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COMMENT

Standardised and referenced acoustic monitoring reliably estimates bat fatalities at wind turbines: comments on 'Limitations of acoustic monitoring at wind turbines to evaluate fatality risk of bats'

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ABSTRACT

Voigt et al. (2021) provide a thorough analysis of the restrictions inherent to the estimation of bat abundance from acoustic surveys, and conclude that limitations of acoustic monitoring impede the reliable evaluation of bat fatalities at wind turbines. We argue that acoustic data recorded at the nacelle of wind turbines have been experimentally validated as a useful and appropriate measure of bat collisions. Therefore, acoustic data can be used to estimate bat fatalities at wind turbines, provided a referenced and standardised protocol for data acquisition and analysis is used.

ZUSAMMENFASSUNG IN DEUTSCH

Voigt et al. (2021) zeigen in einer detaillierten Analyse Einschränkungen auf, die sich für die Bestimmung von Fledermausabundanz auf der Grundlage akustischer Erfassungen ergeben, und kommen zu dem Schluss, dass diese Einschränkungen keine zuverlässige Bewertung der an Windkraftanlagen versterbenden Fledermäuse erlauben. Wir argumentieren, dass in Experimenten validiert wurde, dass an der Gondel von Windenergieanlagen aufgezeichnete akustische Daten ein nützliches und geeignetes Maß für Fledermausschlagopfer sind. Daher können akustische Daten zur Abschätzung an Windenergieanlagen zu Tode kommender Fledermäuse verwendet werden, vorausgesetzt, es wird ein referenziertes und standardisiertes Protokoll für die Datenerfassung und -analyse verwendet.

INTRODUCTION

Understanding the mortality of bats at wind turbines is key to their protection. Initially, the number of bats colliding with wind turbines was estimated from carcass searches (e.g. Arnett et al. 2008; based on the assumption that bats colliding with the rotor are unlikely to survive, we use the terms collision, mortality, and fatality interchangeably). However, these searches are time consuming and costly, and estimates can be very imprecise under the conditions encountered, for example, at many sites in Europe (e.g. high rates of carcass removal by scavengers, and low detectability of carcasses – see Brinkmann et al. 2011). Therefore, acoustic surveys at the nacelle (housing bearing the rotor) of wind turbines are increasingly used to assess the number of mortalities and to develop mitigation measures (Behr et al. 2017, Hayes et al. 2019, Peterson et al. 2021).

Voigt et al. (2021) analysed the restrictions inherent to the estimation of bat abundance from acoustic surveys, and concluded that limitations of acoustic monitoring impede the reliable evaluation of bat fatalities at wind turbines. We agree with many of the issues described by Voigt et al. (2021) that result in limitations for the acoustic recording of bats in general (rapid attenuation of ultrasound, acoustic shadow, directionality of calls, effects of trigger settings, and species-dependent detection range and identification), and appreciate the discussion on the effect of increasing wind-turbine dimensions that render the acoustic estimation of bat abundance and collisions in the rotor-swept area yet more demanding. In our eyes, figure 2 in Voigt et al. (2021), on the acoustic detection range, is an excellent illustration of this complex issue. However, researchers have been aware of these restrictions and, during almost two decades, large efforts have been made to develop methods that extract as much meaningful information as needed from acoustic bat surveys in general and at wind turbines in particular (Appendix S1). The description given by Voigt et al. (2021) of how acoustic data recorded at wind turbines are used to predict and reduce the mortality of bats reflects neither this accumulated knowledge nor the current debate in this field.

RECORDER SENSITIVITY AND DETECTION RANGE

The main argument put forward by Voigt et al. (2021) relates to the distance at which bat calls can be detected by acoustic recorders. To calculate this distance, the authors used a threshold of 60 dB sound pressure level (SPL; the lower the threshold the more sensitive the recorder), which is commonly used with the acoustic recording device 'Batcorder' (produced by one of Voigt's co-authors) at wind turbines. Other detectors specifically designed to sample bats at wind turbines (BATmode, bioacoustictechnology; Batlogger WEX, Elekon) have a substantially lower threshold at 37 dB SPL and thus record much more activity than the Batcorder (Adams et al. 2012, Behr et al. 2018). When compared to figure 2 in Voigt et al. (2021), the detection ranges of these detectors are twice as far as those of the Batcorder, resulting in eight times larger volumes.

Thus, there are detectors that have much larger detection ranges than described by Voigt et al. (2021), while at the same time recording substantially fewer noise signals (Behr et al. 2015, Behr et al. 2018, Table 1, Appendix S2). We do not, however, consider sensitivity and detection ranges as major issues. One reason is that bat activity in the detection range of a microphone installed below the turbine nacelle is much higher than the average in the entire rotor-swept zone, resulting in adequate information to estimate the number of collisions. The reasons for this are, at least in Europe, the decrease in the total activity of all species with the height above ground (Hurst et al. 2017, Wellig et al. 2018, Bach et al. 2020), and the concentration of bats around the nacelle as compared to in free air space at the same height (Cryan et al. 2014, Behr et al. 2015). However, more important than detection range are the standardisation and referencing of acoustic recordings to infer collisions from bat activity at the nacelle (e.g. Peterson et al. 2021).

STANDARDISED AND REFERENCED ACOUSTIC SURVEYS ALLOW FOR A RELIABLE MORTALITY ESTIMATION

Ecological surveys, including acoustic surveys of bats, typically require only a sample of a population (Kenkel et al. 1989). Sampling at wind turbine nacelles is usually extensive compared to sampling in other ecological impact assessments (Appendix S3) and, importantly, typically covers the entire bat activity period continuously – a major advantage since bat activity is often characterised by short peaks that are difficult to predict (Brinkmann et al. 2011). Voigt et al. (2021) argue that acoustic surveys at wind turbines are severely constrained because recorders “cover only approximately 23% of the risk zone for a bat calling at 20 kHz and 4% for a bat calling at 40 kHz”. The statement conveys the impression that more, probably all, bats present in the rotor-swept zone should be recorded. Exhaustive sampling is neither necessary for a turbine shutdown based on real-time bat detection (Hayes et al. 2019) nor necessary in the predictive approach commonly used. Instead, standardised detector measurements are used to assess the level of bat activity and to model relationships between environmental factors and bat activity at a specific turbine, in order to predict future bat activity and to adapt curtailment accordingly. To account for random, seasonal, and inter-annual effects, bat activity should be sampled during more than one complete season (Krättli et al. 2014, Behr et al. 2018, EUROBATS 2019).

The relevant questions are: which biases affect the sample? How they are accounted for? And how much does actual bat activity deviate from the predictions? In the case of a referenced acoustic method used to measure the mortality of bats at wind turbines, many of the existing biases are accounted for by correlating bat fatalities to the number of acoustic recordings in a large dataset from many turbines, using, for example, mixture models (Fig. 1, Korner-Nievergelt et al. 2013, 2018).

Because the activity at a site is compared to bat activity at reference sites, heterogeneous distribution of bats and other effects specific to wind turbines are accounted for. Thus, the statement by Voigt et al. (2021) that “Nacelle monitoring of bats makes the implicit assumption that the distribution of flight altitudes is uniform within the risk zone” is erroneous.

The reference, however, only fits well if the components of the system do not change. A continuous challenge is posed by the effects of turbines with increasing rotor and tower dimensions – compared, and this is the key point, to the turbines the system has originally been referenced for. Such changes in turbine features should be accounted for by extrapolating bat activity with data-based models (e.g. data on spatial distribution of bats in the rotor-swept zone; Behr et al. 2015) and/or by producing reference data for the new turbine types.

There is, however, an ongoing discussion on the combined effects of rotor size and turbine height: what is the effect of an increasing distance between microphone and rotor tip on the correlation of the recorded acoustic activity and fatality numbers? What happens when rotor diameters increase but turbine height does not and, in consequence, rotor tips reach closer to the ground? Answers could be drawn from detailed information on the vertical distribution of bats which is, so far, available from studies at meteorological towers and cranes (Hurst et al. 2017, Roemer et al. 2017, 2019, Wellig et al. 2018) – we suggest that the vertical distribution of bats at wind turbines should be a future focus in research. Voigt et al. (2021) present a schematic concept on the effect of the vertical distribution of bats on their detectability by recorders installed in the nacelle (fig. 5 in Voigt et al. 2021). However, because they do not mention existing approaches used to relate acoustic measurements from wind turbines to references (acoustic and correlated fatality data), their criticism does not contribute to solving the problems currently encountered in practice.

Table 1. Features of acoustic detectors commonly used to record bats at the nacelle of wind turbines; + = has the feature, − = does not have the feature, +/− = partly has the feature. Comparisons of detector data backup, remote control, and connectivity are shown in Appendix S2

	Anabat Swift[1]	ecoObs GSM Batcorder	elekon Batlogger WE X	Bioacoustic-technology BATmode	Wildlife Acoustics SM4	Wildlife Acoustics SMART
Microphone						
Max. number of microphones	1	1	8	4	2	3–6
Omnidirectional[2]	+[3]	+[3]	+[3]	+[3]	+[3]	+[3]
Heating[4]	−	−	−	+	−	+
Calibration[5]	−	+	+	+	−	−
Digital signal transfer[6]	+/−[7]	−	+/−[7]	+/−[7]	+/−[7]	+
Remote sensitivity check[8]	−[9]	+	+	+	−	+/−[10]
Broad band test signal[11]	−	−	+[12]	+	−	+/−[13]
Trigger						
Fixed threshold (dB SPL)[5]	+/−[14]	54, 60, 66, 69[15]	37[16]	37[16]	+/−[17]	+/−[17]
Frequency analysis based on FFT[18]	+/−[19]	+/−[19]	+	+	+	+
Complex bat call filter[20]	−[21]	−[21]	+	+	+/−	+
Transparent trigger settings[22]	+	−	+	+	+	+

[1]The Anabat SD1/SD2, previously used to record zero crossing data of bats at wind turbines, is no longer available. The manufacturer currently recommends the full spectrum recorder Anabat Swift.
[2]An omnidirectional microphone reduces biases caused by a heterogeneous distribution of bats. The term omnidirectional is an approximation and directionality depends on sound frequency. Installation in the turbine wall reduces the scope of the microphone to a hemisphere.
[3]Batcorder, Batlogger, BATmode, and SM4 with SMM-U1 microphone all use electret microphones of the FG series produced by Knowles Electronics. The Swift with US-O V3, SM4 with SMM-U2, and the SMART microphones are based on MEMS (Micro Electro-Mechanical System) technology.
[4]Microphone heating greatly reduces effects of rain and temperature on sensitivity and wear.
[5]The use of calibrated microphones and a fixed trigger threshold reduces biases when comparing data from different sites. With a dynamic threshold, changes in the level of background noise cause differences in detector trigger threshold and, in consequence, in the number of bats recorded. Thus, the higher noise level at sites with higher wind speeds will lead to a lower percentage of bats recorded.
[6]A digital signal transfer from the microphone to the recorder reduces the amount of electromagnetic noise signals recorded and, with fibre optic signal transmission, allows for cable lengths between microphone and detector >100 m.
[7]The Swift, Batlogger, BATmode, and SM4 use integrated microphone amplifiers that transmit a differential analogue signal that offers improved resistance to electromagnetic interference as compared to a simple analogue microphone signal, thus allowing for microphone cable lengths of up to 100 m. For the BATmode, a microphone with digital signal transfer is being developed (according to the manufacturer).
[8]A daily remote sensitivity check is required for reliable and referenced recording.
[9]The Swift has a 'microphone detect' function that can detect complete microphone failure or cable breakage but not a change in sensitivity.
[10]SMART microphones have a redundant backup sensor and a non-calibrated ultrasonic emitter, rendering less information than a calibrated transmitter.
[11]Ultrasound test-signals are usually produced by piezo elements. The acoustic characteristics of these elements (e.g. peak frequency) are influenced by temperature, which makes broadband test signals more reliable.
[12]Available as firmware update.
[13]The SMART currently uses a narrow-band test signal, but is based on an open platform and could be customised to a broadband test signal.
[14]The Swift uses a fixed threshold referenced to the maximum amplitude (in dB FS) but without calibration (in dB SPL).
[15]A 42 and 48 dB SPL threshold are being developed (according to the manufacturer). 60 dB SPL (setting −36 dB FS) is the trigger threshold currently recommended when using the Batcorder to record data to be used in the ProBat Software.
[16]Other trigger threshold settings can be used, also.
[17]For the SM4, a firmware update is available that includes a fixed threshold option (according to the manufacturer). To our knowledge, up to now most users choose the default dynamic threshold option. The SMART uses a dynamic threshold, but a fixed one could be programmed. Wildlife Acoustics offer no calibration service, so any chosen threshold will show fluctuations depending on the specific device, microphone, and microphone condition.
[18]Frequency-based triggering with data that have been fast Fourier transformed (FFT) into a sonogram, as opposed to time-signal triggering, reduces noise recordings to a large extent.
[19]The Swift and Batcorder both offer a trigger that is partly based on frequency criteria but not on FFT. These frequency criteria do not offer, for example, the increase in signal to noise ratio resulting from FFT analysis (see Appendix S2).
[20]A complex bat call filter based on multiple parameters mostly from the sonogram (calculated by FFT).
[21]The Swift uses a trigger criterion based on zero-crossing frequency information but not on FFT. Similarly, the Batcorder has a partly frequency-based 'quality' criterion and a 'noise filter' function, both without publicly available specifications. The ability of these simple frequency criteria to recognise bat calls and to filter noise signals is limited compared to multiple FFT-based criteria. The Batcorder 'noise filter' may affect the number of bat calls recorded which could render it incompatible with the settings in the ProBat software.
[22]Transparency in bat call recognition, with publicly accessible threshold values.

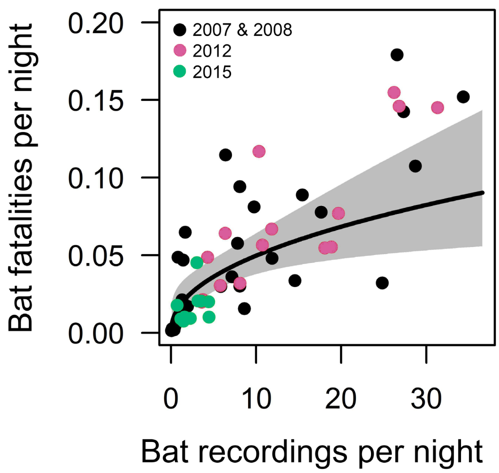

Fig. 1. The relationship between bat recordings and fatalities at wind turbines. Bat activity, quantified as the number of bat recordings at the nacelle per night with a BATmode recorder averaged over the nights after which carcass searches were performed, predicts bat fatality rates for turbine-years. The black regression line shows the partial effect of acoustic activity on the number of fatalities per night from a hierarchical model that accounted for detection probability and also included average wind speed, nacelle height and rotor diameter as predictors (R^2 =0.78). The grey shading shows the 95% credibility interval. Dot colours indicate sample years (2007 and 2008, 2012, and 2015). Turbines sampled in 2015 had larger rotor diameters than in the previous years. See Appendix S4 for methods and details.

Voigt et al. (2021) state that recorded acoustic data "…are then used to identify the environmental conditions […] at which bats are most active". Many curtailment systems are, however, more complex, calling for joint efforts between fundamental and applied research to develop appropriate and feasible solutions. For example, in ProBat (a browser-based online tool used to calculate mitigation algorithms in Central Europe, www.ProBat.org), mortality assessment (probability of collisions) and curtailment decisions are based on the standardised measures of the level of acoustic bat activity, accounting for wind speed, month, time of night, the region of the turbine site, and temperature. To render mortality assessment more robust and less prone to random effects of a small sample size (e.g. extreme weather conditions), the relationships between environmental factors, bat activity and ultimately mortality are informed by a data-base from hundreds of turbines with more than 65000 detector-nights recorded during more than 10 years (Brinkmann et al. 2011, Behr et al. 2015, 2018). Moreover, the effectiveness of the curtailment algorithms resulting from the models has been experimentally validated at 16 turbines from eight sites (Behr et al. 2015). Another example is the TIMR system that uses real time acoustic data in addition to wind speed data (Hayes et al. 2019).

The apparently simple solutions proposed in Voigt et al. (2021), such as the use of additional acoustic detectors, would be of little help since the interpretation of the recorded data is only possible if referenced with data from fatality searches (Appendix S5), as has been done for detectors installed in the bottom of the nacelle (Korner-Nievergelt et al. 2013, Behr et al. 2018). In summary, Voigt et al. (2021) give a very useful overview of the restrictions of acoustic sampling of bat populations in general, but they do not account for the way in which extensive acoustic data are used to predict and reduce the mortality of bats at wind turbines (e.g. Peterson et al. 2021).

We are concerned that stating that there is an unsolved 'green-green dilemma' (Voigt et al. 2021), while largely ignoring existing solutions and standards, will be detrimental to bat populations; in the long run, we argue that it could also be detrimental for the development of wind energy, since a unified and accepted standard approach increases planning reliability. Existing approaches to mitigate the impact of wind energy on bat populations based on standardised and referenced acoustic surveys have been shown to be effective and have continuously been improved. We are convinced that these solutions are key to the expansion of renewable energy with limited and tolerable mortality for the bat fauna.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's website.

Appendix S1. References on surveys of the bat activity at wind turbines.
Appendix S2. Additional information on acoustic detectors commonly used to record bats at the nacelle of wind turbines.
Appendix S3. Information on ecological impact assessment at wind turbines.
Appendix S4. Methods for Figure 1.
Appendix S5. Information on a standardised and referenced protocol for acoustic acquisition of bat data at the nacelle of wind turbines.

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SUPPORTING INFORMATION

APPENDIX S1

There is a lot of information available on acoustic sampling of bats in general, including topics like detection range and species identification (a small selection: Adams et al. 2012; Barré et al. 2019; Brigham et al. 2004; Dubos et al. 2021; Fenton 2000; Froidevaux et al. 2014; Kerbiriou et al. 2019a; Kerbiriou et al. 2019b; López-Baucells et al. 2019) and specifically for meteorological towers and wind turbines including topics such as inter-annual variability of bat activity, correlation of pre- and post-construction surveys, the use of real-time acoustic data to inform curtailment strategies, and the effect of increasing wind turbine dimensions (e.g. Bach et al. 2020a; Bach et al. 2020b; Baerwald & Barclay 2011; Behr et al. 2017a; Behr et al. 2017b; Behr et al. 2018; Behr et al. 2015; Beucher et al. 2011; Brinkmann et al. 2011; Corcoran & Weller 2018; Schmieder et al. 2019; Hayes et al. 2019; Hein et al. 2013; Hüppop & Hill 2016; Hurst et al. 2017; Korner-Nievergelt et al. 2018; Korner-Nievergelt et al. 2013; Lindemann et al. 2018; Lintott et al. 2016; Richardson et al. 2021; Roemer et al. 2017; Smallwood & Bell 2020; Solick et al. 2020; Sutter & Schumacher 2017; Weller & Baldwin 2011; Wellig et al. 2018). Also, more and more data are also available from alternative and complementary sampling methods, mainly thermal imaging (Gorresen et al. 2017; Gorressen et al. 2015; Hochradel et al. 2019; Hochradel et al. 2021; Hochradel et al. 2018; Peterson et al. 2021; Pinzari et al. 2019).

APPENDIX S2

For the Batcorder (Ver 1.0 without 'noise filter', trigger threshold -36 dB FS = 60 dB SPL; the unit 'dB FS' is a relative reference to the maximum amplitude (**f**ull **s**cale) of the recorder while 'dB SPL' is referenced to an absolute **s**ound **p**ressure **l**evel; for additional device settings see Behr et al. 2015) only 0.3 to 20 % of recordings included bat calls (i.e. the rest were noise recordings) whereas 29 to 92% of Avisoft/BATmode recordings contained bat calls (Behr et al. 2015, pages 77-78; Behr et al. 2018, pages 35-38). The lower trigger threshold and increased detection range of the Avisoft/BATmode system as compared to the Batcorder resulted on average in a 2.0 (SD ± 0.3) times higher number of 10-min intervals with recorded bat calls during 5385 h of parallel recording with both detector systems at 8 wind turbines (see Behr et al. 2015, Figure 16 on page 78). The theoretical detection ranges of the two systems were also verified in a playback experiment using a quadcopter equipped with a GPS module and an ultrasound loudspeaker that broadcasted artificial 25 kHz bat calls in defined distances to the nacelle where acoustic detectors were installed (Behr et al. 2015, pages 69-71).

The surprising fact of fewer noise recordings and at the same time much lower trigger threshold can, in addition to differences in construction (e.g. shielding against electromagnetic noise – see differential signal transition in footnote 7 to Table 1) of the detectors, be explained by the different trigger mechanisms of the detectors: the batcorder uses an amplitude threshold with one additional quality criterion and an unspecified noise filter, whereas Batlogger, BATmode, SMART, and with some limitations also the SM4 use complex frequency-domain filters applied to the fast-Fourier-transformed (FFT) acoustic signals in addition to an amplitude threshold. FFT not only allows for more accurate parameter-based bat call recognition but also greatly increases the signal to noise ratio (s/n) in comparison to a time-signal trigger. For instance, the FFT bandwidth of a 300 kHz signal with a 256 window is 1.2 kHz, while the bandwidth of the time signal is greater than 120 kHz, even with a highpass filter at e.g. 15k Hz. Assuming white noise this reduction in analysis bandwidth improves the s/n ratio by a factor of about 10 = 20 dB.

Table: comparison of detector data backup, remote control, and connectivity

	Anabat Swift	ecoObs GSM Batcorder	elekon Batlogger WE X	Bioacoustic-technology BATmode	Wildlife Acoustics SM4	Wildlife Acoustics SMART
data backup						
backup in device[23]	-	-	+	+	-	+
backup in cloud[24]	+[25]	+[25]	+	+	-	+
history log file[26]	+/-[27]	+/-[28]	+	+	+/-[29]	+
remote control						
Remote access via	(Ethernet, LTE, satellite)[25]	SMS (Ethernet, WIFI, LTE)[25]	Ethernet, WIFI, LTE, SMS	Ethernet, WIFI, LTE, SMS	-	Ethernet, WIFI, LTE, SMS
full remote access[30]	+[25]	+[25]	+	+[31]	-	+
daily status message	-	+	+	+	-	+
connectivity						
Plug in point for meteorological sensors	-	-[32]	+/-[33]	+	+	+

[23]**Backup on an extra storage device** inside the detector.

[24]**Cloud backup** also allows for data download and analysis already during the survey season.

[25]Third party add-on required.

[26]A history log file should record shut downs, microphone sensitivity, and microphone failures during the sampling period.

[27]Since it is not being measured, the Swift log file does not contain information on microphone sensitivity (but on settings and microphone status).

[28]The Batcorder does have a log file but microphone sensitivity and failures have to be checked for manually.

[29]The SM4 has a 'summary' file indicating recordings made, battery voltage, detected microphone, etc. but without information on microphone performance.

[30]A full remote access to recordings and settings allows e.g. to identify noise recordings during the recording period and to adjust settings if necessary.

[31]Full remote access to the BATmode also allows for remote manual or automatic species identification in the recordings stored on the hard disk of the device.

[32]The Batcorder provides an integrated temperature sensor but no plug-in for external sensors.

[33]The Batlogger provides integrated temperature, humidity, and air pressure sensors but no plug-in for external sensors.

APPENDIX S3

For example, when monitoring a turbine nacelle, the sample of the risk zone per year is about 100 to 1000 times larger than samples commonly taken on a ground transect survey, e.g. for a projected road (where the future collision risk is one of several study objectives). With the transect survey, the risk zone sampled will comprise 0.03 % of the relevant space and time per year even under the unrealistic assumption that all the space sampled will be inside the future risk zone (assuming a typical sampling effort using a hand held detector with a detection distance of 30 m, 15 surveys per year, 4 hours each for a projected road 3 km long that will affect bats up to a height of 4 m above ground). Another advantage of the wind turbine survey is that it samples the activity with the turbine in situ, thus accounting for changes in habitat use caused by the construction (Hochradel et al. 2015; Richardson et al. 2021).

While the amount and reliability of automated acoustic sampling at the turbine nacelle may be higher than what can be acquired by manual sampling at ground level, we still consider manual and automated sampling at ground level or, preferably, at meteorological towers before the construction of turbines as vital in order to avoid sites with exceptionally high potential of bat collisions. Such sites may be near to important roosts or at migration passages. While mitigating bat collisions at these sites would probably be possible, the resulting loss in energy production may be substantial and render the site unattractive for developers.

APPENDIX S4

The correlation of acoustic activity and fatality rates of bats was analyzed using a dataset of 3517 fatality searches from 56 turbine-years (43 individual turbines) with a total of 94 dead bats found below turbines in Germany. A hierarchical model was used that accounts for a detection probability of less than one for fatalities (based on additional data on carcass removal rates, spatial distribution of carcasses and searcher efficiency, see e.g. Korner-Nievergelt et al. 2013). Beside acoustic activity the model included average wind speed, nacelle height and rotor diameter as predictors for bat fatality rates. Therefore, the regression line shows the partial effect of acoustic activity, i.e. the correlation between acoustic activity and fatality rates given average wind speed, average nacelle height and rotor diameter. The observations show a stronger correlation compared to the regression line because the high fatality rates on the top right of the figure (above the regression line) are from turbines with lower than average nacelle heights and the observed fatality rates below the regression line (green dots in bottom left part) are from turbines with larger than average nacelle heights. Dot colors distinguish sample years: Wind turbines sampled in 2007 and 2008 during RENEBAT I with a rotor diameter of 66 to 71 m; wind turbines sampled in 2012 during RENEBAT II with a rotor diameter of 66-70m; wind turbines sampled in 2015 during RENEBAT III with a rotor diameter of 101-127m. The black curve shows the fitted regression line, and the grey shading shows the 95 % credibility interval. Figure 1 was modified from figure 12, page 179 in Nagy et al. (2017).

APPENDIX S5

In a first step, the number of recordings should be referenced to a large data-set recorded during several years with the same calibrated detector system and methods (e.g. detector settings) at many turbines in similar environmental conditions and with a similar bat fauna. This will allow for rating the fatality risk as relatively high or low. More information can be extracted when the number of recordings is translated into dead bats per year, e.g. by searching for fatalities in parallel to the acoustic monitoring (Korner-Nievergelt et al. 2013). In order to increase the accuracy of fatality estimates, bat passes exposed to turbine operation should be differentiated from those that occur while rotors are idle, for example by including wind speed as an additional predictive variable (Peterson et al. 2021). Also, we would highly welcome more research using methods other than acoustic surveys to record bats at wind turbines in order to have independent test data.

However, even if we would know the number of bats being killed at a wind turbine exactly we run into another uncertainty on a different level: are 0.1, 1, 10, or 100 dead bats per turbine and year a problem, morally, legally, or ecologically speaking? This is still an ongoing debate in many countries and the answers differ considerably, with cumulative effects being only one of the uncertain factors (Lindemann et al. 2018). In Germany, the maximum number of bat fatalities permitted per year and turbine range from 0.5 to 2 individuals per turbine per year (Schuster et al. 2015) but these numbers are not based on scientific evidence.

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