratio (SNR) greater than 30 dB were retained. Calls were first isolated from individual sequences and categorized using the BatScope® 2.0 automatic classification algorithm, which attributes a probability of species identity for each single call, and – crossing the information embedded in all calls within a sequence – for each continuous sequence. Detailed information about operation of BatScope® are given in supplementary material (Appendix S2). Altogether, we could discriminate between 15 species or groups of species. Sequences with a probability of correct classification lower than 80% were generally discarded. However, for the three rare target species, we checked all sequences visually in order to avoid too conservative outer-filtering.

Wind speed measures obtained at the crane (10 and 70 m a.g.l.) had to be intra-/extrapolated for the elevations at which the recording devices were placed (5, 20, 35, 50 and 65 m). For this, we used the following classical formula which accounts for topographic friction:

$$v_x = 1/2.1789 * ln(h_x/0.003) \quad \text{(eq 1)}$$

where v is wind speed in m/s, and h = elevation in m

In order to appraise the relationships between bat activity and wind speed, we relied on three different estimates of bat activity.

1) Cumulative number of bat passes per hour (one bat pass corresponding to a single recorded sequence, see above).

2) Probability of activity occurrence per hour: activity data was transformed into presence/absence (binomial distribution), with presence holding true if more than one bat pass was recorded per hour (less than one bat pass corresponds thus to absence)

3) Projected activity occurrence per hour, which is the number of bat passes per hour multiplied by the probability of projected activity occurrence per hour (p):

$$p = exp(\alpha * X + \beta)/(1 + exp(\alpha * X + \beta)) \quad \text{(eq 2)}$$

with α being the slope and β being the intercept of the relationship between estimate 2 and wind speed per hour (GLMM) and X being the categorized wind speed.

This latter estimate was used to avoid either the risk of emphasis put on the same individual bat recurrently foraging around the recorder (estimate 1) or a too conservative approach of bat activity (estimate 2). It thus represents a compromise likely to better reflect real bat activity.

Vertical activity profiles

The number of bat passes per hour recorded by the two devices set at each elevation (one facing NW, the other SE) was averaged in order to retain only one value per elevation. This was necessary given the quite high overlap in recordings obtained with the two detectors at the same elevation (Fig. S3). In comparison, the overlap in recordings from two adjacent elevations was also high (Fig. S3), but we didn't account for this potential bias because it is not possible to allocate simultaneously recorded bat passes to a single elevation only. For the estimation of the vertical distribution of bat activity, we looked at the data obtained from 1) the bat community as a whole; 2) the most common species (*P. pipistrellus* and *H. savii*); 3) the three rare target species (*M. myotis, M. blythii*, *T. teniotis*). Due to logistic reasons we could not measure activity above 70 m. We thus tried to extrapolate the data available to 150 m (which is the highest elevation of operating blades in most European tall turbines) to estimate the proportion of bats being active in the whole dangerous rotor-swept zone (50 – 150 m).

Activity at planned wind turbine sites

Bat activity at these sites was estimated based on a procedure similar to the measures of vertical bat activities. The observed activity pattern was compared with that observed at the crane.

Statistical analysis

For statistical analysis of vertical activity profiles we relied on Generalized Linear Mixed-Effects Models (GLMM). For the vertical profiles we used "activity" as a function of "elevation", with "elevation" as a fixed explanatory variable (including an additional quadratic effect) and "night" as a random factor. For the estimation of the proportion of bat activity within the whole rotor-swept area, we used "activity" as a function of the natural logarithm of "elevation", with "night" as random factor. We built a corresponding null model (= reduced model without the variable "elevation") and compared the two models with a likelihood ratio test. These models were calculated for all bat species, for the two most common recorded bats (*P. pipistrellus and H. savii*) and for the rare target species (*M. myotis, M. blythii* and *T. teniotis*). For the statistical analysis of the probability of activity occurrence we used again GLMMs with "activity" as a function of "wind speed" and "night" as random factor. Again likelihood ratio tests were used to compare the models with a null model (= reduced model without the variable "wind speed") This was done for both bat activity at the truck-mounted crane and for bat activity at the foreseen wind turbine sites. Statistical analyses were performed with software package R 2.13.1 (R Development Core Team 2011). For developing GLMMs we needed the R package "lme4".

Results

We collected a total of 1'952 bat passes at the truck-mounted crane (28.4% and 71.6% of passes at the first and second study sites, respectively). As recordings from the same elevations were averaged, analyses were based on 976 bat passes. The two most common species recorded at the crane were *P. pipistrellus* (59.4%) and *H. savii* (18.6%). The three rare target taxa, the *M. myotis*/*M. blythii* sibling species complex (1.2%) and *T. teniotis* (7.5%) were rather scarce.

At the foreseen wind turbine sites a total of 2'551 bat passes were recorded. The most often recorded species were *P. pipistrellus* (82.5% of passes), the *P. kuhlii*/*P. nathusii* species group (4.3%) and *H. savii* (3.7%). Recordings of the target species *M. myotis*/*M. blythii* (2.2%) and *T. teniotis* (2.0%) were again rare.

Vertical activity profiles

The vertical distribution of activity for the whole bat community shows that most activity took place at lower elevation (below 50 m, i.e. outside of the rotor-swept area), with a minimum reached at 50 m elevation followed by a regain in activity at the higher levels (Fig. 1). We found a highly significant difference between the model including the fixed explanatory variable "elevation" and the null model (likelihood-ratio test: $\chi^2 = 12.17$, df = 1, $p < 0.001$). A similar pattern is found for the most frequently recorded bat species, *P. pipistrellus* and *H. savii*), but significant difference against null model was only found for the former (likelihood-ratio test: χ^2= 13.55, df = 1, p < 0.001). As regards the rare target species *M. myotis/M. blythii,* most activity was recorded at very low elevation. This model was also significant different from the null model (likelihood-ratio test: χ^2= 7.85, df = 1, p < 0.01). *T. teniotis* showed a different pattern, with apparently more activity at higher elevation (65 m and 70 m) although this model was is not significant different from the null model (likelihood-ratio test: χ^2= 0.6, df = 1, p > 0.1).

The extrapolations to 150 m elevation of the bat activity recorded up to 70 m (Fig. 2) suggest that 28% of the whole community activity takes place within the potentially hazardous rotor-swept zone. There are, however, noticeable differences between species: only 15% of the activity of *P. pipistrellus* and 1% of the activity of the *M. myotis/blythii* species group would take place at dangerous elevations. In contrast, these figures reach 41% and 73% for *H. savii* and *T. teniotis,* respectively.

Bat activity vs wind speed

Truck-mounted crane

Bat activity recorded at the truck-mounted crane showed a decreasing trend (number of bat passes per hour) with increasing wind speed. Here, a significant difference against the null model was found (likelihood-ratio test:

χ^2= 44.08, df = 1, p < 0.0001; Fig. S4a). Above ~ 3.5 m/s wind speed, the probability of activity occurrence dropped to ca. 10% if considering all elevations; this threshold was ca 3.8 m/s if one considers only elevations above 50 m, i.e. the dangerous zone. This model was significant different from the null model (likelihood-ratio test: χ^2= 10.33, df = 1, p < 0.01; Fig. S4b).

The projected activity occurrence per hour decreased with increasing wind speed for all species (Fig. S5). There was almost no bat activity above a wind speed of 4 m/s for most species, and even above 2 m/s for *M. myotis/M. blythii* (Fig. S5). A similar pattern was found when considering the dangerous zone only (≥ 50 m a.g.l.) (Fig. S6), except again for *M. myotis/M. blythii* that were recorded almost exclusively just above the ground. Yet, the projected hourly activity occurrence was overall lower when taking into account only data from the dangerous zone, except as concerns *T. teniotis* which yielded similar activity estimates (compare Y axes in Figs S5 and S6). This means that all bat species but *Tadarida teniotis* tended to be less active at higher elevation for a similar wind speed.

The cumulative sum of number of bat passes per hour confirms the pattern from the previous two estimates (Fig. 3). The 90% asymptote is typically reached around 2.3 - 3.1 m/s, depending on species, with a dramatic decline in activity above ca. 4 m/s. Note however that the thresholds are lower in *P. pipistrellus* and *M. myotis/M. blythii*, which appear to be more sensitive to increases in wind speed.

Bat nocturnal phenology showed a clear peak of activity around 10 pm, i.e. at dusk (Fig. S7), while 55% of all bat passes were recorded between 8 pm and 11 pm.

Foreseen wind turbine sites

Recordings at the foreseen wind turbine sites indicate an unexpected increase in the probability of bat activity occurrence with increasing wind speed up to 4 m/s, which was the maximum wind speed at ground level in this study. This model was significant different from the null model (likelihood-ratio test: $\chi^2 = 8.08$, df = 1, $p < 0.01$; Fig. 4). Combining data from the crane and the foreseen wind turbine sites and remodeling them for different elevations (low: 5 and 20 m; intermediate: 35 and 50 m; high: 65 and 70 m) suggests that there was a shift in activity from higher to lower elevations with increasing wind speed (Fig. 5).

At the foreseen wind turbine sites there was a trend towards more bat activity in open fields than in fruit tree plantations (Fig. S8). The projected activity occurrence at the six sites indicates, in contrast to the previous estimate, that there might be a decrease in bat activity above 3 m/s wind speed at ground level also (Fig. S9), thus corroborating the findings at the crane. This is further supported by the cumulated curve of bat passes per hour, which yields a 90% asymptote of 3.4 m/s (Fig. S10).

Bat nocturnal phenology of activity showed a peak at dusk, but this peak is less marked than at the crane (Fig. S11), with 64% of all bat passes being recorded from 8 pm to 11 pm.

Discussion

The main objective of this research was twofold: firstly, to assess which segments of bat communities typically inhabiting the bottom of large Alpine valleys are at risk of collision with wind turbines; secondly, to determine the relationships between vertical bat activity profiles and wind speed. Based on this information, we can propose management recommendations for operating wind turbines in a bat-friendly way. We focused on tall wind turbines, whose rotor-swept area is situated at 50-150 m a.g.l., because these are becoming the rule in continental Europe, if not worldwide.

The establishment of vertical bat activity profiles from ground level up to 70 m elevation, with extrapolations up to 150 m, shows that the activity of the whole bat community (72% of the recorded bat passes) takes place below the rotor-swept area (i.e. below 50 m a.g.l.). Pre-construction studies from the US have also found a higher activity of high-frequency echolocating bats at lower elevations (Arnett *et al.* 2007; Hein *et al.* 2011; Redell *et al.* 2006). The dominant bat species in our study area also fly and/or forage mostly in this lower, non-dangerous zone, where occurred 85% and 59% of the total activity of *P. pipistrellus* and *H. savii*, respectively. Among the rare target species, mouse-eared bats were rarely recorded. This came as a surprise as there is a nursery colony in close vicinity to the projected wind park and because the two species are locally known to exploit farmland (Arlettaz 1996; Arlettaz *et al.* 1997b; Arlettaz 1999), which dominates the landscape matrix on the valley bottom in the study area. However, their low-intensity echolocation calls (Russo *et al.* 2007) may also explain the scarce recordings. Their activity was anyways restricted to very low elevations (only 1% of activity recorded in the rotor-swept area), just above the ground level, which is in accordance with their mostly gleaning foraging strategy (Arlettaz 1996). The species that appears to be most threatened, based on both its regional conservation status and flying mode (Rydell & Arlettaz 1994), is the European free-tailed bat *T. teniotis*, for which 73% of activity was projected to lie within the dangerous zone (50 - 150 m a.g.l.).

The techniques used so far for investigating vertical activity profiles of bats, notably prior to wind park construction, include 1) thermal infrared cameras (Horn *et al.* 2008); 2) Doppler radar (McCracken *et al.* 2008); 3) bat detectors attached onto helium-filled balloons (Fenton & Griffin 1997; McCracken *et al.* 2008); 4) bat detectors attached on the tether of kites (Gillam *et al.* 2009; McCracken *et al.* 2008); 5) bat detectors placed on meteorological towers or flux towers (Arnett *et al.* 2007; Hein *et al.* 2011; Kalcounis *et al.* 1999; Redell *et al.* 2006; Reynolds 2006; Weller 2007) and 6) bat detectors put on the jib of a crane (Hayes & Gruver 2000). The method used here, although limited to 70 m a.g.l., which is the apex of the fully developed truck-mounted crane we used, is advantageous because it provides rather detailed information about vertical activity profiles from ground level up to 70 m a.g.l., based on measurements obtained at six different elevations (roughly every 15 m), which enabled us to project activity profiles up to 150 m a.g.l., which is the apex of the blades in modern tall turbines. This detailed elevational information is typically lacking in former studies. In addition to our truck-mounted crane measurements, we also recorded bats at the six sites foreseen for the installation of the wind turbines: this provides further information about which turbines harbour the largest and/or more diverse bat communities (information not presented here as it has mostly a local relevance) (Baerwald & Barclay 2009).

Pre-construction estimation of the potential collision risk for bats is crucial for the establishment of environmental impact assessments, although it is still unclear whether pre-construction bat acoustic data are able to properly predict post-construction bat fatalities (Fiedler 2004; Hein *et al.* 2013). There remains also the issue that findings from local studies cannot be used ubiquitously because bat community composition usually differs between areas (Piorkowsky *et al.* 2012), which requires adequate local surveys. In our study area, for instance, the community is dominated by sedentary bat species and there were very few recordings of migratory species, even in the late summer and fall when migration can be quite intense over Central Europe, in particular Switzerland. In fact, in the Alps most of the autumn migration takes place at high altitude, with bats commuting mostly over mountain passes, while our projected wind park is situated at valley bottom level (ca. 500 m a.s.l). In our sample, we typically lack fast-flying species such as *Vespertilio murinus* or *Nyctalus leisleri* that migrate over Alpine passes (Arlettaz *et al.* 1997a). Our observations and subsequent management recommendations would thus primarily apply to major Alpine valley bottoms.

The investigation of the links between bat activity and wind speed at different elevations provides threshold values for operating wind turbines in conditions the least detrimental possible to bats (e.g. Behr *et al.* 2007, 2011b). Note that we did not account for other environmental factors that may influence bat activity, such as ambient temperature or precipitation (Baerwald & Barclay 2011; Behr *et al.* 2011a; Hein *et al.* 2011). The three different metrics used in our study yielded very comparable results and will thus be discussed without discriminating between their outcomes. Even if all measurements on the truck-mounted crane were performed during nights with low to moderate wind speed (up to 10 m/s as we were not allowed, for safety reasons, to operate the crane above 11 m/s), we could nicely correlate bat activity with wind speed. Bat activity dramatically decreased with increasing wind speed. Two factors may explain this pattern: on the one hand, there is a decrease in the activity of flying insects in windy conditions (e.g. as observed in adult stoneflies by Briers *et al.* 2003); on the other hand, flying in windy conditions may represent a real energetic challenge for bat species, which deters them from remaining active above a given wind speed threshold depending on species (von Busse *et al.* 2013). This may in turn explain the increase of bat activity up to 4 m/s observed at ground level at our six foreseen turbine sites: a shift in bat activity seems thus to be operated from the higher to the lower elevations with increasing wind speed, probably because the bats can benefit from the wind-breaking effect of the vegetation shelter (Verboom & Huitema 1997). Note that we could not record bats at ground level above 4 m/s as this was the maximum wind speed achieved during our surveys. The estimation of the projected activity occurrence per hour, one of our three metrics, indicates, however, that activity might already start to decrease just above ground level when wind speed approaches 4 m/s (Fig. S9). Other studies of bat activity at low elevations have also shown that there is first an increase in bat activity with slight wind speeds followed by a decrease when wind speed exceeds a certain threshold, e.g. between 3 - 4 m/s (measured at 2 - 4 m a.g.l. in Behr *et al.* 2011a) or around 8 - 9 m/s (measured at 10 m a.g.l. in Arnett *et al.* 2006). Our observation of a more intense activity at ground level among open fields than in fruit tree plantations at a first glance contradicts this view of a vertical activity shift for benefitting from vegetation shelter. It is thus possible that activity just above the ground provides enough slowing of the wind speed, due merely to topographic friction, for providing suitable foraging conditions to bats within this wind speed range (up to 4 m/s). Data obtained at the crane are comparable, with 90% of the asymptote of activity being reached between 3.6 - 3.8 m/s. The projected activity occurrence per hour further shows two dramatic drops in activity at two successive steps around 2.5 and 3.5 m/s, respectively. Moreover, that metric indicates that activity vanishes almost completely above 4 m/s. The pattern observed for *P. pipistrellus*, which makes the bulk of the sample, is similar to that of the entire community. *H. savii* instead seems to occur proportionally less frequently in our study sites in quiet nights, possibly because it is more tolerant to wind. For *M. myotis/M. blythii* no activity was detected above a wind speed of 2 m/s. The other target species, *T. teniotis*, remains quite active up to 3 m/s, but no activity was recorded when wind speed went faster than 4 m/s.

The nocturnal phenology of bat activity peaked around dusk, both at ground level and higher elevations although this peak was more marked at intermediate and high elevations, i.e. at the crane than at the six foreseen turbine sites. Similar temporal patterns have been described by Arnett *et al.* (2006).

Recommendations for bat-friendly wind turbines operation

Based on the status of local bat populations, their vertical activity profiles and activity vs wind speed, we can formulate recommendations for operating tall wind turbines in a more bat-friendly way. From the projected occurrence per hour and cumulative number of bat passes per hour, it appears that *H. savii* and *T. teniotis* remain largely active above a wind speed of 2.5 - 3 m/s, which is a traditional cut-in-speed for operating tall turbines in Central Europe; this threshold for operating the rotors is typically applied at the three wind turbines already installed on the Rhone valley bottom next to our study area. Yet, most activity (71%) of the common and abundant *H. savii* is concentrated in the non-dangerous zone (< 50 m a.g.l.), whilst the rare *T. teniotis* faces a much higher potential collision risk given that up to half (because this bat is the only species likely to fly even higher up than 150 m, see Fig. 2) of its activity was within the dangerous zone between 50 - 150 m a.g.l.. In brief, it seems that the main conservation threat represented by the wind turbines for the local bat assemblage concerns *T. teniotis*. As its activity completely vanishes above 4 m/s we suggest to set the cut-in-speed for operating tall wind turbines at valley bottom level within the Alps at 4 m/s. This threshold appears much lower than in most studies carried out so far, with values typically around 5 - 7 m/s (Arnett *et al.* 2011; Baerwald *et al.* 2009; Brown & Hamilton 2006; Good *et al.* 2011). Again, it is best explained by the absence of fast-flying migratory bats in the study area (see above), *T. teniotis* being the only bat species flying high and quick in the local bat assemblage.

Setting the cut-in-speed to 4 m/s would reduce potential detrimental effects to a very residual risk for that species in particular, and more generally minimize the risks of collision for the whole bat community. Until deterrent of bat activity at wind turbines are developed (see the trials by Arnett *et al.* 2013; Nicholls & Racey 2007), it seems that regulating the cut-in-speed is the most effective measure (after renouncement of construction of course) for mitigating bat fatalities at wind turbines (Arnett *et al.* 2011; Baerwald *et al.* 2009). However, as *T. teniotis* remains active in winter, including at the northern border of its distribution, due to both a very peculiar physiology (Arlettaz *et al.* 2000) and a reliance on moths having a winter phenology, this cut-in speed limitation measure should be applied beyond the vegetation period, i.e. the whole year round. Given the low efficiency of wind turbines in terms of electricity production at low wind speed, given also the fact that electricity production does not increase anymore above a certain wind speed situated around 11 m/s, setting the cut-in speed at 3.5 m/s or 4 m/s would cause a loss of energy production of only 0.35% and 1.2%, respectively (own estimations). Although it is not possible to totally eliminate the risks of collision of bats with operating wind turbine blades, this risk can be drastically diminished if the electricity industry accepted such a tenuous loss of production.

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Figures

Fig. 1. Vertical activity profiles (mean number of bat passes per hour averaged across the nights, here on the X-axis for a more realistic representation of elevation, the latter as Y-axis) at the truck-mounted crane for the whole bat community as recorded, and for *Pipistrellus pipistrellus*, *Hypsugo savii*, *Myotis myotis/Myotis blythii* and *Tadarida teniotis* separately. Error bars indicate the standard error of the mean (SEM). The horizontal line indicates the lower elevation of the rotor-swept area (50 -150 m, representation up to 70, which is the maximum elevation of our recordings) of the locally planned wind turbines. The number of bat passes recorded are also indicated. The p-values are from between elevations comparisons (ANOVA).

Fig. 2. Extrapolated vertical activity (mean number of bat passes per hour and night) at the truck-mounted crane of the whole local bat community, and of *Pipistrellus pipistrellus*, *Hypsugo savii*, *Myotis myotis/Myotis blythii* and *Tadarida teniotis* separately. The grey-shaded area indicates the dangerous rotor-swept area (RSA).

Fig. 3. Cumulative number of bat passes per hour in relation to wind speed at the truck-mounted crane for the whole bat community, and for *P. pipistrellus, H. savii, M. myotis/M. blythii* and *T. teniotis* separately. The red line indicates the 90% asymptote.

Fig. 4. Probability of activity occurrence per hour in relation to wind speed for the whole bat community recorded at the six foreseen wind turbine sites. Significance of trend from GLMM.

Fig. 5. Probability of activity occurrence per hour in relation to wind speed for the whole bat community recorded both at the foreseen wind turbine sites (ground, upper curve) and at the truck-mounted crane (three lower curves; crane low: 5 - 20 m; intermediate: 35 - 50 m; high: 65 - 70 m).

Fig.1.

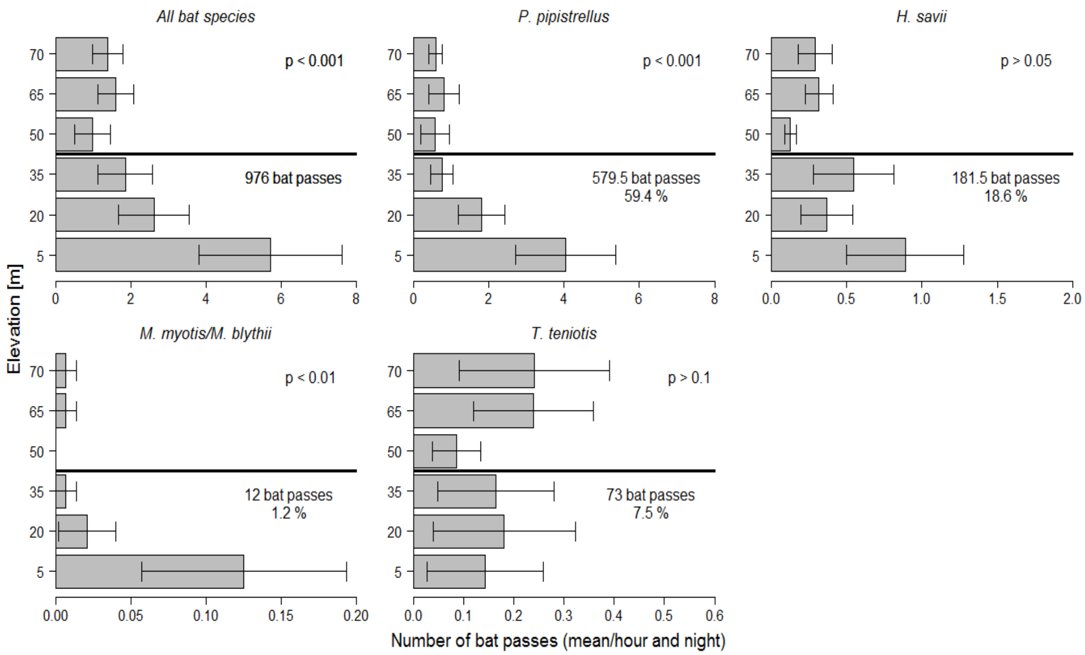
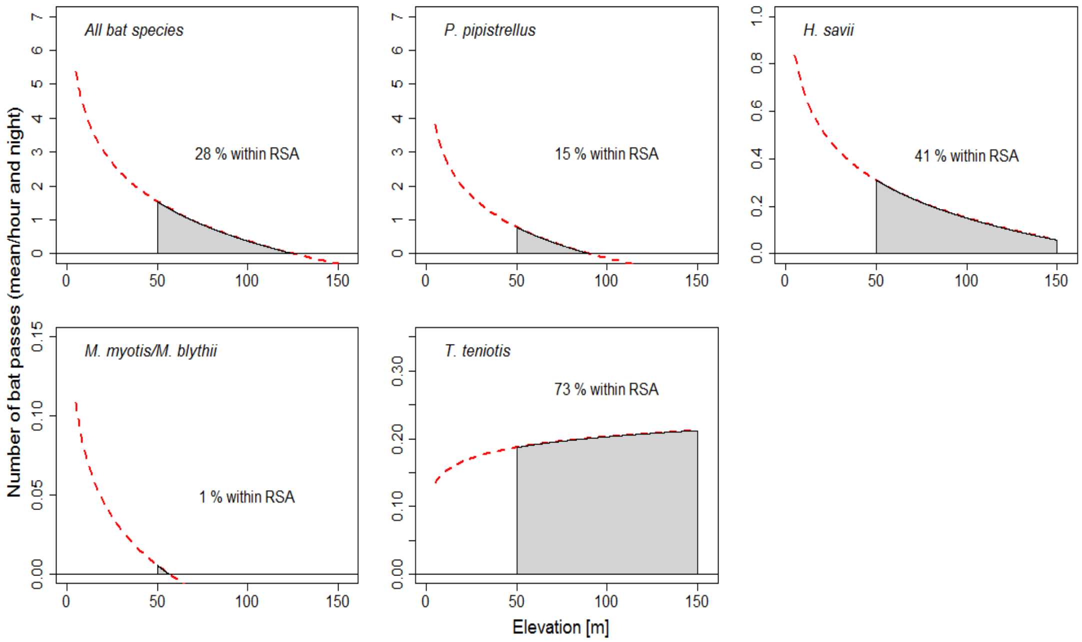

All bat species
P. pipistrellus
H. savii
M. myotis/M. blythii
T. teniotis
p < 0.001
976 bat passes
p < 0.001
579.5 bat passes
59.4 %
p > 0.05
181.5 bat passes
18.6 %
p < 0.01
12 bat passes
1.2 %
p > 0.1
73 bat passes
7.5 %
Elevation [m]
Number of bat passes (mean/hour and night)

Fig. 2.



All bat species
28 % within RSA
P. pipistrellus
15 % within RSA
H. savii
41 % within RSA
M. myotis/M. blythii
1 % within RSA
T. teniotis
73 % within RSA
Number of bat passes (mean/hour and night)
Elevation [m]

Fig. 3.

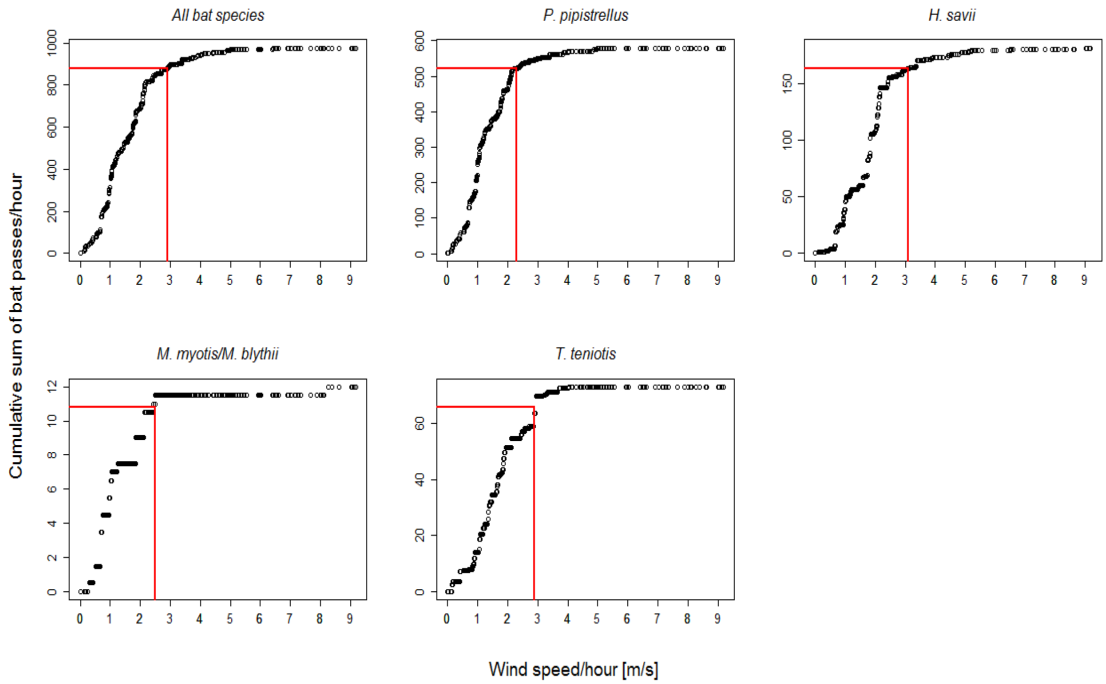
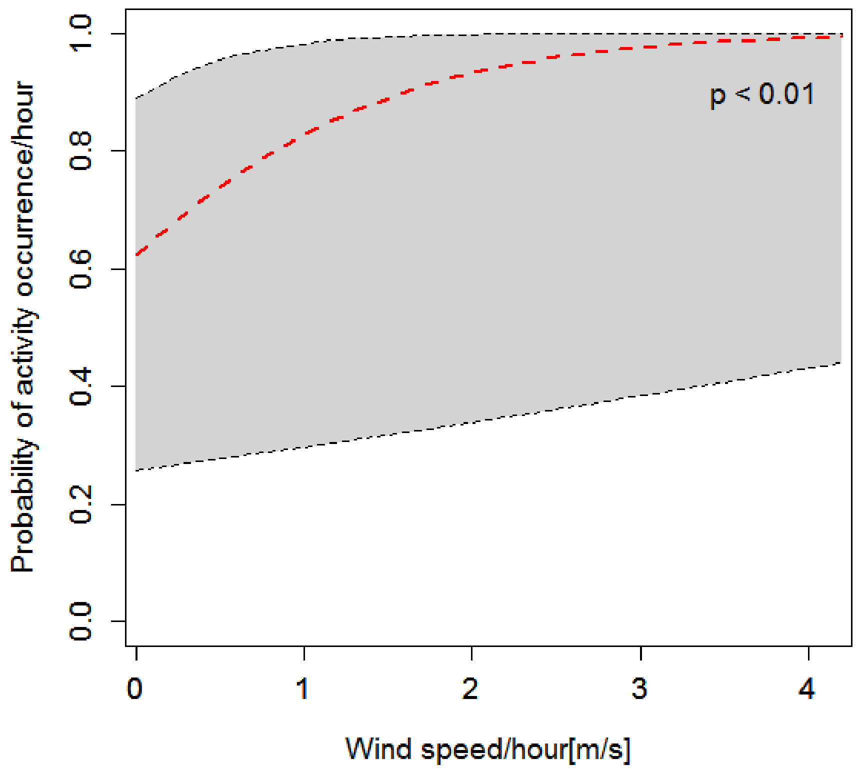
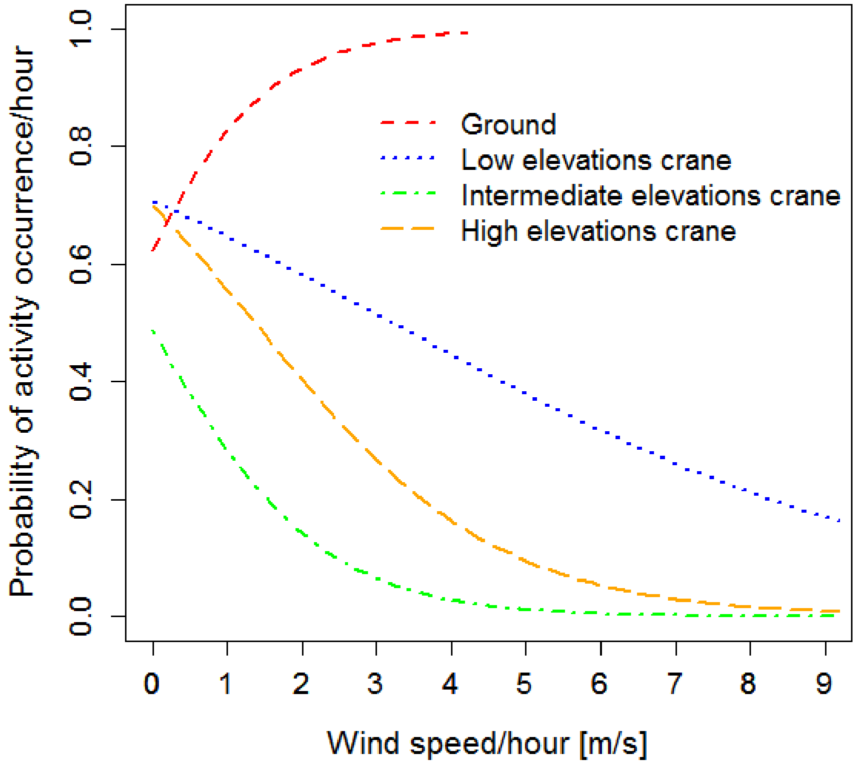

All bat species
P. pipistrellus
H. savii
M. myotis/M. blythii
T. teniotis
Cumulative sum of bat passes/hour
Wind speed/hour [m/s]

Fig. 4.



p < 0.01
Probability of activity occurrence/hour
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2
3
4
Wind speed/hour[m/s]

Fig. 5.


Ground
Low elevations crane
Intermediate elevations crane
High elevations crane
Probability of activity occurrence/hour
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2
3
4
5
6
7
8
9
Wind speed/hour [m/s]

Supplementary material online

Appendix S1: Information about the local bat community

The two sibling species *Myotis myotis* and *Myotis blythii* hunt primarily by gleaning their prey from bare ground, leaf litter and grass (Arlettaz 1996; Arlettaz *et al.* 1997; Arlettaz 1999). At moderate speed, they fly close to the topography, around 30 – 70 cm above ground; when a prey is detected, they land, pick it up and fly off (Arlettaz 1996). *M. myotis* feeds predominantly on ground-dwelling insects, mainly carabid beetles (Carabidae) (Arlettaz 1996; Arlettaz *et al.* 1997b; Arlettaz 1999). It forages mainly in habitats offering access to ground such as freshly mown meadows, orchards and forests without understorey, field or grass layer (Arlettaz 1999). *M. blythii* preys mostly on grass-dwelling arthropods, mainly bush crickets (Tettigoniidae), gleaning them from dense grass cover, preferring steppe, pastureland and dense meadows as foraging habitats (Arlettaz *et al*. 1997b; Arlettaz 1999). Both uncluttered substrate granting access to the ground and cluttered substrates with dense vegetation cover can be found at the wind park site. Next to gleaning, mouse-eared bats also hunt by aerial hawking, i.e. catching prey from the air in flight (Arlettaz 1996). They use this hunting technique especially for cockchafers *(M. melolontha)*, which they prey upon in April-June (Arlettaz 1996). While foraging, mouse-eared bats fly at moderate speed; on commuting flights they can reach up to 50 km/h (Arlettaz 1995). For detection and localisation of prey, *M. myotis* and *M. blythii* use passive listening when gleaning and echolocation during aerial hawking (Arlettaz *et al.* 2001; Russo *et al.* 2007). While bats are listening for prey-generated noise, they do constantly echolocate for orientation in space but calls are weak with low amplitudes ("whispering echolocation") (Arlettaz et al. 2001; Russo *et al.* 2007). For *M. myotis* the call frequency of highest energy (FMAXE) lies at 31 – 54 kHz, for *M. blythii* at 33 – 52 kHz (Russo & Jones 2002).

Next to the above mentioned species, there are another 24 bat species in Valais. Widely distributed are the Brown long-eared bat *(Plecotus auritus)* and Pipistrelle bat *(Pipistrellus pipistrellus).* Alpine species such as Northern serotine bat *(Eptesicus nilssonii)* occur in Valais and in the neighbouring cantons of Ticino and Graubünden. In Valais, the Noctule bat *(Nyctalus noctula)* and Savi's pipistrelle bat *(Hypsugo savii)* reach the northern boundaries of their distribution ranges. Other species inhabiting Valais are Leisler's bat *(Nyctalus leisleri),* Common serotine bat *(Eptesicus serotinus),* Parti-coloured bat *(Vespertilio murinus),* Nathusius' pipistrelle bat *(Pipistrellus nathusii),* just to name some (Arlettaz *et al.* 1997a).

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Appendix S2: How does BatScope® operates

In a first step, it cuts out the recognized bat calls from the sequences, and, in a second step, classifies them using built-in classifiers, the Support Vector Machine (SVM), a K Nearest Neighbour (KNN) classifier, and Quadratic Discriminant Analysis (QDA). Each call within a sequence is subjected to classification and assigned to a bat species. For each call each classifier proposes a most likely species. After a species has been proposed, BatScope® tests the three most distinctive features i.e. call duration, peak frequency and bandwidth of a call against reference values of the proposed species. For a classification to be accepted all values have to lie within a 95% confidence interval of the reference values. BatScope® summarizes classification results of single calls and from these, calculates overall statistics for each sequence. This way, each sequence ends up with a given classification probability. Since not all of these species are likely to be found in the lower Rhône Valley and others are almost impossible to be distinguished correctly from one another by their calls, we combined some species, creating 15 groups of bat species for further analysis. Only bat calls with a signal-to-noise ratio (SNR) of > 30 dB (based upon a recommendation by M. K. Obrist from the WSL Birmensdorf (Switzerland); if the SNR is above 30 dB the signal stands out clear enough against the background noise to allow classification) were taken into account. In a further step we applied a filter to the classification probability (= quality) which had to be ≥ 80%. Sequences with a quality < 80% were discarded. Unfortunately there were very few recordings of threatened target species as *M. myotis* (Greater mouse-eared bat), *M. blythii* (Lesser mouse-eared bat) and *T. teniotis* (European free-tailed bat) when threshold ≥ 80% was chosen. Therefore, all sequences < 80% classification probability had to be controlled visually in detail to find any sequence of target species. One sequence was assumed to be one bat pass of a given bat species, because it is not possible to distinguish between number of sequences and real abundance.

Supplementary material

Table S1. Location characteristics of the different sites: six foreseen wind turbine sites (ValEole 1-6) and vertical activity profiles (Solverse and Marais d'Ardon).

Site	Coordinates	Surrounding land type
ValEole1	577350/108900	Pasture/Fruit tree plantation
ValEole2	576982/108990	Pasture/Fruit tree plantation
ValEole3	577124/109657	Pasture/Maize field/Fruit tree plantation
ValEole4	576986/110063	Pasture/Fruit tree plantation
ValEole5	577652/110175	Fruit tree plantation
ValEole6	578263/110570	Fruit tree plantation
Solverse	576938/110051	Pasture/Fruit tree plantation
Marais d'Ardon	586046/116158	Wetland/Maize field/Fruit tree plantations

Fig. S1. Left: Installation system on the truck-mounted crane (vertical activity profiles): iron pipes between metal cables indicate the different elevations where bat detectors (red squares) were installed. Two anemometers were also attached to the cables. Right: bat detector (inside the black protection box) attached at one end of an iron pipe. The microphone is inside of a protection tube (white). During measurements microphones were directed downwards with an angle of approximately 45° to prevent damage from rain.

Fig. S2. Installation system with plastic sticks for measurements at the foreseen wind turbine sites. The microphone is inside a protection tube (white) and the bat detector is inside the protection box (black). During measurements microphones were directed downwards with an angle of approximately 45° to prevent damage (from rain, etc).

Fig. S3. Relative overlap in recordings (bat passes) on the truck-mounted crane (vertical activity profiles). Left bar: recordings from the same elevation (SE vs NW). Right bar: recordings from two adjacent elevations. Bars indicate the standard error of the mean (SEM)

Fig. S4. Probability of activity occurrence per hour for the whole bat community with respect to mean hourly wind speed (m/s) at the truck-mounted crane. a) All elevations; b) elevations ≥ 50 m, i.e. in the dangerous zone). P-values of trends stem from GLMM.

Fig. S5. Projected activity occurrence per hour at the truck-mounted crane (all elevations pooled) in relationship to wind speed for the whole bat community and for *P. pipistrellus, H. savii, M. myotis/M. blythii* and *T. teniotis* separately.

Fig. S6. Projected activity occurrence per hour at the truck-mounted crane (only elevations above 50 m a.g.l.) in relationship to wind speed for the whole bat community and for *P. pipistrellus, H. savii,* and *T. teniotis* separately.

Fig. S7. Phenology of nocturnal activity (mean number of bat passes per hour, from 20 h to 5 h) for the whole bat community as recorded at the truck-mounted crane. Error bars indicate the standard error of the mean (SEM).

Fig. S8. Probability of activity occurrence per hour in relation to wind speed for the whole bat community at the six foreseen wind turbine sites and with respect to habitat type. Upper curve: overall activity in both habitats combined; middle curve: open field; lower curve: fruit tree plantations.

Fig. S9. Projected activity occurrence per hour at the foreseen wind turbine sites of all species. X-axis: wind speed per hour (categorized). Y-axis: projected activity occurrence per hour.

Fig. S10. Cumulative number of bat passes per hour at the six foreseen wind turbine sites for the whole bat community. The red line indicates the 90% asymptote.

Fig. S11. Phenology of nocturnal activity (mean number of bat passes per hour, from 20 h to 5 h) for the whole bat community as recorded at the six foreseen wind turbine sites. Error bars indicate the standard error of the mean (SEM).

Fig. S1

Fig. S2

Fig. S3

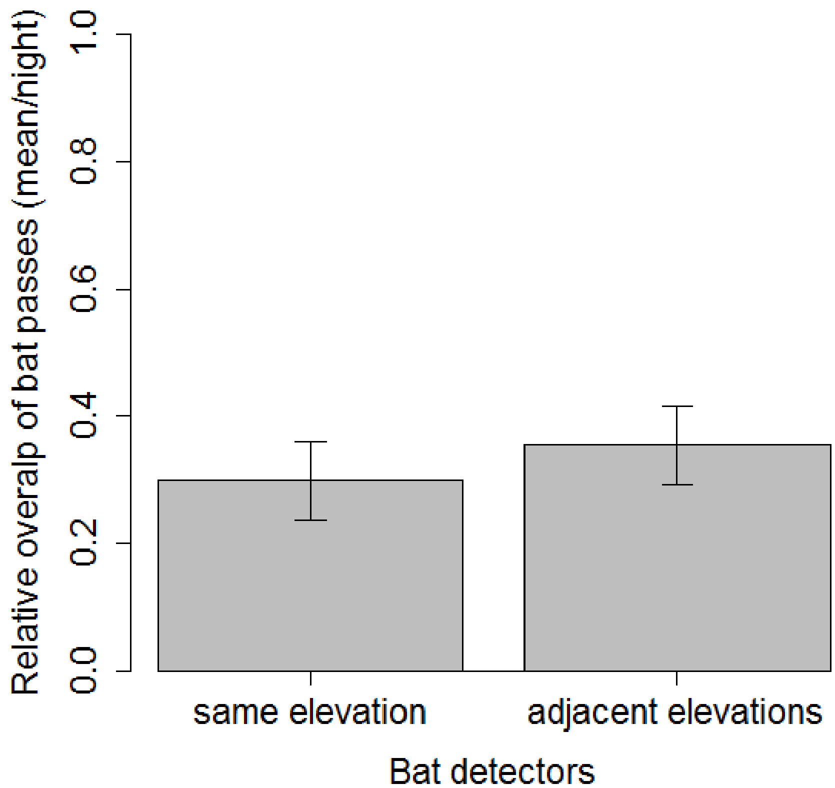
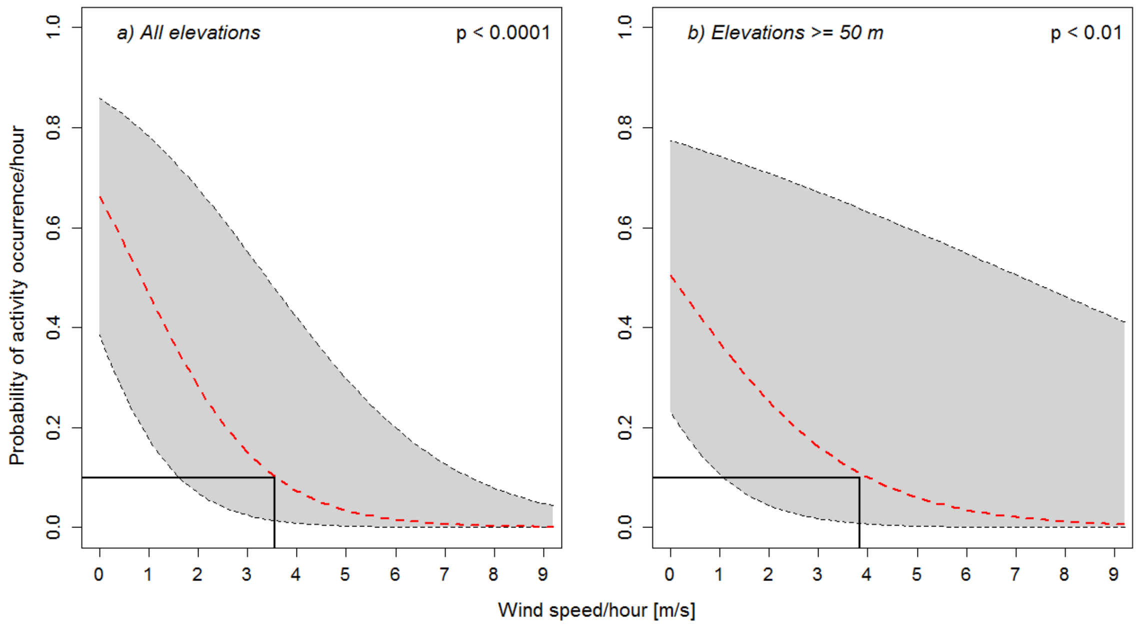

Relative overalp of bat passes (mean/night)
0.0
0.2
0.4
0.6
0.8
1.0
same elevation
adjacent elevations
Bat detectors

Fig. S4



a) All elevations
p < 0.0001
b) Elevations >= 50 m
p < 0.01
Probability of activity occurrence/hour
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2
3
4
5
6
7
8
9
Wind speed/hour [m/s]

Fig. S5

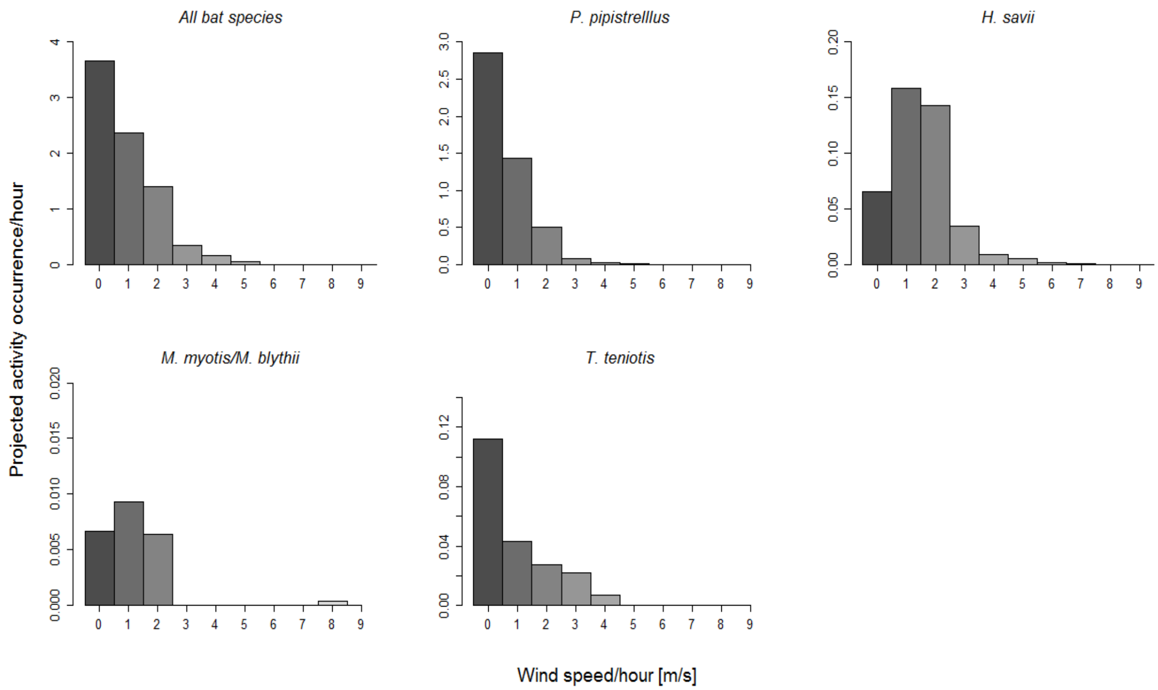

All bat species
P. pipistrelllus
H. savii
M. myotis/M. blythii
T. teniotis
Projected activity occurrence/hour
Wind speed/hour [m/s]

Fig. S6

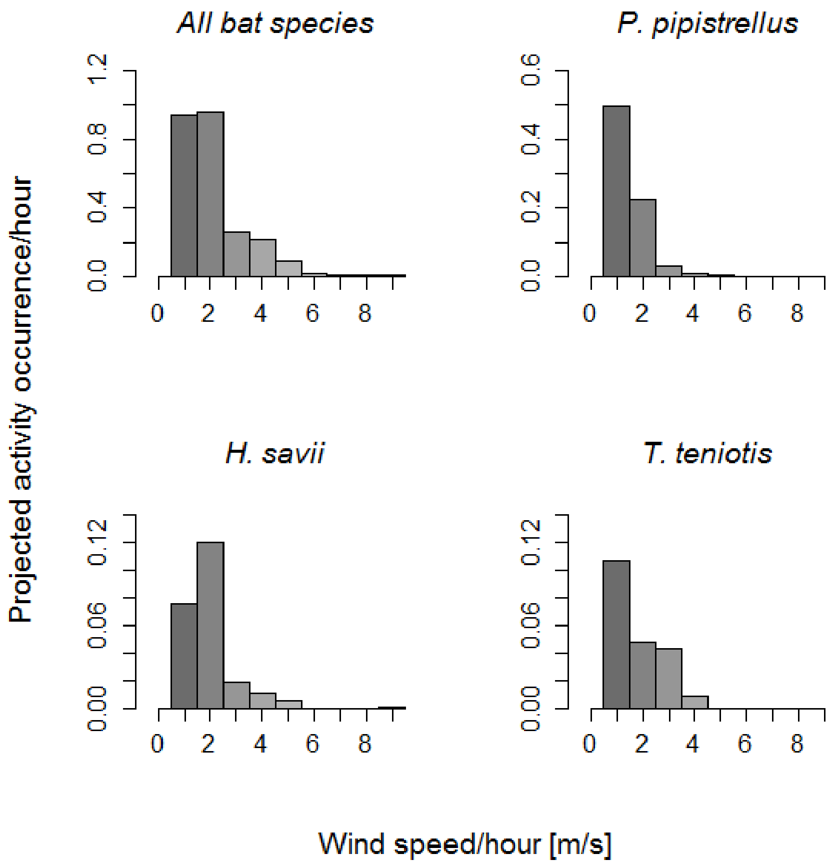

All bat species
P. pipistrellus
H. savii
T. teniotis
Projected activity occurrence/hour
Wind speed/hour [m/s]
0.0
0.4
0.8
1.2
0.2
0.6
0.00
0.06
0.12
0
2
4
6
8

Fig. S7

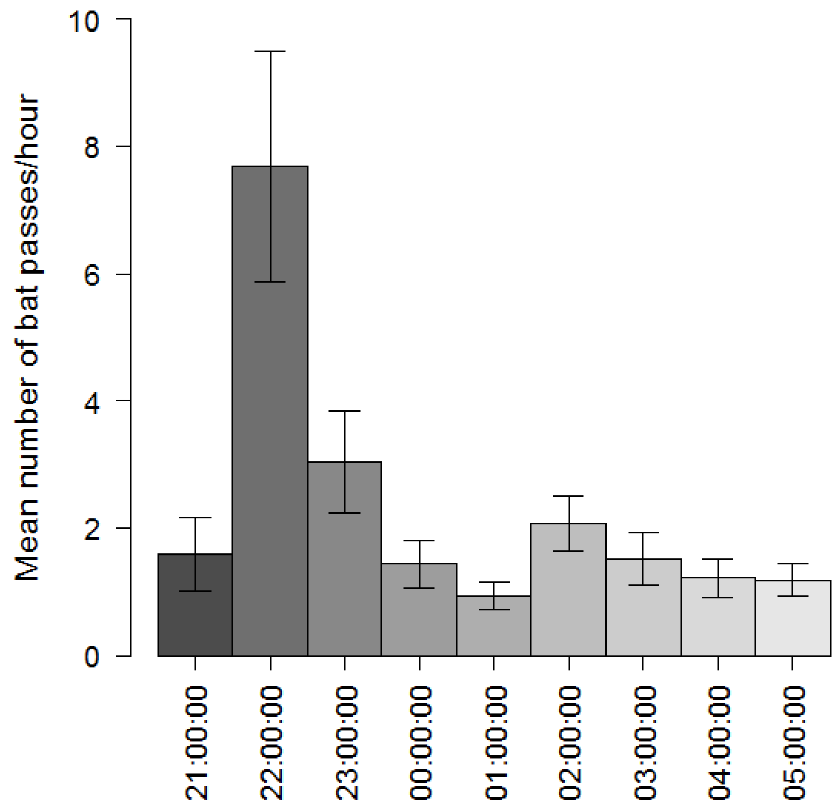
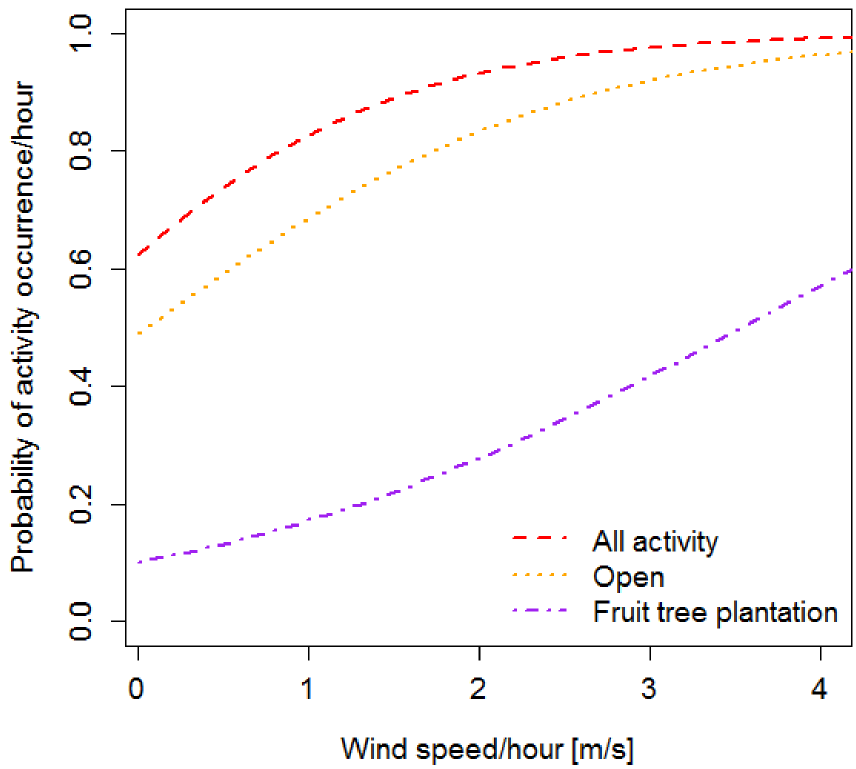

Mean number of bat passes/hour
0
2
4
6
8
10
21:00:00
22:00:00
23:00:00
00:00:00
01:00:00
02:00:00
03:00:00
04:00:00
05:00:00

Fig. S8



Probability of activity occurrence/hour
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2
3
4
Wind speed/hour [m/s]
All activity
Open
Fruit tree plantation

Fig. S9

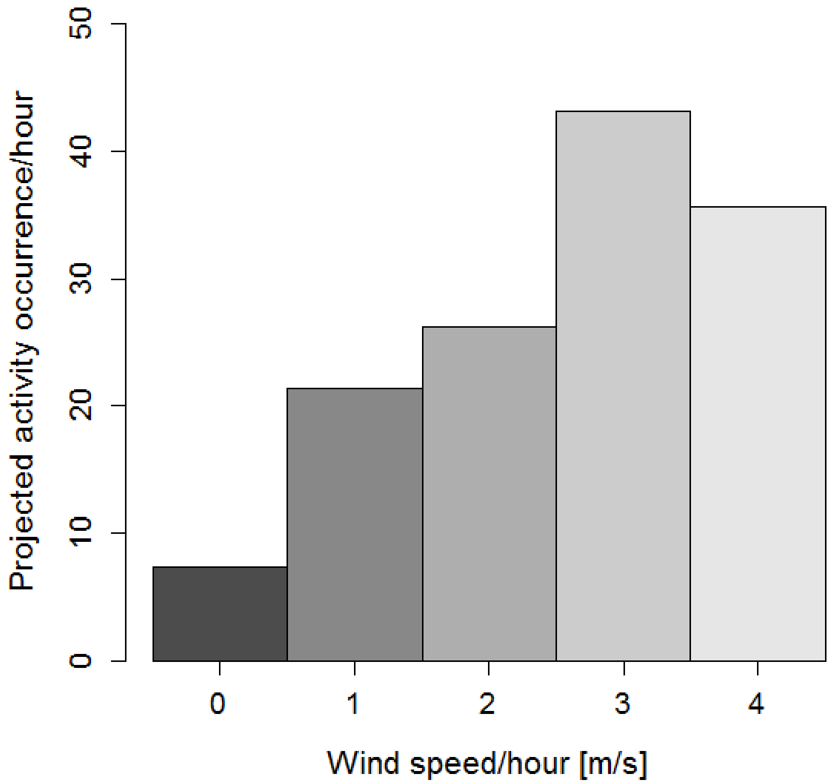
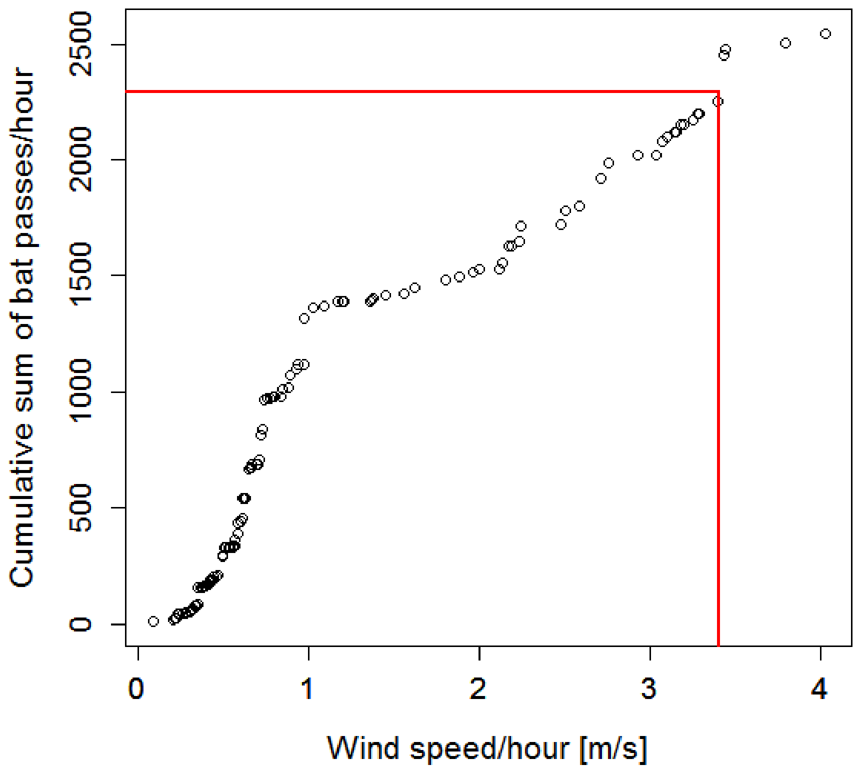
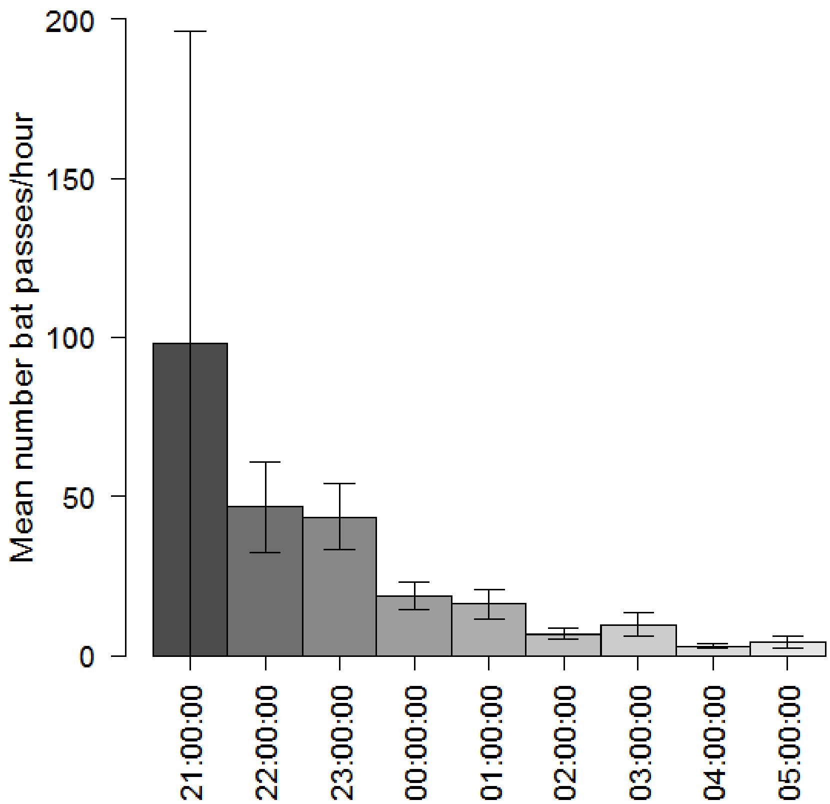

Projected activity occurrence/hour
0
10
20
30
40
50
0
1
2
3
4
Wind speed/hour [m/s]

Fig. S10



Cumulative sum of bat passes/hour
Wind speed/hour [m/s]
0
500
1000
1500
2000
2500
0
1
2
3
4

Fig. S11



Mean number bat passes/hour
200
150
100
50
0
21:00:00
22:00:00
23:00:00
00:00:00
01:00:00
02:00:00
03:00:00
04:00:00
05:00:00

Erklärung

gemäss Art. 28 Abs. 2 RSL 05

Name/Vorname: Wellig Sascha

Matrikelnummer: 08-126-682

Studiengang: Master of Science in Ecology and Evolution

Bachelor ☐ Master ☒ Dissertation ☐

Titel der Arbeit: Mitigating the negative Effects of tall Wind turbines on Bats: Vertical activity profiles and Relationships to Wind speed

LeiterIn der Arbeit: Prof. Dr. Raphaël Arlettaz

Ich erkläre hiermit, dass ich diese Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen benutzt habe. Alle Stellen, die wörtlich oder sinngemäss aus Quellen entnommen wurden, habe ich als solche gekennzeichnet. Mir ist bekannt, dass andernfalls der Senat gemäss Artikel 36 Absatz 1 Buchstabe r des Gesetztes vom 5. September 1996 über die Universität zum Entzug des auf Grund dieser Arbeit verliehenen Titels berechtigt ist.

Bern, 11.09.2013

Ort/Datum

S. Wellig

Unterschrift