# Wind turbines and bats in the Netherlands

## *Measuring and predicting*

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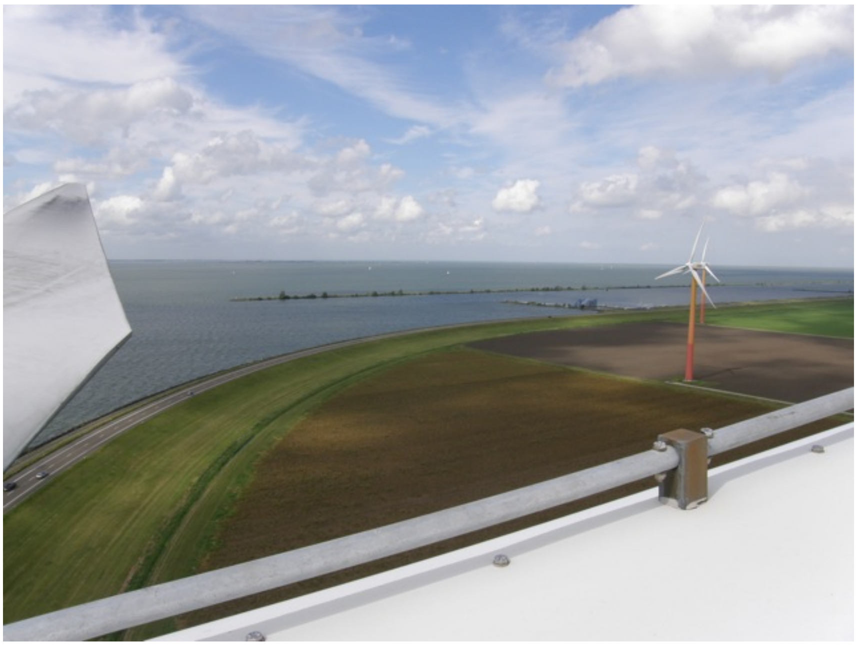

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## Summary

In order to enhance the process of planning and development of onshore wind energy, NL Agency – in cooperation with ENECO and NUON – assigned a study regarding bat fatalities in relation to wind energy. The study aligns to a predictive model developed in Germany.

The model allows estimating the real number of bat casualties based on standardised assessment of the number of casualties found around a wind turbine, wind speed and the acoustic activity of bats at nacelle height. The number of casualties can also be estimated by using acoustic activity and wind speed alone. This is particularly meaningful in situations where casualty searches are impossible, such as offshore wind farms. In addition, the model allows the development of algorithms for efficient curtailment of turbines. The turbines can be curtailed at those time intervals when the risk of bat fatalities is high and the loss of energy production is low. This results in a 80-90 % reduction of the number of casualties with less than 1% loss of energy production.

In the Netherlands, five wind farms were studied in the provinces of 'Noord-Holland', 'Flevoland' and 'Zuid-Holland'. The study focused on the autumn migration period between the beginning of August and the end of September 2012. At each wind farm, acoustic activity of bats was recorded at ground level and nacelle height of one turbine. Fatality searches were done at two or more turbines, with an total area equivalent to 2 times 100% searchable area within a 50 m radius, resulting in 25 searched turbines in the five sites. Protocols were developped for a standardised assessment of acoustic activity and the number of fatalities. The protocols include searcher efficiency and carcass persistence tests, estimation of searchable area and searchability classes, weather and landscape parameters. All protocols are described in Dutch in a separate report (Boonman *et al.*, 2013).

The common pipistrelle *(Pipistrellus pipistrellus)* showed the highest activity, followed by Nathusius' pipistrelle *(P. nathusii)* and the Nyctaloid group. The between site variation was relatively large, with differences between 2,5-30 recordings/hour for the common pipistrelle, 1,2-15 rec/h for Nathusius' pipistrelle and 0,5-1 rec/h for the Nyctaloid group. Activity at ground level was on average 15-20 times higher than at nacelle height. Myotids, such as the pond bat, were regularly recorded at ground level but only a few times at nacelle height. Bat activity at nacelle height was related to night time and several weather variables. The results show that bat activity can be predicted by using wind speed, night time and temperature. Bat activity is highest at low wind speed, during the first half of the night and during high temperatures. The effect of rain and wind direction is less pronounced.

Despite a searcher efficiency equal to or higher than in the German study, only two casualties were found: a Nathusius' pipistrelle and a common pipistrelle, both at sites in Noord-Holland.

The low number of fatalities found in our research demonstrates a low risk at the studied sites. This is positive for wind farm development. However, the low number in combination with the large variation in acoustic activity, lead to a lower

predictive power and larger statistical uncertainty for predictions based on the now available Dutch data.

Therefore estimates of casualties for the five wind farms are, as yet, not accurate. For all sites and searched turbines together, the estimate lies between 4 and 50 casualties (95% confidence interval). Depending on the used estimator, this leads to an average estimate of 14 or 18 casualties for the total of the combined 25 turbines searched at the study sites and within the study period (August/September). This demonstrates that the number of casualties can be estimated, but as yet, accuracy is low.

Based on found fatalities and acoustic activity at nacelle height, using the German model, the following predictions can be made:

A) Using only Dutch data for the correlations between found casualties, acoustic activity and weather in the model, the estimated number of actual fatalities for all wind farms combined, lies between 3 and 227 (95% confidence interval) with an average of 35.

B) Using the combination of German and Dutch data for correlations, and the Dutch data for estimates, the estimate lies between 83 and 253 casualties (95% confidence interval), with an average of 142.

C) Using the German data for correlations, and the Dutch data for estimates, the estimate lies between 77 and 259 casualties (95% confidence interval), with an average of 135.

These scenarios demonstrate that prediction works well, but working with the now available Dutch data, either the confidence interval is rather large, or overestimation for the Dutch sites occurs as a result of dominant effect of the German data.

In scenarios B and C the uncertainty, in the sense of 95% confidence intervals in relation to the average, is smaller. However, the estimate in scenario A is about a factor 4 lower. So the estimates based on only Dutch data have a higher uncertainty, but indicate a lower risk at the five now studied sites in the Netherlands, in comparison to the larger set of sites studied in Germany.

Using the German data for the correlations, whether or not complemented with the Dutch data (above scenarios A, B and C), estimates can be made for individual Dutch sites: A) For the individual sites average estimates lie between 1 (0-4; 95% confidence interval) and 14 (0-92), for scenario B) between 4 (0-9) and 20 (11-33) and for scenario C) between 13 (7-23) en 43 (20-89) fatalities.

Excluding the Flevoland site (with very high acoustic activity, but no found casualties) in the estimate based on just the Dutch data (scenario A), and thus correlating the Dutch casualties with lower acoustic activity, leads to an increase of estimated fatality risk by a factor 2.

**General conclusions**

A standardised assessment of all relevant parameters proved to be possible using the protocols.

Found carcasses were very few (two) and the acoustic activity showed a large variance. The explanatory power of landscape parameters from Dutch sites is poor since only five wind farms were studied with rather similar landscape parameters.

Fitting and aligning data from the five Dutch wind farms to the German model resulted in workable estimates. Due to the comparatively small volume of Dutch data, the German data, for now, will have a large impact on the generated estimates, leading to a lower accuracy and overestimation of fatalities or collision risk for the Dutch situation. Generating estimates based on only Dutch data is possible, but as yet is imprecise. Estimates of collision risk based on only the Dutch data are possible, but they still have a large variation and are thus not very accurate.

The protocols and models work well, but due to the small Dutch sample size and large variance, estimates and predictions are too imprecise. It is, therefore, of utmost importance to enlarge the number of study sites, and to use the protocols for assessing fatalities, acoustic, weather and landscape data in the Netherlands. These data should be made available, to be able to use them in improving the reliability of the predictions with the model.

Overall, the protocols and models from the German project were tested with positive results. However, the estimates and predictions presented in this study lack the precision required to accurately determine the number of fatalities for the studied wind farms. Nevertheless, based on the now available data, bat fatality risk seems low for the studied wind farm sites.

# 1 Introduction

***Innovation agenda 'on shore wind turbines'***

In assignment of the Ministry of Economic Affairs the agency 'NL Agency' is managing the Innovation Agenda Energy, an essential part of this is the agenda regarding 'on shore wind turbines'. The national governments ambition is to remove barriers that the application of wind energy might encounter and to enhance and speed up processes of innovation in the different sectors relevant to this policy.

With the current speed of development, the ambitions for on shore wind energy (6.000 MW in 2020) will not be met. Therefore a main goal of the Innovation Agenda for on shore wind energy is to release the potential for on shore wind energy. This potential can be interpreted as the amount of MW that could be realized, as well as the number of possible sites for wind farms, but also as an increase in the (administrative) basis in society, efficient forms of cooperation and effective planning processes.

***Bats and wind energy: problems in the interaction***

Wind turbines affect flying animals: birds and bats. In recent decennia the possible negative effect on birds has been the topic of an extensive number of studies (Witte & van Lieshout 2003, Brenninkmeijer & van der Weyde 2011). Potential effects on bats (Arnett *et al.* 2005), however, have seen much less studies in the Netherlands (Limpens *et al.* 2007). All species of bats in the Netherlands are strictly protected, in concurrence with their place on appendix IV of the European Habitats Directive. Since the introduction and application of the Flora and Fauna Act since 2002, and to a lesser intent the Nature Protection Law since 1998 (both implementation of the European Habitat Directive in our domestic legislation), gaps in our knowledge are resulting in delays in the planning process.

One of the most important issues is the current inability to provide a good quantitative estimate of expected fatalities for a wind farm development or upgrading. This often leads to extensive ad hoc research, and uncertainties in the planning process and whether a planning permit will be achievable. As a result of the lack of concrete quantitative data, a worst case scenario is often mandatory for the planning process. Extra costs, delays and uncertainty thus hamper the development or upgrading of wind farms, and leaves part of the potential of (on shore) wind energy unexploited.

Filling the gaps in our knowledge regarding the effects of wind turbines on bats, will lead to more effective planning processes and a more complete exploitation of the potential of wind energy.  In addition it helps developers as well as planning authorities to full-fill the obligations deriving from nature legislation.

Generic quantitative research is needed to substantiate how and which landscape parameters determine fatality risks for bats on different sites, which measures might mitigate fatality risk, and which measures might work under which circumstances. Negative effects might be (partially) mitigated through site selection and/or targeted after construction measures. Availability of quantitative insight in these relations will facilitate the spatial planning process.

***Knowledge available in the Netherlands***
Recent research regarding bats and wind turbines in the Netherlands has predominantly been done on the level of the individual development project. Systematic fatality searches have been carried out on a very limited scale (Boonman *et al.* 2011).

In 2007 in a study assigned by the predecessor of NL Agency, Zoogdiervereniging (Dutch Mammal Society) has collated internationally available information on bats and wind turbines through an extensive literature search (Limpens *et al.* 2007). This information was interpreted in relation to the situation in the Netherlands. The study showed that although no data or knowledge on fatalities were known from the Netherlands, it was very probable that effects on bats occur. At the same time it was clear that site selection might provide chances to mitigate effects, and might make coexistence of wind energy and bats a possibility, as was also concluded by Winkelman *et al.* 2009.

The current study is the first Dutch study which is set up broader and more fundamental, including the development of standard or best practice methods.

***Research and knowledge abroad***
In different European countries, as well as in the USA, Canada and Australia, studies on the possible negative effects of wind turbines on bats, assigned by the authorities and conducted by universities, research institutes and consultancies are available.

Besides in the USA, this is especially the case in Germany where approximately the same species as in the Netherlands occur. In recent years the German Federal Ministry for Environment allowed for basic and fundamental research into the effects of wind turbines on bats (Brinkmann *et al.* 2011). Follow-up research by the same research group is on-going.

In this research a statistical relation between different types of parameters – acoustic activity at ground level and at turbine height, the found and estimated numbers of fatalities, season, weather conditions and landscape parameters – could be established. On the basis of such data and correlations it is expected to be possible to estimate potential fatalities on the basis of acoustic activity and landscape, and to predict and advise when and how mitigation would be most effective. This approach might provide relatively simple and effective means of predicting risks and quantifying risk factors.

***Advancing research in the Netherlands***
The described “state of the art” research in Germany has partially been targeting landscape types and bat species groups that are similar to those in the Netherlands. That part of the German data and its modelling may be seen as applicable on the Dutch situation. To be able to adapt the German data and predicting model for use in the Netherlands, additional basis research needs to be done to ‘calibrate’ and adjust the information, the model and its applicability for the Netherlands.

The current report describes the testing and adjusting of the German method and model(s) (Korner-Nievergelt *et al.* 2011a, b, 2013) to predict risk and to advice effective mitigating measures, in a number of test localities in the Netherlands. This is done to make the new knowledge and model(s) applicable in the planning process for wind energy the Netherlands.

***Cooperation***

There are many stakeholders regarding the potential problem of windturbines and bats, such as the Dutch Ministries of Economic Affairs and Infrastructure and Environment, provinces, as well as the wind energy industry, research institutes and Consultancies. It was and is of great importance that available expertise in this field is combined, and that the much needed research is done in cooperation. Therefore both the research proposal and the actual study was developed and done in cooperation between the Dutch Mammal Society and Bureau Waardenburg. The Dutch Mammal Society has extensive experience with the study and ecology of bats. Bureau Waardenburg has extensive experience in the field of birds and wind energy, along with extensive experience in the field of bats.

It is of essential importance to do the research in a standardised statistically valid approach. Therefore this current research project is done in cooperation with the German and Swiss researchers involved in the inspiring project in Germany, Frinat (Dr. R. Brinkmann) and Oikostat (Dr. F. Korner-Nievergelt). They participate in the set up of the program, as well as in the analyses, modelling and interpretation of data.

The research project was primarily funded with a grant from NL Agency. The actual fieldwork, with registration of acoustic activity and fatality searches, was done in 5 different existing wind farms. Cooperation was sought with operators of these sites (see table 1), NUON (contact: H.J. Kouwenhoven) and ENECO (contact: C. van den Hoven) for both on site practical work, as well as co-funding of the project.

*Table 1 Wind farms and turbines equipped with ultrasound acoustic equipment*

| wind farm | proprietor | Location | turbine number acoustic equipment | turbine type | rated power | tower height | rotor diameter |
|---|---|---|---|---|---|---|---|
| Jaap Rodenburg | Nuon | Almere | A3 | Vestas V66 | 1,65 MW | 67 m | 66 m |
| Waterkaaptocht | Nuon | Wieringermeer | 4 | Vestas V66 | 1,75 MW | 78 m | 66 m |
| Waardtocht | Nuon | Wieringermeer | 2 | Vestas V66 | 1,75 MW | 78 m | 66 m |
| Burgervlotbrug | Eneco | Alkmaar | 7 | Vestas V52 | 0,85 MW | 65 m | 52 m |
| Herkingen | Eneco | Goeree-Overflakkee | 2 | Neg Micon 80 | 2,75 MW | 80 m | 80 m |

| wind farm | Latitude | Longitude | X-coordinate | Y-coordinate |
|---|---|---|---|---|
| Jaap Rodenburg | 52°22'30.90"N | 5° 7'25.90"O | 137.067 | 487.511 |
| Waterkaaptocht | 52°52'40.54"N | 5° 2'29.40"O | 131.729 | 543.475 |
| Waardtocht | 52°48'22.23"N | 4°55'27.48"O | 123.794 | 535.520 |
| Burgervlotbrug | 52°46'02.80"N | 4°41'34.60"O | 108.147 | 531.347 |
| Herkingen | 51°42'31.64"N | 4° 6'46.61"O | 66.935 | 414.088 |

# 2 Project aims

## 2.1 General project aims

The general aim of the project is to generate knowledge on the effects of wind turbines on bats, which will facilitate the planning process at wind farm development. This approach will also contribute to the conservation of bats.

This project aims at:

- developing and enhancing possibilities to predict fatality risk on the basis of risk factors such as, landscape parameters, weather conditions and season,
- and enhancing the possibilities of site specific advice for mitigation, such as a curtailment at high risk periods,
- through standardised assessment of relevant risk factors and fatalities at specific sites,
- modelling the relation between risk factors and fatality incidence, based on Dutch data.

The prediction is based on German models, which have been developed by analysing the acoustic activity at 72 turbines in 36 wind farms (of which 6 wind farms in northern lowland landscapes), as well as casualty searches at 30 turbines in 15 wind farms. These 15 wind farms were equally distributed over landscape types (Brinkmann *et al.* 2011, Korner-Nievergelt *et al.* 2011, Korner-Nievergelt*et al.* 2013).

On short term such models are necessary to be able to estimate the real numbers of fatalities, based on standardised assessment of acoustic activity, fatality searches and other relevant parameters. Or e.g. to estimate fatalities based on acoustic activity alone for sites where fatality searches are not possible. In this study pooling with German data (Brinkmann et al, 2011) will be necessary to enhance our data on 5 wind farms.

Gathering and pooling standardised assessment data in the Netherlands and other countries in Europe will (step by step) enhance the possibility of generating estimates of fatalities based on acoustic activity data from ground level.

At the same time, the project aims at producing standards for

- assessment of base data i.e. standardized statistically valid methods for fatality searches and assessment of acoustic activity and of risk factors, and
- the resulting extrapolation of results and risk assessment regarding bats, in relation to the development of new on shore wind energy sites will be established and formulated.

The standards build on, and adhere to, the approach in Germany (Brinkmann *et al*. 2011), as well as the resolutions and Guidelines produced under EUROBATS (e.g. Doc.EUROBATS.AC18.6 IWA, 'Wind Turbines and Bat Populations, Rodrigues *et al.* 2008). Using such standards in future assessment of fatality risk in the Netherlands, will be the basis for enhancement of the model.

## 2.2 Scope of project

Research into fatalities of bats at wind turbines and the factors influencing this risk, is relatively recent. Many basic data are not yet available. As a result, broad and fundamental research would be necessary and meaningful.

Different factors may be expected or are known to influence the numbers of fatalities or the spectrum of bat species in or near wind farms, such as:

- geographic locality in the Netherlands, and
  - the resulting average wind speed
  - and the resulting abundance of different bat species;

- the surrounding landscape / landscape parameters in distances of hundreds or thousands of meters, among which proximity to:
  - higher vegetation (bushes and trees),
  - build structures,
  - open water;

- the natural physical geographical (FGR) area in the Netherlands, such as: lower Netherlands versus higher sandy soils; coastal areas, inland areas, open areas versus areas with higher vegetation structures (forest, tree lanes, hedges, et cetera);

- the landscape in relation to habitats: used for seasonal migration (coast, shores, dykes, linear landscape structures); used as roosting or feeding grounds during migration (traditional mating areas); used as swarming sites during mating / migration season; used as feeding rounds in summer; used as daily commuting routs between roosts and feeding grounds; and/or used as summer or maternity roosts;

- season and weather conditions, in relation to phenology and behaviour of bats and their insect prey;

- characteristics of the wind turbines, such as:
  - turbine hub height,
  - rotor diameter,
  - cut in speed,
  - average duty cycle / hours of production,
  - possible other factors such as number or shape of turbine blades.

Given the available time and budget, we targeted the current research on the enhancement and development of a model to estimate fatality risk and advise mitigation, resulting in a focus on, and limitation to those factors (landscape, season, weather, turbine characteristics) relevant for the model. We focus on data that allow statistical linking to the model developed in Germany (Brinkmann *et al.* 2011), for those German landscapes similar to the open lowlands of the Netherlands.

## 2.3 Focus and limitations

From literature (Brinkmann *et al.* 2011, Jones *et al.* 2009, Limpens *et al.* 2006, Winkelman *et al.* 2009) it is clear that a peak in fatalities occurs in the period between end of July – beginning of October, during mating season and the migration from summer to winter habitats.

Other possible relevant periods for fatality risk, in spring migration (approximately end of March – end of April), as wells as maternity season (end of May – beginning of July) have received less attention.

Given the available time and budget, the fieldwork (measurement of acoustic activity on ground level and on turbine height, searches for fatalities, assessment of landscape data) was focused on the period of autumn migration, and performed fieldwork from the end of July until the end of September.

- There is variation in fatality risk in different parts of the season, as well as and related to different functions of the landscape for bats such as commuting between feeding ground and roosts, feeding, swarming and migration.
  → This research project focusses on fatality searches in the most important migration period in the autumn, the period in which based on studies abroad fatality risk is highest.

- There is variation in fatality risk in different landscapes. Site selection which would allow us to compare different landscapes and/or landscape structures would have been preferred. We were, however, dependent on such sites as where the site operator could grant access.
  → The current project could not focus measurement of acoustic activity and fatality searches on sites that would have allowed for comparing different landscapes.
  → The current project focusses on the typical open landscape in which most wind farms in the Netherlands are situated and in which, given the current policy for development of on shore wind farms, development of new wind farms is most likely to occur.
  → Thus the current project focusses on the Dutch natural physical geographical area (FGR) ‘laagland’, equal to the German ‘Naturraum Norddeutsche Tiefebene’, which in the Netherlands is the lowland landscape towards coast of the North sea.

- There is variation in fatality risk, or variation may be expected, in relation to different types of wind turbines. Again we were dependent on such sites as where the site operator could grant access.
  → As far as possible this research project focusses on turbine types which, given the current policy, are most likely used for re-powering and new on shore development (turbine axis 60-80 meter or higher, power 2 MW or more).

In this way the project focussed primarily on the influence of seasonal and weather factors, and bat activity, and the resulting (differences) in fatality risk, in the context of the typical lowland landscape. Given the restrictions of the sites available for research, all other potentially important factors were kept as constant as possible to allow for solid statistical analysis.

However relevant, the following elements were not taken into account in this research:

- Wind farms in development (no before and after construction comparison),
- Bat populations (relevance of the wind industry induced mortality rate on local and larger bat populations, the ecological and legal definition of the population which might be effected, population size)
- Geographical patterns in bat activity,
- Specific behaviour (attraction to, disturbance by, migration, use echolocation near turbines et cetera),
- Effect of turbine and rotor blade dimensions and characteristics (turbine height, type, cut-in speed et cetera) on bat collision risk.
- Experimental testing of effectiveness of mitigation measures
- Monitoring of fatalities or effectiveness of mitigation on the longer term.

# 3 General set up of the research project

## 3.1 Introduction

The research project and field work, its general set-up and research protocols, were developed in cooperation between the Dutch Mammal Society and the consultancy Bureau Waardenburg, and in close consultation with the expert from the German project Dr. R. Brinkmann, as well as the companies exploiting the specific wind energy facility.

The project span was about 1,5 year, starting with contacts with several companies, selection of sites and general preparation in spring 2012, comparative fieldwork in autumn 2012, and analysis of data and reporting in late autumn 2012 to spring 2013. Targeted briefing of the energy companies, consultancies and authorities will take place in autumn 2013.

The following parameters were assessed:

- Fatality numbers (incl. search efficiency per person, carcass persistence)
- Bat activity at ground level and at turbine level
- Weather and landscape parameters

A minimum of five existing sites with wind turbines were selected. Access and cooperation with the companies exploiting these sites, as well as landscapes fitting the profile for new developments in the Netherlands, were used as the main selection factors.

Fatality searches beneath turbines were done at a minimum of two turbines per wind energy site (also see chapter 5), where an optimization between probability of detection, searchable area and available hours was sought. Search locations or specific turbines at the site, were not selected randomly, rather turbines were selected where detection of fatalities was expected to be high.

At five sites, at one of the two turbines selected for fatality searches, bat activity registered as acoustic activity on an automatic bat detector (microphone, Anabat bat detector, laptop and UTM router), was measured on ground level and turbine height.

The general research set up, and specific standardized and statistically valid research protocols (see Boonman *et al.* 2013) were developed for:

- Acoustic monitoring of activity, including technical equipment and set up,
- Fatality searches, including assessment of possible search biases (size and visibility classes of searchable area per turbine and site, carcass persistence rate per wind farm, search efficiency per person),
- Assessment of all relevant landscape parameters (distance to surrounding key habitats for bats; area of habitats in different radiuses; natural physical geographical area (Dutch FGR).

The fieldwork, acoustic monitoring of activity, fatality searches and tests of carcass persistence and search efficiency per person, was performed between the beginning of August until the end of September 2012.

Technical preparation and installation of the equipment for registering acoustic activity, at ground level and in the turbine (for detailed description see chapter 4) was done by Bureau Waardenburg with the aid of Dutch Mammal Society.

Fatality searches (for detailed description see chapter 5) were done by Dutch Mammal Society at the wind farms Burgervlotbrug-Alkmaar and Jaap Roodenburg-Almere, and by Bureau Waardenburg at Waterkaaptocht-Wieringermeer, Waardtocht-Wieringermeer and Herkingen-Goeree-Overflakkee. Fatality searches at a specific site were always done by the same fieldworker. Raw data from individual search events per site were collated by Dutch Mammal Society.

The field tests of carcass persistence per site and searcher efficiency per fieldworker (for detailed description see paragraph 5.5 and 5.6) were prepared by Dutch Mammal Society and performed per individual fieldworker and site. Assessment and classification of searchable area was done by the fieldworker per site and per search round. Raw data per fieldworker and site were collated by Dutch Mammal Society.

Relevant landscape parameters (distance to surrounding key habitats for bats; area of habitats in different radiuses; natural physical geographical area (Dutch FGR) were calculated by GIS specialists at Bureau Waardenburg using the European CORINE land use database and relevant classes used in the German project (Brinkmann *et al.* 2011).

### 3.2 Steps in analysis

Analyses of acoustic raw data to species or species group level, was done in cooperation between Dutch Mammal Society and Bureau Waardenburg.

The further analysis of acoustic data focussed

- on the functionality of equipment,
- activity levels in terms of occurrence of bats in general and determinable species or species groups,
- differences between sites and recordings at ground or nacelle level,
- and correlations between activity levels and period in the night and season, wind speeds, temperature and wind direction.

Data on fatalities including carcass persistence and searcher efficiency were collated by Dutch Mammal Society.

These base data are necessary to test whether the German model(s) can be applied to the Dutch situation.

Therefore, all data on acoustic activity, carcass searches and weather were then statistically analysed by Dr. F. & Dr. P. Korner-Nievergelt, using the methods developed in the German project (Brinkmann *et al.* 2011).

The target was testing whether fatality risk could be predicted based on found carcasses alone, on a combination of carcasses and acoustic activity, and on acoustic activity alone.

Where necessary, data from the German project were used to test whether this would enhance precision of the results. This was on forehand expected to be necessary for the estimation of fatality numbers.

# 4 Acoustic monitoring of bat activity

## 4.1 Introduction

Bats emit high frequency sound for navigation and ranging (sonar). These vocalizations of bats can be detected and recorded by bat detectors. The detectability differs between species (e.g. Limpens & Roschen 1996, 2002). The actual number of bats present in the area cannot be determined by acoustic monitoring. Nevertheless, the number of recorded bat calls or the number of bat files can be used as a relative measure of bat activity. This level of activity can be measured during a whole range of different weather conditions, seasons or in different locations to determine the bats' preferences.

In the last decade several systems / detectors have become available for continuous registration of ultrasonic sound. This has opened up possibilities for the acoustic monitoring of bats from locations that are not easily accessible, such as the nacelle of wind turbines. As wind speed (and sometimes temperature) is measured at the nacelle of wind turbines, bat activity levels can precisely be related to the environmental conditions. In a large study in Germany, a significant correlation between bat activity at nacelle height and the number of fatalities was found (Korner-Nievergelt *et al.* 2011). Acoustic monitoring thus provides accurate information about the conditions during which fatalities are likely to occur. Furthermore, in offshore wind farms or wind farms situated in high and dense vegetation fatality searches cannot (properly) be done. In these locations acoustic monitoring is the only method to determine the possible impact of wind turbines on bats.

## 4.2 Method

Acoustic monitoring was carried out in five wind farms (figure 4.1) by using Anabat SD2 detectors (Titley). The used method is in line with the approach in Germany (Behr *et al.* 2011a, b). At each wind farm one bat detector was placed at ground level and one at the nacelle height at a single turbine. The detectors were calibrated by I. Niermann to equalize the sensitivity of the detectors (level 4-5; Behr *et al.* 2011a).


*Figure 4.1 Locations of the five wind farms in this study.*

***Monitoring at nacelle height***

Given the selection of turbines with possibilities for carcass searches, in each wind farm a "silent" turbine was selected from which bat activity was recorded. Some rotor blades produce high frequency sound while moving because of light impairment of the tip or dirt that has accumulated there. It is usually only present in one of the three blades of a rotor. This sound can be within the frequency range of the bats' echolocation signals and can thus hamper the detectability of bats.

At the nacelle, the microphone of the Anabat was placed through a hole in the nacelle floor directing downwards. The detector thus remained indoors with only the external surface of the microphone protruding through the floor (figure 4.3). These holes were pre-existing (Vestas V66) or need to be drilled (NegMicon 80, Vestas V52). As the nacelle directs itself against the wind, the back of the nacelle is located at the leeward side of the tower while the front is at the windward side of the tower. The hole in the nacelle floor where the detector was installed was situated in front between the rotor and the tower (figure 4.2). Bats were thus recorded in the area where fatalities might occur. Cables between the Anabat and the microphone were not used because of their sensitivity to electromagnetic radiation.

The Anabat was connected to a battery and a laptop. The Anabat files were saved on the hard disk of the laptop as well as on an USB stick. The laptop was connected to the Internet by using a router and antenna. The Internet connection allowed us to check whether the Anabat operated properly but was generally too weak to transfer all the files from the previous night.

*Figure 4.2 Hole in the nacelle floor between the rotor and the tower where the equipment was installed.*

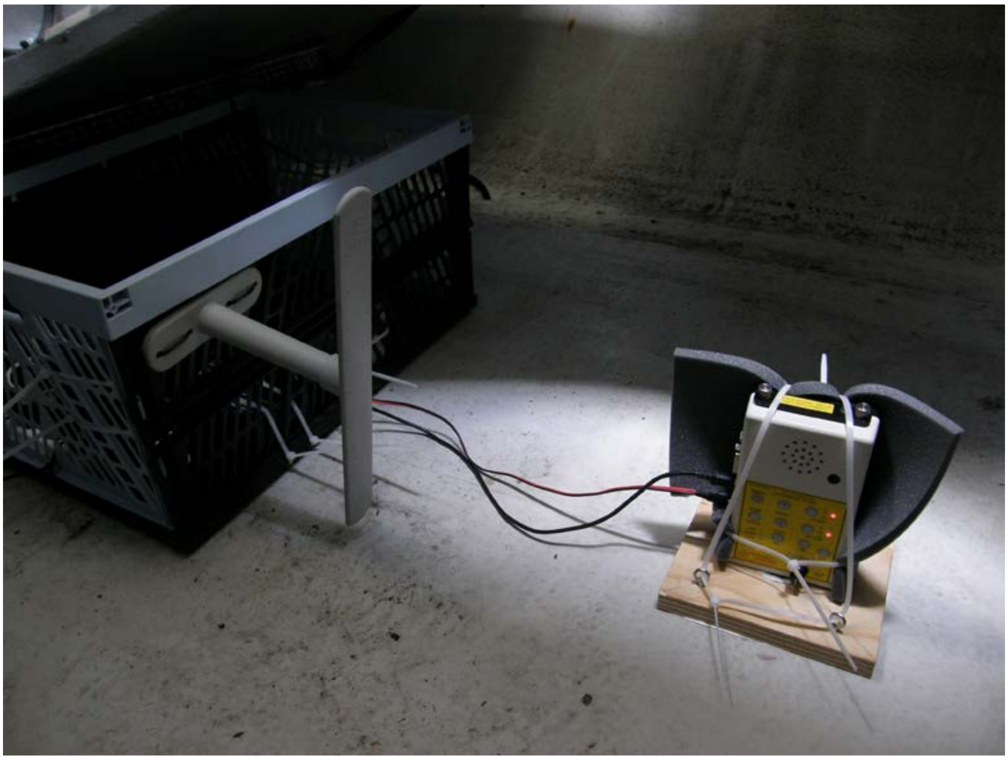

*Figure 4.3 View from the installed bat detector seen from the inside of the nacelle.*

*Figure 4.4 The bat detector situated at ground level.*

***Monitoring at ground level***
The Anabat at ground level was placed in a metal box and was powered by a battery. In the metal box, a small opening corresponding to the size of the microphone was made. The box was placed underneath the stairs of the turbine's entry with the microphone directed away from the mast (figure 4.4).
The Anabat files were stored on a 4 GB Compact Flash card. This card was changed every three days together with the battery.

***Processing of Anabat files***
All Anabat files were scanned with the program Analook (Titley) using the filters developed by Behr *et al.* (2011a) with a few modifications of the "Pipistrellus nathusii" and "Nyctaloid" filter. "Myotis" and "Myotis dasycneme CF" filters were developed in this study (Appendix I). ANL list was used as output format. The frequency division system of the Anabat does not allow identification of most nyctaloids and myotids. A list of scientific and English species names is presented in appendix VII. Filters identified the following species and groups of species:

**All bats**: the most important filter. Used to distinguish between bat sounds and noise.
**Nyctaloids**: group of species consisting among others *Nyctalus noctula, Eptesicus serotinus* and *Vespertilio murinus*.
**Nyctalus noctula CF**: typical qCF calls of the noctule bat of 16-20 kHz.
**Pipistrellus pipistrellus**: Common pipistrelle.
**Pipistrellus nathusii**: Nathusius' pipistrelle.
**Pipistrellus pygmaeus**: Soprano pipistrelle.
**Myotis**: group of species consisting among others *Myotis daubentoni* and *Myotis dasycneme*
**Myotis das CF***:*typical qCF calls of pond bat of 10-18 ms and $F_{max}$ 35 kHz.

The "Nyctaloid" filter picked up all nyctaloid bat calls including the qCF calls of the noctule bat. The "Nyctalus noctula CF" filter did not identify all noctule bat calls. Therefore it can be used as an indication of the presence of noctule bats, but not as a quantitative parameter. In the same manner the "Myotis dasycneme CF" filter only identifies the typical qCF calls of the pond bat, which can be used as an indication of the presence of this species, but not quantitative. The "Myotis" filter picked up only FM myotis calls. The sum of all myotids was defined as the sum of both filters counting the individual files with a positive output of both filters just once.

All output files were copied to a single excel file. Because moving rotor blades and wind make background noise, nights without Anabat files are practically non-existing when the detector is operating properly. The Anabat was considered non-operational when no recordings were made for more than 6 hours or when the status file indicated that the detector stopped working. In this study we did not use a device that produces ultrasonic signals, such as a Marderschreck[1], to determine the non-operational time of the detector. In the German study, a Marderschreck is only operating twice a day at the beginning and end of the night for one minute (pers. comm. R. Brinkmann). If regularly used throughout the night, such devices can potentially attract or deter bats and have been even tested to reduce the number of fatalities at wind turbines (Arnett *et al.* 2011).

Files with a positive filter output indicating the presence of bats, while the "all bats" filter did not detect any bats were described as 0 bats. Double identification (different filters identified the same bat call) was reduced by applying a set of rules (Appendix II). All files containing soprano pipistrelle and all files with myotids at nacelle height were checked manually. At the nacelle height of the turbine at Jaap Rodenburg, the all bats filter picked up noise as bat calls. This noise consisted of constant frequency pulses of approximately 16 kHz resembling qCF pulses of the noctule bat. All the files with a positive all bats output were checked manually for this location.

For each period of ten minutes the number of files containing bats was determined. The number of bat files occurring per ten minute category was subsequently linked to the weather conditions in the same time frame. To eliminate invalid zero observations (files indicating the absence of bats when bats could not have been detected) all daytime files were removed. Sunrise and sunset time of De Bilt (centre of the Netherlands) was used for all wind farms for practical reasons. Within the Netherlands the moment of sunrise/sunset differs up to a few minutes depending on the geographical location but this seems negligible to a night length of more than 6 hours. Night-time weather files for ten minute periods where the Anabat was non-operational were not used.

***Weather data***

Wind direction, wind speed and temperature are measured at the nacelle of wind turbines and are incorporated in the SCADA system of wind turbines. Weather data of the turbines where the equipment was installed was provided by Nuon and Eneco. For each period of ten minutes an average wind speed, wind direction and temperature is given.

Wind speed data was available for all wind turbines. Wind direction was missing in Herkingen and Waardtocht. For Waardtocht, wind direction of the neighbouring wind farm Waterkaaptocht was used instead. For Herkingen wind direction of the nearest KNMI weather station was used.

Precipitation is not measured at wind turbines. Precipitation data was used from the nearest KNMI weather station. These stations are situated up to 30 km away from the wind farm. Weather is measured close to ground level at these stations and presented as hourly averages.

***Statistical analysis***

Here, statistical analysis of the acoustic data, assessed at the Dutch sites is discussed. We used generalized linear mixed models (GLMM) to predict the number of bat calls per ten minute interval from date, time, and weather. The Poisson error distribution was assumed and the logarithm link function used. We included the wind farm as a random factor to account for between-wind farm variance in overall bat activity. In the full model, we included the following fixed effects: proportion of the night up to the 5th polynomial (*i.e.* time in relation to sunset and sunrise), day of the year up to the 2nd polynomial, wind speed up to the 2nd polynomial, the sine and cosine of wind direction as well as the sine and cosine of twice the wind direction. Since we expected that the influence of wind direction on bat activity

[1] Marderschreck: a high frequency signal to warn of beech martens *(Martes fiona).*

might differ between different locations due to differences in topography, we allowed the effect of wind direction to vary between the wind farms. We tested whether overdispersion was present by including an observation level random factor (Gelman and Hill, 2007). Whether the overdispersion parameter was important, was assessed by the BIC (Burnham and Anderson, 2002). Then, the following parameters were stepwise, in the given order, deleted from the model if they were not important according to the BIC: 1. wind farm-specific second order sine and cosine of wind direction, 2. wind farm-specific sine and cosine of wind direction, 3. 5th polynomial of proportion of night, 4. second order of sine and cosine of wind direction. We expect all other terms to be biologically important. For this, and to prevent overestimation of effect sizes (Whittingham *et al.,* 2006), these terms remained in the model independent of their significance. To test whether a zero-inflation is present we used posterior predictive model checking (Gelman *et al.*, 2004). Temporal autocorrelation is measured but not accounted for here. Since unaccounted autocorrelation results in the underestimation of uncertainty, we do not give uncertainty estimates.

The R-code for the analyses is given in Appendix III.

To test whether bat activity at nacelle height can be predicted by bat activity at ground level, bat activity at nacelle height level was related to bat activity at ground level for Jaap Rodenburg by using a GLM negative binomial regression model. The total number of bat recordings per night was used as a measure of bat activity. A poisson regression model showed a poor fit because of over-dispersion of the data. Apart from bat activity at ground level and nacelle height, night length and the average wind speed was included in the negative binomial model.

### 4.3 Results acoustic monitoring

***General results***

During the study between the 2nd of August 2012 and the 1st of October 2012 the ten Anabats recorded 33121 files with bat calls at ground level and 2303 files with bat calls at nacelle height during 2576 and 3218 nightly operational hours respectively.

*Table 2 Number of operational hours and % of non-operational time of the bat detectors during the study.*

| | Number of operational hours (night) | | % non operational time (night) | |
|---|---|---|---|---|
| | ground | nacelle | ground | nacelle |
| Jaap Rodenburg | 487 | 533 | 27 | 20 |
| Waardtocht | 469 | 663 | 29 | 0 |
| Waterkaaptocht | 645 | 663 | 3 | 0 |
| Herkingen | 407 | 617 | 39 | 7 |
| Burgervlotbrug | 568 | 742* | 14 | 0 |
| Total | 2576 | 3218 | 22 | 5 |

*This specific detector has been recording until late into October, longer than the actual research period, i.e.. in the calculations, only the 663 hours from the regular research period were used.

Non-operational time was highest at ground level with 22% of the total time. At nacelle height the detectors performed better with only 5% non-operational time.

Jaap Rodenburg (Almere) ground level had the highest bat activity with 44 bat files per hour (table 3). Activity in the other wind farms was 5-20 times lower. The most frequently recorded species were common pipistrelle (*Pipistrellus pipistrellus*), followed by Nathusius' pipistrelle (*Pipistrellus nathusii)* and the nyctaloid group. Typical calls of the noctule bat were recorded at every wind farm both at ground level as at nacelle height. Myotids were usually only found at ground level in relatively low numbers (<10%). At ground level pond bats were registered at all locations. The soprano pipistrelle was not recorded in any of the locations.

*Table 3 Number of files with bats / operational hour (night).*

| | allbats | nyctaloid | Nyc noc CF | Myotis | Myotis das CF | Myotis total | Pip nath | Pip pip |
|---|---|---|---|---|---|---|---|---|
| Jaap Rodenburg ground | 43.67 | 10.61 | 2.42 | 0.20 | 3.87 | 3.95 | 15.95 | 33.83 |
| Jaap Rodenburg nacelle | 3.75 | 2.36 | 1.15 | 0.01 | 0.01 | 0.01 | 0.27 | 1.22 |
| Waardtocht ground | 4.08 | 0.49 | 0.00 | 0.17 | 0.02 | 0.18 | 1.19 | 2.62 |
| Waardtocht nacelle | 0.13 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 | 0.08 |
| Waterkaaptocht ground | 2.38 | 0.63 | 0.00 | 0.05 | 0.02 | 0.06 | 1.41 | 0.84 |
| Waterkaaptocht nacelle | 0.08 | 0.08 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Herkingen ground | 8.66 | 0.60 | 0.01 | 0.51 | 0.11 | 0.59 | 2.16 | 6.59 |
| Herkingen nacelle | 0.17 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 | 0.09 |
| Burgervlotbrug ground | 8.59 | 2.12 | 0.59 | 0.22 | 0.11 | 0.29 | 3.78 | 4.02 |
| Burgervlotbrug nacelle | 0.07 | 0.03 | 0.02 | 0.00 | 0.00 | 0.00 | 0.02 | 0.02 |
| Total ground | 12.86 | 2.82 | 0.59 | 0.21 | 0.78 | 0.95 | 4.76 | 9.01 |
| Total nacelle | 0.72 | 0.42 | 0.21 | 0.00 | 0.00 | 0.00 | 0.07 | 0.24 |

There are marked differences in the species composition between ground level and nacelle height (see below) and between wind farms. Species composition is shown for each wind farm in appendix IV. At Waterkaaptocht, Nathusius pipistrelle was more common than common pipistrelle at ground level and the percentage of the nyctaloid group was highest at Burgervlotbrug.

***Ground level versus nacelle height***

Bat activity was much higher at ground level than at nacelle height. For all bat species together bat activity was 15-20 times higher at ground level (table 3). Bat activity in most wind farms was too low to correlate the number of bat recordings at ground level with those at nacelle height. In Jaap Rodenburg, the wind farm with the highest bat activity, nacelle height activity could be related to bat activity at ground level when the sum of all recording per night is used (figure 4.5).

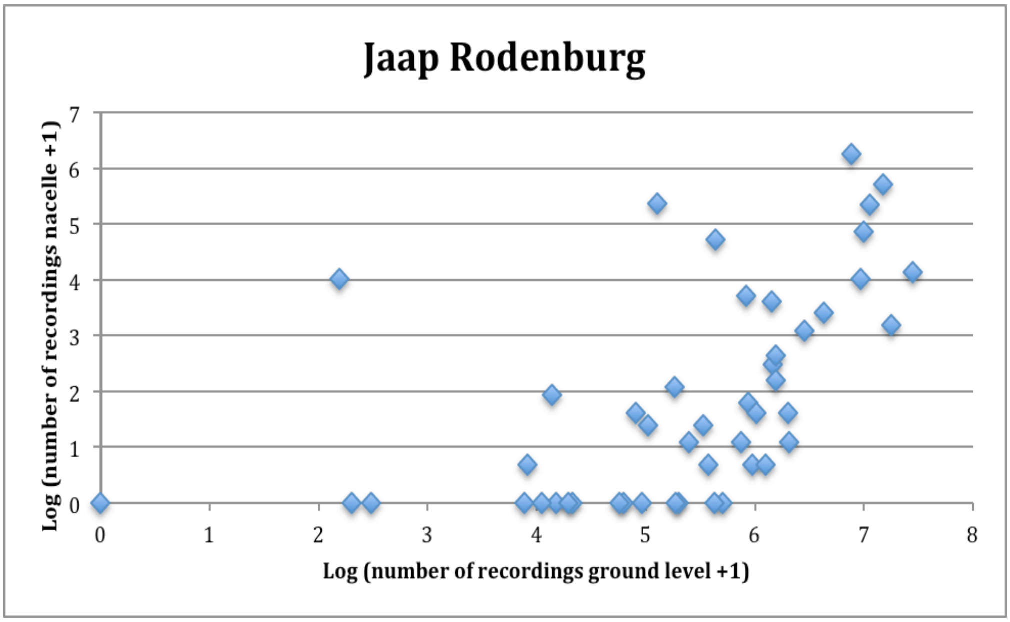


*Figure 4.5 Correlation between the number of bat recordings per night at ground level and at nacelle height (n=47). The natural logarithm was used for ease of presentation.*

During nights with high bat activity at ground level the activity at nacelle height was also elevated. If no bats were recorded at ground level, none are recorded at nacelle height.
The variance of the number of recordings is larger than the average, meaning that over-dispersion is present. The results of the negative binomial regression model are shown in table 4. If 'all_bats_ground' increases with a hundred bat recordings, the mean 'all_bats_nacelle' increases by 0,1. Two models were tested to predict bat ,activity at nacelle height. One model with wind speed and bat activity at ground level and another with just wind speed. Both models are significant with similar AIC values (314 with d.f 4 and 3 respectively). However, in the model with both wind speed and bat activity at ground level, bat activity at ground level is not significant (table 3).

*Table 4. Results of the negative binomial regression model relating bat activity at nacelle height with wind speed and bat activity at ground level.***= significant, n.s.= not significant.*

| | Estimate | Std. Error | z value | Pr(>\|z\|) |
|---|---|---|---|---|
| (Intercept) | 6.9 | 1.1 | 6.5 | <0.001 *** |
| all_bats_ground (100) | 0.1 | 0.06 | 1.8 | 0.07 n.s. |
| av._windspeed | -1.1 | 0.17 | -6.1 | <0.001 *** |

This means that although there is a correlation between bat activity at ground level and nacelle height, the relation does not seem to be the most important one. At this wind farm, bat activity at nacelle height is more reliably predicted by wind speed than by bat activity at ground level.

***Species composition***

There is a clear difference between the species composition recorded at ground level and nacelle height (figures 4.6 & 4.7). The percentage of the nyctaloid group is 3-4 times higher at nacelle height. In absolute numbers the nyctaloid group is 5-10 times more frequently recorded at ground level than at nacelle height. The qCF calls of the noctule bat are three times more often recorded at ground level. The myotids are close to absent at nacelle height.

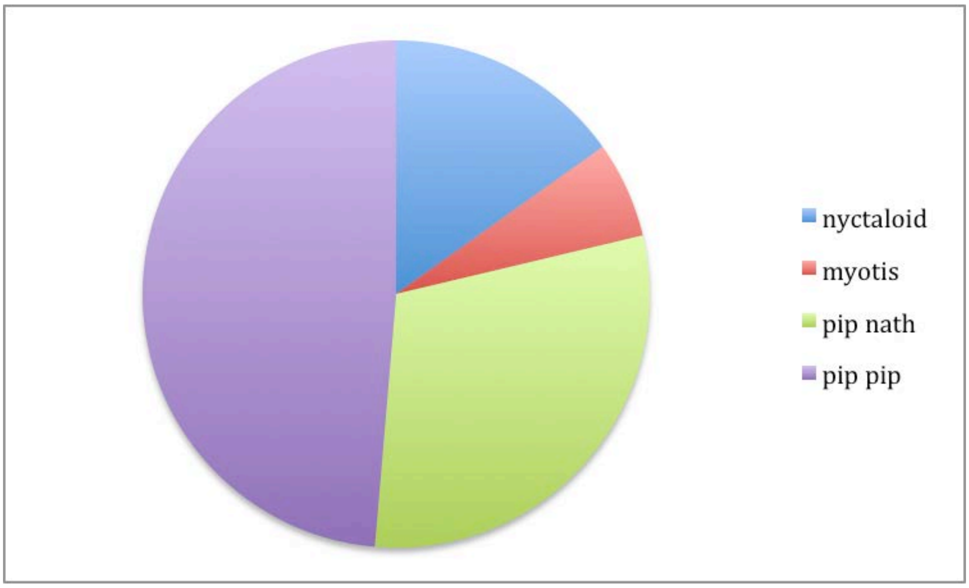


*Figure 4.6 Species composition recorded at ground level (n=33121)*

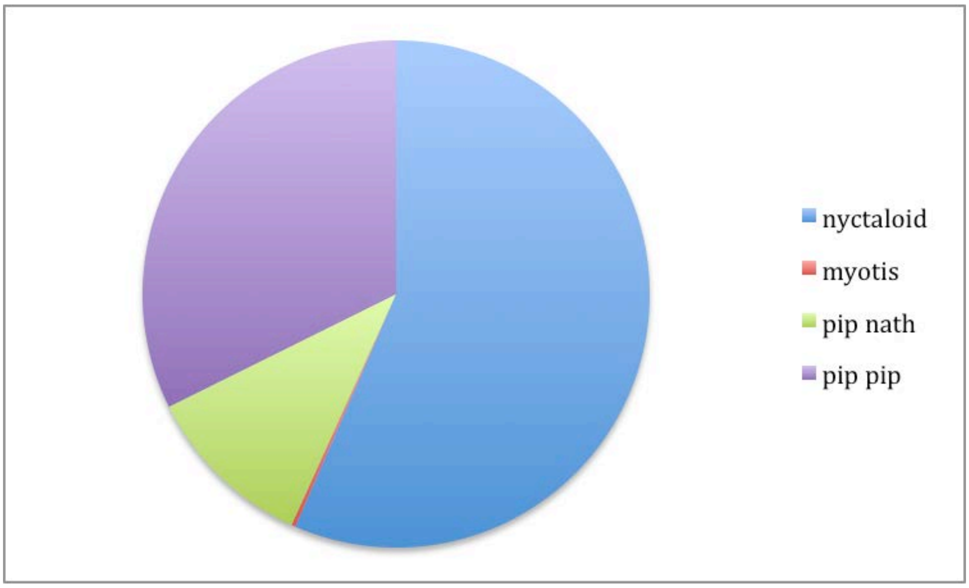


*Figure 4.7 Species composition recorded at nacelle height (n=2303).*

Within the pipistreloid group the results differ per wind farm. In Waardtocht and Herkingen the percentage of Nathusius' pipistrelles is highest at nacelle height. In Jaap Rodenburg the percentage Nathusius' pipistrelles is lower at nacelle height. Surprisingly, in Waterkaaptocht no pipistrelles were recorded at nacelle height. The files of this location were processed again and the same results were found. The

Anabat used in Waterkaaptocht was checked afterwards and performed well, recording hundreds of pipistrelles. In absolute numbers Nathusius' pipistrelle was recorded 60-70 times more often at ground level than at nacelle height. For the common pipistrelle this figure is 30-40.

***Influence of weather and night time on bat activity at nacelle height***
***Statistical analyses***
A GLMM model that included night time, day, wind speed, direction, rain, and wind farm had the lowest BIC (BIC difference to the second best model: 7) meaning that it was best in explaining the variance in bat activity at nacelle height.

The diagnostic plots of the residuals show that the model fit deserves improvements. Particularly, for low wind speeds the average of the residuals seems to be smaller than zero, *i.e.* the model seems to overestimate activity for low wind speeds. The qq-plots of the variance parameters (residuals, wind farm and additional variance) show a distinct bend, which may be an indication of zero-inflation. Zero-inflation means that excess zeroes are present as well as normal zeros. A possible explanation for this is that bats are not recorded because they are simply not present in the area (excess zeros in this context), or because of unfavourable conditions such as strong winds (normal zeros).

Further, significant positive temporal autocorrelation is present. Autocorrelation means that the observations (bat recordings / 10 minute interval) are not random events, but related events. This is not surprising since one bat can be recorded during several 10 minute intervals if it stays in the area. As a consequence, the data are pseudo-replicated and all the standard errors you calculate while ignoring autocorrelation will be too narrow, i.e. you will be overconfident in your result. Autocorrelation needs to be taken into account when constructing uncertainty intervals. We have not accounted for autocorrelation due to computer capacity limitations. This is why effect sizes of each variable are only presented by parameter estimates without standard errors (table 5).

The proportion of 10 minute intervals with zero bat calls in the real data was 0.974. In 95% of the data sets simulated from the model, this proportion was between 0.979 and 0.981. Thus, the model overestimated the proportion of zeros. The maximal number of bat calls seems to be appropriately modelled: the 95% interval was 35 - 51 and the observed maximum was 37 bat calls. Overall, the model fit needs to be improved. It cannot yet be used to reliably predict bat activity, which would be needed to construct a curtailment algorithm.

*Table 5 Model estimates of the GLMM to predict bat activity for each 10-min interval. The numeric predictors were standardized (i.e. z-transformed, thus effect sizes may be comparable between the different predictors with higher values mean stronger effects; further negative values mean negative effects). ^2 is the second polynomial. Note that uncertainty intervals are not presented because autocorrelation is present.*

| | estimate |
|---|---|
| intercept | -9.40 |
| proportion of night (nighttime) | -0.04 |
| proportion of night ^2 | 1.30 |
| proportion of night ^3 | -0.49 |
| proportion of night ^4 | -0.84 |
| day (season) | -0.91 |
| day ^2 | -0.46 |
| wind speed | -2.050 |
| wind speed ^2 | -0.76 |
| wind direction.sin | 0.80 |
| wind direction.cos | 0.28 |
| rain (occurrence) | -0.20 |

***Wind speed***

There is a huge variation in bat activity. A night with no bat activity can be followed by a night with a few hundred bat recordings at nacelle height. A large proportion of this variation can be explained by wind speed (table 5). Wind speed has a negative effect on bat activity (bat activity decreases when wind speed increases).

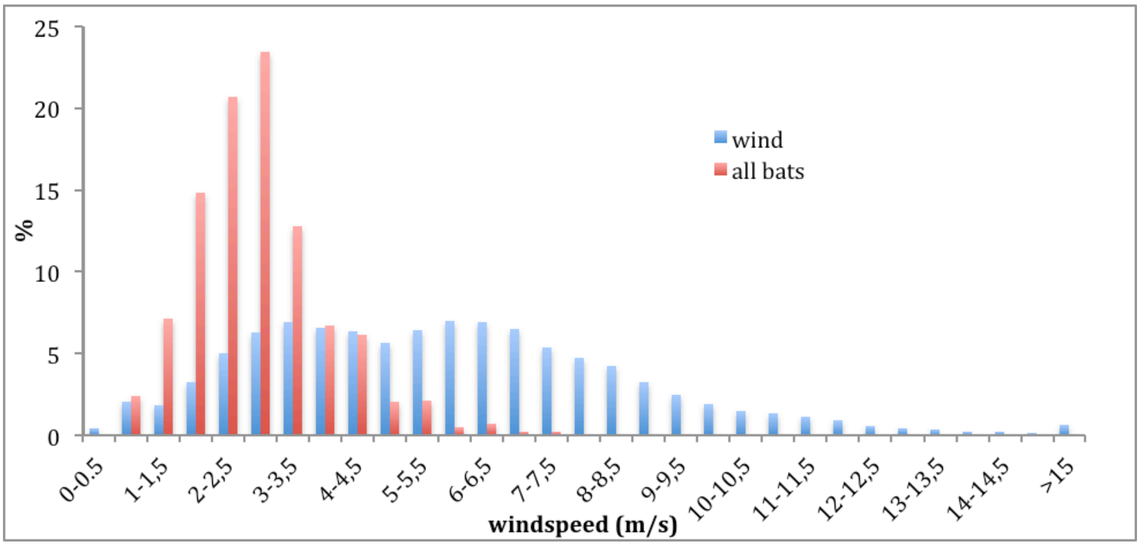


*Figure 4.8 The relative abundance of bats during different wind speeds (m/s) and the presence of these wind speeds at nacelle height of all wind farms during the study period (n=22051 periods of ten minutes; n=2371 bat recordings). For the presence of wind only those nights when the detectors were operational were used.*

The vast majority of all bat activity takes place at wind speeds lower than 5 m/s (figure 4.8). Higher wind speeds regularly occurred during the study period but bat activity is incidental during these conditions. There are clear differences between species. Nathusius' pipistrelle is the most wind tolerant species. 95% of all activity is this species is recorded during wind speeds lower than 5-5.5 m/s. For the nyctaloid group this figure is 4.5 m/s and for the common pipistrelle 4 m/s (figures 4.9 & 4.10).

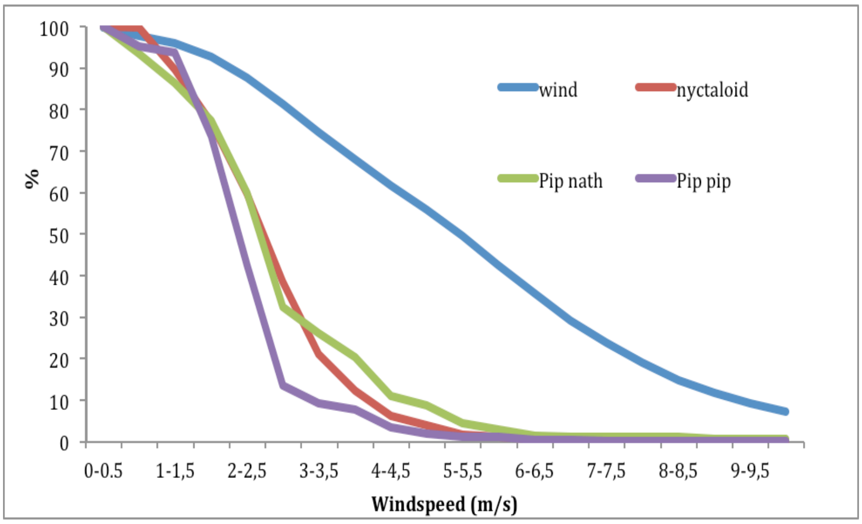


*Figure 4.9 Inverse cumulative distribution of bat activity at nacelle height during different wind speeds (m/s; n=22051 periods of ten minutes; n=2371 bat recordings).*

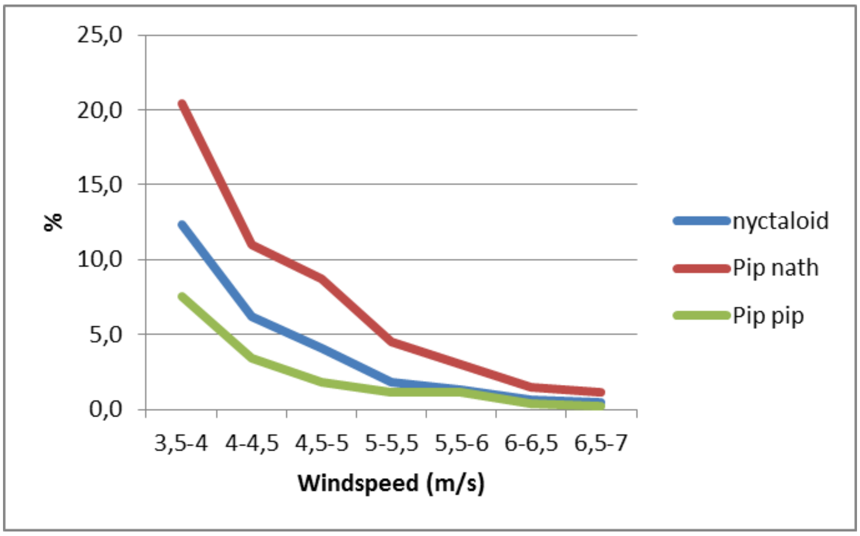


*Figure 4.10 Excision of figure 4.9 for wind speeds between 3.5 and 7 m/s. Inverse cumulative distribution of bat activity at nacelle height during different wind speeds (n=22051 periods of ten minutes; n=2371 bat recordings).*

The preference of bats to a certain wind speed was established by dividing the number of recordings by the number of hours that this wind speed occurred (figure 4.11). The most preferred wind speed lies between 1 and 3 m/s. Above 3 m/s the number of recordings per hour rapidly declines until 0.03 recordings / hour for the highest wind speeds. Surprisingly, the number of bat recordings is relatively low at wind speeds between 0 and 1 m/s. In Jaap Rodenburg, the wind farm with the highest bat activity, these wind speeds were rare. Wind speed of 0-1 m/s especially occurred in wind farms with a relative low bat activity.

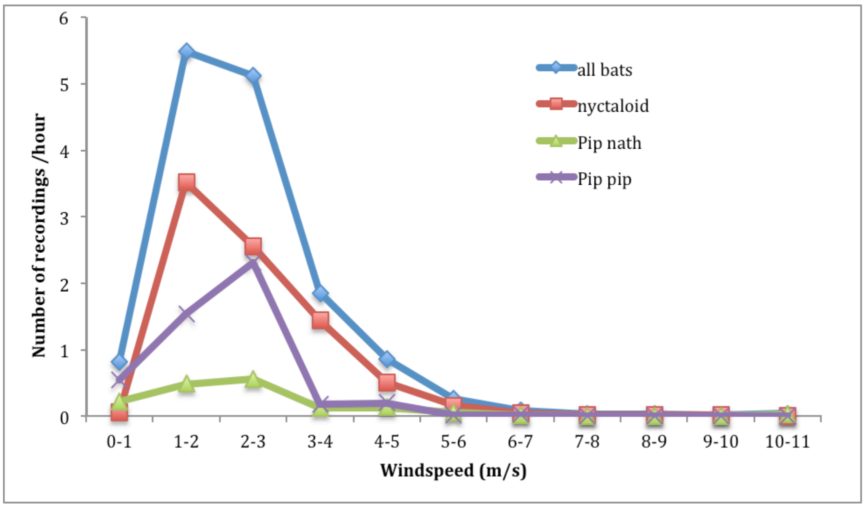


*Figure 4.11 Number of bat recordings per hour at nacelle height for different wind speed (m/s) categories. For wind distribution, only wind speed data for relevant periods (night time with operational equipment) were used in the analysis. (n=22051 periods of ten minutes; n=2371 bat recordings).*

***Temperature***

The effect of temperature on bat activity at nacelle height is less pronounced than that of wind speed. Temperatures between 15 and 20 degrees Celsius were most common during the study period but the majority of bat activity took place at temperatures between 18 and 26 degrees Celsius. Bats seem to prefer temperatures between 22 and 26 degrees Celsius and this pattern is observed in all bat species (figure 4.12). Above 26 degrees Celsius the number of recordings is somewhat lower. This is not surprising since the highest temperatures occur right after sunset when bats have not yet reached the wind farms. Below 13 degrees Celsius only five bats were recorded although these temperatures occurred during 172 hours.

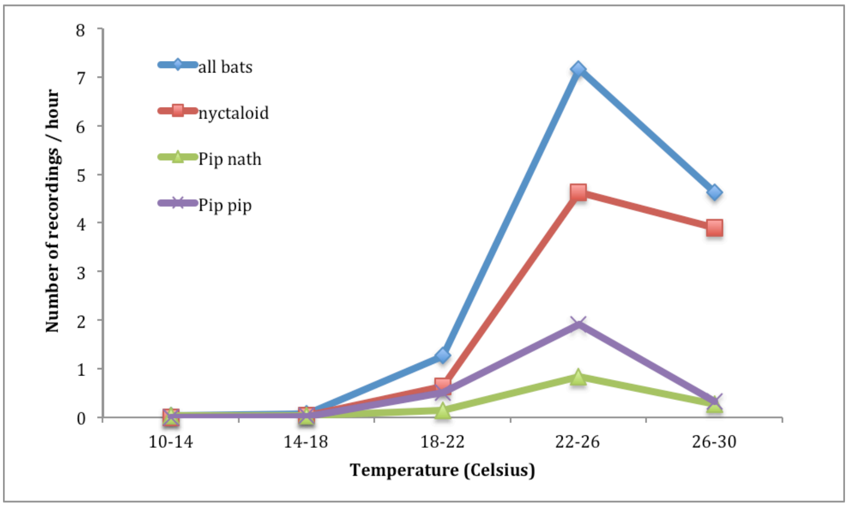


*Figure 4.12 Number of bat recordings per hour at nacelle height for different temperature (degrees Celsius) categories. For the temperature distribution only those nights when the detectors were operational were used (n=22051 periods of ten minutes; n=2371 bat recordings).*

***Precipitation***

The effect of precipitation (rain) could not be established in the same detail as temperature and wind speed because precipitation is not measured at the nacelle of wind turbines. The hourly values of the nearest weather station are likely to be less precise. Nevertheless it can be seen in figure 4.13 that bat activity is higher during dry nights than during nights with rain. The amount of rain did not seem to matter. This probably explains why precipitation had a low standardized predictor estimate of the GLMM model (Table 5).

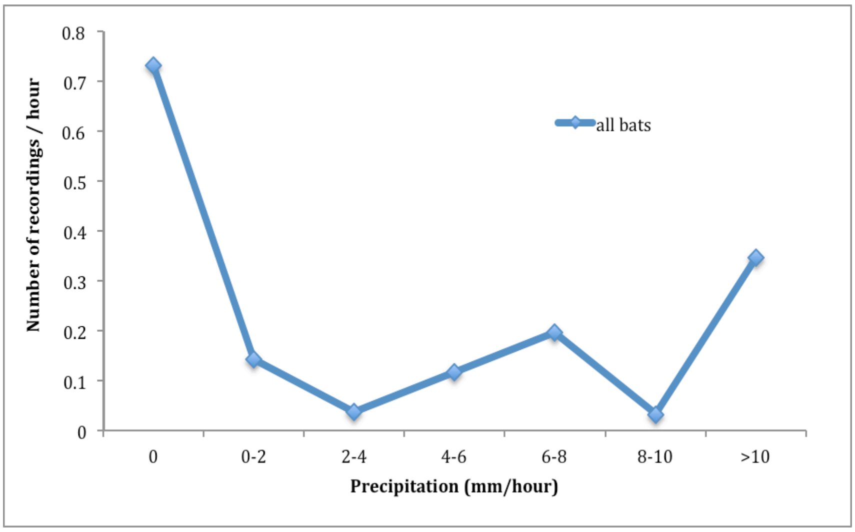


*Figure 4.13 Number of bat recordings per hour at nacelle height for different precipitation (mm/hour) categories. For the distribution of precipitation only those nights when the detectors were operational were used (n=22051 periods of ten minutes; n=2371 bat recordings).*

***Night time***

Bat activity clearly varies in the course of a night. The activity is quite low during the first 10% of the night when many bats have not reached the wind farms yet (figure 4.14). As the average night length is 10.5 hours during the study period this approximately represents the first hour and a half after sunset. The following hours bat activity is at the highest level. In the middle of the night the activity is much lower and a second peak in activity is seen between at night time 0.7 to 0.9. The activity then quickly drops and is close to zero during the last hour before sunrise.

The activity pattern for Nathusius' pipistrelle is different. There is no clear peak in the first quarter of the night. The activity of this species is elevated in the middle of the night.

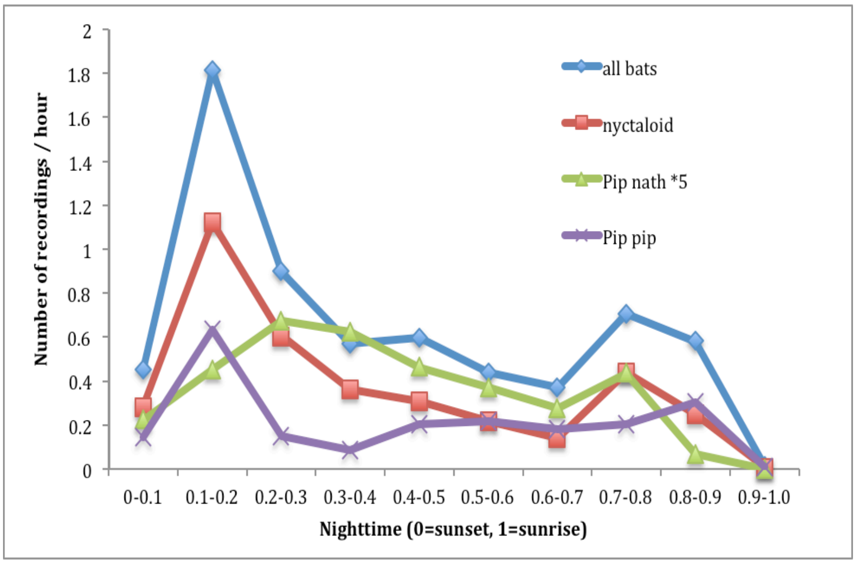


*Figure 4.14 Number of bat recordings per hour at nacelle height for different night time categories. Only those nightly hours when the detectors were operational were used (n=22051 periods of ten minutes; n=2371 bat recordings). As night length differs, night time was expressed relative to sunset and sunrise (0=sunset, 1=sunrise). The number of recordings for Nathusius' pipistrelles is raised with factor five for ease of presentation.*

***Wind direction***

The effect of wind direction is likely to differ between wind farms because of differences in the topography of the areas which are relevant for bats. A particular wind farm can be in the leeward side of a nearby tree line during a particular wind direction, while the same wind direction might place another wind farm to be in the windward side of a forest. The effect of wind direction can only be properly observed per wind farm. In this paragraph we look at the effect of different wind directions on bat activity at wind farm Jaap Rodenburg at nacelle height. Only low wind speeds (<5 m/s) were used, since strong winds were predominantly from the south and bat activity is low during strong winds.

Bat activity appears to depend somewhat on wind direction, and is highest during westerly winds. The most likely explanation for this is that insects from the nearby 'IJsselmeer' (a large freshwater lake) are blown into the wind farm during this wind.

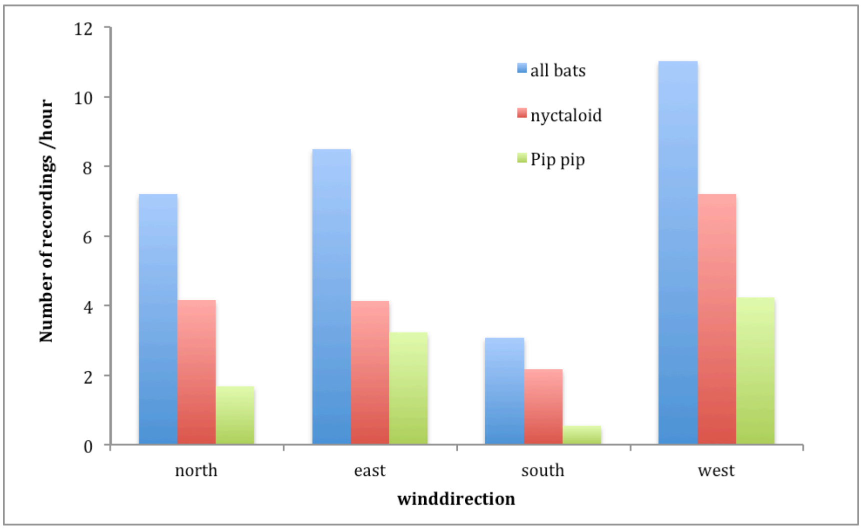


*Figure 4.15 Number of bat recordings per hour at nacelle height of Jaap Rodenburg for different wind directions during low wind speed (<5 m/s). Periods with strong wind speeds are not used since bat activity is low then and strong winds are predominantly from the south (n=1483 periods of ten minutes; n=1847 bat recordings).*

### *Seasonal differences*

Our study period was too short to fully describe seasonal differences in bat activity. A few differences were nonetheless detected. Bat activity was higher in August than in September, especially at Jaap Rodenburg (Almere) and Waardtocht. Nathusius pipistrelle was more abundant in September than in August, whereas common pipistrelle was more abundant in August than in September (Figure 4.16).

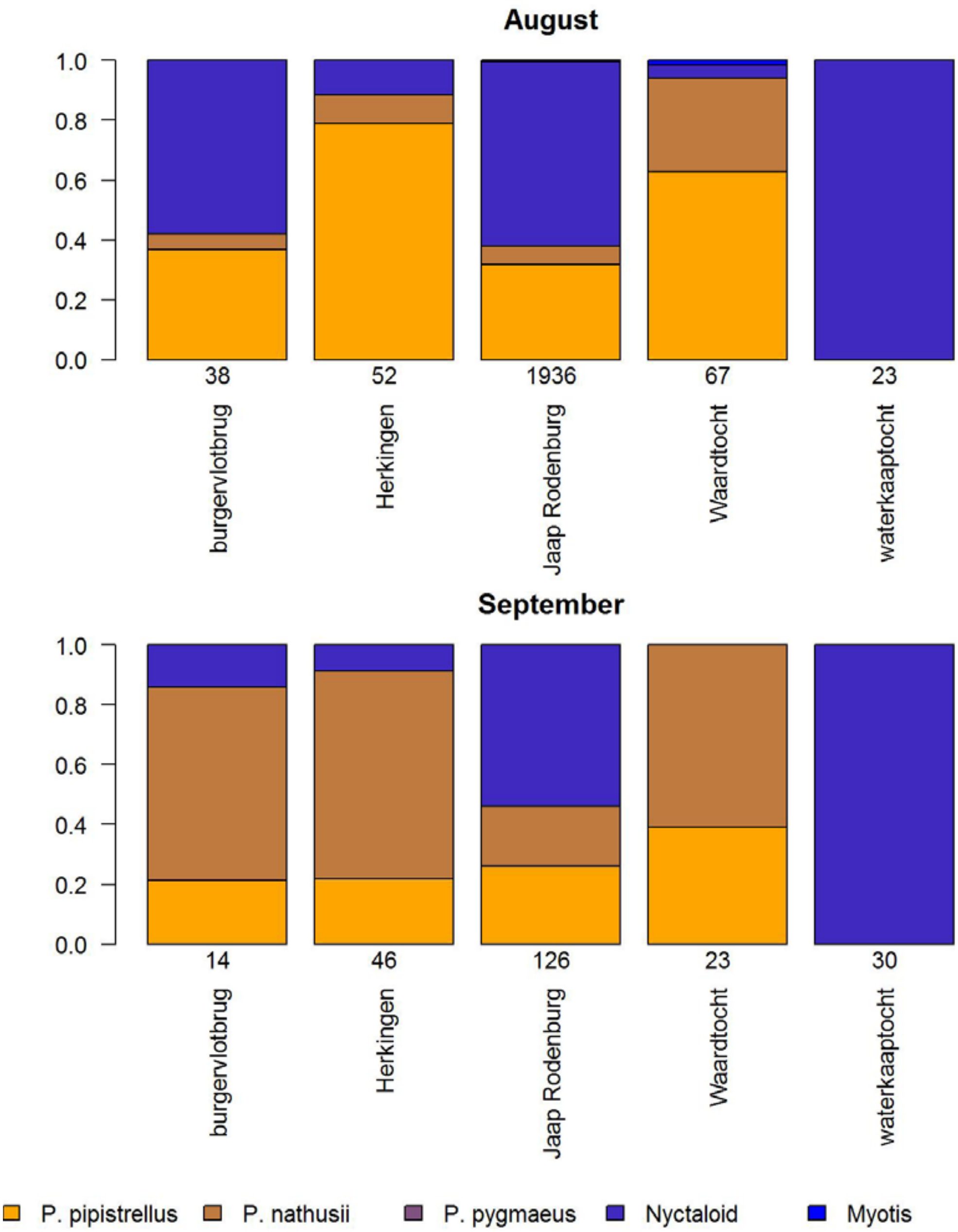


*Figure 4.16 Composition of the identified bat calls per wind turbine and month. The numbers below the bars give the absolute number of identified bat recordings.*

## 4.4 Discussion acoustic monitoring

***General results***

The equipment performed relatively well during this study. Particularly at nacelle height the percentage of non-operational time was low compared to other studies (Behr *et al.* 2011a).

There are large differences in bat activity and species composition between wind farms. At some wind farms the percentage of migratory bats like Nathusius' pipistrelle is rather high. The migration of this species is highly seasonal (Pētersons 2004). If the bats that pass through the wind farm are migrating, their behaviour can be different from that of non-migratory bats that regularly return to the wind farm for foraging. Each wind farm is likely to have its own bat activity patterns and general results can therefore not easily be applied to new wind farms. At Waterkaaptocht no pipistrelles were recorded at nacelle height although one common pipistrelle fatality was found in this wind farm. In wind farms where bat activity is low a study period of only two months with one detector per wind farm at nacelle height might be too short to properly describe bat activity patterns.

***Ground level versus nacelle height***

Bat activity at nacelle height is related to the number of fatalities (Korner-Nievergelt *et al.* 2011). A possible relation between bat activity at ground level and nacelle height could be used for pre-construction surveys to predict post-construction fatality risk. A possible flaw is the fact that high structures such as wind turbines can attract bats in an open landscape. During this study, bat activity at ground level could therefore be higher than during pre-construction surveys. Relating pre-construction survey data to post-construction fatalities is also suboptimal because it entails the comparison of different years with potentially huge differences in weather conditions and bat abundance. In the USA where wind farms with large numbers of fatalities occur, a significant correlation between pre construction activity and post construction fatality was nonetheless found (Hein *et al.* 2013).

This study shows that for wind farms with a relatively high bat activity, it seems possible to predict the activity at nacelle height by using ground level data but the relation between the two is not necessarily causal. For Jaap Rodenburg, activity at nacelle height was reliably predicted by using wind speed alone but not by bat activity at ground level when wind speed was included in the model. One might argue that pre-construction surveys are therefore not useful. However, more data from different wind farms could lead to more promising results. Secondly, pre-construction surveys seem unavoidable to assess which risk species are present in the area.

Although the relation between the activity at ground level and nacelle height was determined for all bat species taken together, there are clear differences between species. In absolute numbers the nyctaloid group is 5-10 times more frequently recorded at ground level than at nacelle height but this figure is 30-70 for pipistrelles.

The difference in species composition between ground level and nacelle height does not necessarily reflect differences in abundance. Low frequency calls of nyctaloids and in particular the qCF calls of the noctules are less attenuated than calls of the common pipistrelle and can thus be recorded from a larger distance. Maximum theoretical detection distance is 38 m for 40 kHz (pipistrelle) and 70 m for 20 kHz (noctule bat; appendix V). This detection distance applies to both ground level and nacelle height. If we assume that all bat species have an identical distribution over altitude with most activity at low elevation, the percentage of the common pipistrelles that can be detected is much higher at ground level than at nacelle height. This is different for the noctule bat. Measured from modest wind turbines a large proportion of noctule bats flying at lower elevation can still be detected from the nacelle. Therefore the recorded pipistrelle/noctule ratio can be much lower at nacelle height than at ground level even if both "species" have exactly the same height distribution.

Myotids are only incidentally recorded at nacelle height, but regularly at ground level. It is likely that this species group is rare at nacelle height.

***Influence of weather and night time on bat activity at nacelle height***
The relation between bat activity and wind speed, temperature, precipitation and night-time as found during this study is very similar to the ones described by (Behr *et al.* 2011b). Bats prefer dry nights with wind speeds below 5 m/s and relative high temperatures. 95% of all activity of the Nathusius' pipistrelle was recorded during wind speeds lower than 5-5.5 m/s. For the nyctaloid group this figure is 4.5 and for the common pipistrelle 4 m/s. The differences in wind tolerance between species, is also in accordance with (Behr *et al.* 2011b). An appropriate value for a raised cut-in speed for wind turbines will depend on the species composition of the wind farm, the number of fatalities that is considered acceptable and several other factors. A general value for a raised cut-in speed can thus not be given, without risking too little effect on mitigation of casualties, or too much loss of energy production in relation to the achieved mitigation for bats.

Above 26 degrees Celsius the number of recordings is relatively low. This is not surprising since the highest temperatures occur right after sunset when bats have not yet reached the wind farms. Below 13 degrees Celsius bat activity was nearly absent. It is uncertain whether this also applies to early spring when temperatures are generally low because this lies outside the studied season. In early spring, bat activity can be substantial during temperatures below 10 degrees Celsius (pers. comm. R. Brinkmann). Rain has a negative effect on bat activity but the amount of rain does not seem to matter. During this study we found two peaks in bat activity for most species. The highest peak occurs between one and three hours after sunset. The second peak is much lower and occurs a few hours before sunrise. This activity pattern has not previously been found at nacelle height but is often observed in studies that measure bat activity from ground level. It is generally believed that this bimodal activity pattern is linked to the activity pattern of insects and is particularly present during lactation and weaning (e.g. Swift 1980).

The Nathusius' pipistrelle shows a different activity pattern, with activity somewhat elevated in the middle of the night. A possible explanation for the difference in activity pattern between Nathusius' pipistrelle and the other species is that most recorded Nathusius' pipistrelles are migrating through the wind farms, while the other species visit the wind farm for foraging (Behr *et al.* 2011).

Bat activity in Jaap Rodenburg was highest during westerly winds. During this wind, insects from the IJsselmeer are blown into the wind farm. These results support the general assumption that the reason why bats visit wind farms within the rotor swept area, is foraging (Rydell *et al.* 2010).

### 4.5 Bat friendly curtailment algorithms

Wind turbines on forested hills or in marshes in North-western Europe can have a high mortality rate of 10-40 bats per turbine annually (Rydell *et al.* 2010). The impact of this mortality might not be sustainable by bat populations (Kunz *et al.* 2007). In the current study, in the selected five wind farms, such a high mortality rate was not found. However, there is one known location in the Netherlands (which was not included in this study) with a mortality rate of more than 10 bats per turbine annually (Boonman *et al.* 2011). This shows that high mortality rates are not singly linked to habitats or geographical regions outside the Netherlands. Mitigation measures that reduce bat mortality are particularly important at these locations and can also be applied in wind farms with a large number of turbines where the cumulative effect on bats can be significant.

Many different mitigation methods have been proposed (acoustic deterrent, radar, changing the colour of wind turbines; Horn *et al.* 2008, Nicholls & Racey 2009; Long *et al.* 2010) but none of these have proved to effectively reduce bat mortality. Targeted curtailment i.e. stopping or slowing down the rotor blades of a wind turbine during periods of high bat activity is the only known method that effectively limits bat mortality. Curtailment obviously reduces energy production and it is therefore essential to limit curtailment to those periods with high bat activity. Bat activity differs clearly between wind farms but the main factors that influence bat activity are generally the same. Season, time of night and wind speed are measured or known at wind turbines and can effectively be used to predict bat activity (Behr *et al.* 2011). Temperature is measured at the nacelle of some turbine types but led to a low improvement of the model in Germany and was therefore not used in their curtailment algorithms (Behr *et al.* 2011). In southern France temperature was effectively used (Lagrange *et al.* 2013). In the south of France nights with a substantial lower temperature occur when the wind is coming from the north (mistral). This probably explains the bigger explanatory value of temperature in this region. Precipitation is not measured at the nacelle and is therefore not readily applicable for timing the curtailment of wind turbines.

Bats are usually only present in wind farms during low wind speeds (<6.0 m/s). Curtailment can be done by simply raising the cut-in speed of wind turbines to 5 or 6 m/s during the entire period when bats are active (summer, night). This is usually accompanied by changing the blade feathering position to prevent turbines from freewheeling or only spin at very low rpms, generally less than 1 rpm. In Canada and the U.S. this resulted in 60-80 % reduction in the number of fatalities (Baerwald *et al.* 2009; Arnett *et al.* 2009, 2010a, b, 2011) and a 2% loss of energy production. This method is effective, but rather crude. It ignores the fact that bats are most active in the first half of the night and for example more active in August than in June.

There are a few curtailment methods which are more precise: bat friendly curtailment algorithms developed in Germany (Behr *et al.* 2011) and the French system called Chirotech.

These curtailment algorithms are multivariate models, which take several factors into account at the same time. The system called Chirotech uses a variable cut-in speed modulated by season, temperature, and night-time (Lagrange *et al.* 2012). The cut-in speed can be as high as 7.5 m/s during high temperature in August at the beginning of the night. During cold nights in spring, the cut-in speed is not elevated above the operational value. This system has shown a reduced mortality of 64-90% and an associated energy production loss lower than 0.15%.

The bat friendly curtailment algorithms from Germany are developed to reduce the number of fatalities to a certain value that is previously decided upon: e.g. two dead bats per turbine annually. The algorithms use their established relationships between:
a). The number of fatalities and the acoustic activity.
b). Acoustic activity and the variables season, time of night and wind speed.
The number of fatalities is subsequently estimated from the variables season, time of night and wind speed. The algorithm determines the time frame where the quotient between expected energy production loss and the estimated number of fatalities is minimal. During these time frames the wind turbine is stopped. To reduce to number of fatalities to two, the expected annual energy production loss is around 0.5%.

Energy production losses depend on turbine type, number of operational days, occurring wind speeds etcetera and cannot easily be compared. It seems likely however that these two (French and German) site-specific curtailment algorithms are more effective in reducing bat mortality with lower energy production losses, than a general cut-in wind speed.

Species composition and activity patterns differ strongly from site to site requiring curtailment algorithms to be site specific. The Nathusius' pipistrelle and noctule are more wind tolerant than the common pipistrelle (Rydell *et al.* 2010 a, b; Behr *et al.* 2011). At sites where noctules are the predominant species at risk, a higher cut-in speed might be acceptable. Some sites show pronounced activity during the first half of the night, while others show seasonal patterns that seem to correspond with the migration period of the Nathusius' pipistrelle. Bat activity measured at the nacelle height can be used to calculate the parameters used in the model, thereby determining the strength of the variables and the way they interact with each other.

# 5 Bat fatality searches

## 5.1 Sources of bias

To be able to estimate the number of bat fatalities at a wind energy site or specific turbine, it is necessary to not only search for fatalities, but also measure the possible sources of bias of the specific site (see protocols in Boonman *et al.* 2013). These sources of bias are inherent to the method and cannot be avoided. They can, however, be limited and their magnitude can be estimated (Niermann *et al.*, 2011a).

Meaningful fatality searches therefore consist of a number of different obligatory components, with their own methodical set up.

1. Determining search period and search frequency. The found numbers of bat fatalities change with different behavioural patterns of bats in the course of the season. The search period needs to be adjusted to a relevant part of the season. Search frequency influences the probability of finding fatalities (paragraph 5.2).
2. Determining search area dimensions and searchable area. Most casualties fall within a certain distance to the turbine tower. Not every vegetation type or ground cover can actually be searched. (paragraph 5.3).
3. The basic searching of fatalities (paragraph 5.4).
4. Determining the carcass persistence time, or rate at which carcasses are broken down or removed per site. Bat carcasses are constantly being removed due to activity of different types of scavengers, from molluscs and insects to birds and mammals. The probability of finding a given casualty therefore is dependent on the time period between searches. The speed at which carcasses are being removed, or the time the carcasses persist, will differ per site, and needs to be established in a field experiment with purposely placed dead bats or similar sized and coloured mice or rats. This determines the probability that an actual casualty bat is still present after a certain period, and might be found during a search (paragraph 5.5).
5. Determining probability of detection, or searcher efficiency. This measure is predominantly dependent on vegetation type or ground cover and the person searching for fatalities. The probability that an actually present dead bat would be discovered by the actual searcher, needs to be established in a field experiment with randomly placed dead bats, or similar sized and coloured mice or dummies. This can be done per site, but needs to be done per turbine when differences in ground cover are large. Where probability of detection alters through differences in vegetation and ground cover, it may be necessary to repeat the searcher efficiency (paragraph 5.6).

## 5.2 Period and search frequency

Searching for bat fatalities is possible in those parts of the season in which bats are active, and thus are at risk of collision with a wind turbine. In the Netherlands this would roughly be a period between the beginnings of March to the end of October. The beginning and ending of the 'bat season' is, however, dependent on the weather conditions and especially the temperatures early and late in the year.

Depending on ambient temperatures, emergence from hibernation will occur from the end of March to the end of April. For e.g. Nathusius' pipistrelles, this will also be the period of spring migration. In this spring period, however, relatively little research into fatalities at wind facilities has been done (Niermann *et al.* 2011a, Rydell *et al.* 2010, Boonman *et al.*, 2011). The available limited results, however, show a comparative low amount of fatalities.

For some non-migrating species, such as the common pipistrelle, the abundance of individuals in maternity sites and the high feeding activity during maternity season, this period, between end of May and end of June, may be a high risk period (Niermann *et al.* 2011a, Rydell *et al.* 2010a, b, Boonman *et al.* 2011).

Again, depending on weather and predominantly ambient temperatures, autumn migration occurs between the end of July and the beginning of October (Niermann *et al.* 2011a, Rydell *et al.* 2010 a, b, Boonman *et al.* 2011). In this period the relatively higher migrating populations including juveniles and their specific behavioural patterns may be expected to lead to a higher fatality risk.

*Table 6 Periods in which a high intensity of searching bat fatalities – e.g. at least three times per week – might be favourable, as a result of higher risks through relatively high bat activity levels.*

| **Period** | **Behavioural period** |
|---|---|
| End of March – end of April | Spring migration |
| End of May – end of June | Maternity season |
| End July – beginning of October | Autumn migration and mating season |

Search results will profit from a constant and short interval. Searching every day would deliver the most optimal results, but will also need a high input of labour and expenses.

In accordance with the available budget we have worked with searches tuned to the autumn high risk period. At all sites, searches were done during a 9 week period, from beginning of August till the end of September, with searches every 3 days. In this way 18 search visits have taken place. All sites were searched by the same fieldworker, with searches starting at sunrise and continuing until approximately until 2 - 2,5 hours after sunrise.

## 5.3 Search area dimensions

***Search radius***

Fatality searches are performed in a circular plot, with radius R, around the wind turbine base. Here distance to turbine tower is indicated rather than to a possible above ground foundation. The search area is equal to $R^2$. The number of fatalities, as well as the density of fatalities, however, decreases with the distance to the turbine base (Niermann *et al.*, 2011a, b). As a consequence, the benefit of searching a larger area, rapidly decreases above a certain distance and area. Bat casualties appear to be found relatively concentrated around the turbine tower (Brinkmann et al, 2011).

It would be expected to find bats at larger distances from the turbine tower, with increasing turbine height and rotor diameter. This seems, however, much less the case with bats than with birds. In Germany > 95% of fatalities were found within 50 m of the tower, for turbines with a height of 80-100 (Brinkmann *et al.* 2011). They recommend a radius of 40 m, for turbines of these dimensions, and a radius of 50 m for turbines above this height (e.g. Niermann *et al.*, 2011a).

In this study we have worked with a radius of 50 m.

***Arranging the circular search plot***

The outer perimeter of the circular search plot was marked in the field by planting at least 10 bamboo sticks with a small flag. We used a > 50 m long rope, involving 2 people working together, as well as electronic distance meters. The markers were used to indicate the perimeter as well as to help the searcher walking in a straight line. They were rearranged at every new round, when changes, e.g. in visibility, made this necessary.

***Searchable area***

In the circular plot with a radius of 50 m, in which bat casualties are searched for, there may be inaccessible terrain or terrain where searching is impossible (behind fences/no access granted, crops that are not to be damaged, water bodies et cetera.) as well as areas with a higher vegetation in which effective searching is not possible.

The actual searchable area, as a part of the total area within the 50 m radius, is to be assessed and documented, using maps and areal photographs, before the first search. Changes in the searchable area are to be assessed and documented before every search.

The area that can be searched may show differences in terrain, with differences in searchability due to the actual vegetation structure and height or ground cover. Since we seek synergy with the work done and model built in Germany, the area which can be searched, is to be assessed and documented following the classification given by Niermann *et al.* (2011a).

1. (approximately) bare: paved, bare ground, thin, low vegetation with a cover of less than 10%, vegetation lower than 20 cm.
2. half covered: grass-like or herb vegetation, cover 10-75%, vegetation lower than 20 cm.
3. completely covered: grass-like or herb vegetation, cover > 75%, vegetation higher than 20 cm but lower than 50 cm.
4. too densely covered / inaccessible: herb vegetation higher than 50 cm, thicket and bushes, hedgerows, wooded area, crops not to be damaged, deposit stones/boulder rock, no access granted, water, march and wetland.

These first basic data on searchable areas and searchability are processed with a GIS system in order to make an accurate estimate of the searchable areas within the different searchability classes. This information is not only relevant for the searchable area as such, but also in relation to search efficiency and carcass persistence time and the possibility to estimate and extrapolate fatalities.

Based on the first basic data, a terrain map is produced, as a basis for the assessment of changes in these data at the following search rounds. On this map also circles on 10, 20, 30 and 40 m from the tower are drawn. For all search rounds, any changes as a result of vegetation growth, grazing, mowing, inundation et cetera are documented.

In this study the budget allowed for fatality searches at two turbines per site, based on 100% searchable area per turbine. This was also in accordance with the statistical requirements from the model. In practice the available turbines showed clearly smaller searchable areas. Therefore the available search time was used on searches at a larger number of turbines per site, with a total area up to approximately 2 x 100 % per site. In Almere searches were done at 3 turbines, in Burgervlotbrug at 4, in Herkingen at 3, in Wieringermeer -Waardtocht at 5 and in Wieringermeer-Waterkaaptocht at 10 turbines. In total, carcass searches were done at 25 turbines.

The search area data used for further analysis include the area of each visibility class and the area that could not be searched (in $m^2$ and as proportion) for all searched turbines and for each 10 m distance ring (also Appendix I).

## 5.4 Performing fatality searches

***Timing of searches***
Searches were in all cases done starting at sunrise and continuing approximately until 2-2,5 hours after sunrise.

***Systematic walking and searching within the circular plot***
Within the circular search plot, searching of fatalities or injured bats is done on foot. The searcher systematically passes through the circle along straight and parallel search trails, with a 3 m distance between them. The searchers attention is on the 1.5 m on both sides of his path.

In the field it has proven to be practical to keep the search trails parallel to obvious landscape structures such as roads, ditches, dikes or fields with crops, and or parts of the terrain with non-searchable cover.

Times of beginning, ending, weather conditions and special details are documented.

## 5.5 Documenting casualties and injured bats

***Documenting***
Any found bat casualty or injured bat is labelled with date, time and unique number. Its position is registered with a GPS and accurately noted on the search area map / field form. Additionally distance and direction relative to the tower are documented.

If possible the following characteristics are documented on the field form: species, sex, and indication of age, state of deterioration of the carcass, visible outer injuries, traces of scavengers and other details. The fatalities or injured animals are photographed and collected in a labelled bag. All animals are handled with gloves.

***Further processing***
Any found carcass will be transported from the site in a cooler-container with ice, and frozen as soon as possible.
Before freezing the carcasses or injured bats are identified by an experienced bat specialist, where relevant data documented in the field are checked and completed.

The completed data from field forms and maps were then put in a data base, including dates and names of those searching and processing the animals and relevant data. Field forms and maps are filed.

## 5.6 Carcass persistence time

At all sites a test was done, where carcass persistence time of bat carcasses was simulated, using dead dark brown mice, or small rats, of an age of 2 to 3 weeks, all animals of colour and size similar to bats. Carcass persistence time can be very different between wind farms. Therefore this test needs to been done at all individual research sites (wind farms).

The mice or rat carcasses were deposited in the different searchability classes 1 to 3, in numbers approximately following the relative area of these classes. They were deposited during the night, before regular morning-visits, and checked for their presence/absence daily in the following four days. After this period of four days, checks were combined with the regular bat carcass searches every 3 days. Bat carcass persistence time can be very short (hours instead of days). Therefore the exact time of deposit and the exact time of the (first) check were noted.

The test was done at the end of August, in the middle of the search period. For longer search periods it might be important to repeat this test, as persistence time may fluctuate between seasons.

The data on carcass persistence times contain the history of 79 carcasses that were laid out at all 5 wind farms. They were controlled over 12 days. For each day and each individual carcass it is indicated whether the carcass was still present (also see Appendix I).

## 5.7 Searcher efficiency

Finding bat carcasses depends not only on the carcass persistence time, but also on the search efficiency of the researcher, which is related to visibility of bat carcasses in different types of vegetation. By conducting a search efficiency test, it is possible to measure and correct search efficiency for each involved searcher.

A searcher efficiency test was done in all 5 wind farms, by spreading a total of 84 dummy ‘bat carcasses’ underneath one or more representative wind-turbines, with different numbers of dummies in different types of vegetation. The involved searchers did not know where, nor how many dummies had been placed, to prevent a learning effect or an increased focus to find dummies.

The searcher efficiency test was done in the second week of August. In projects with a longer research-period it is recommended to repeat the test once or twice, depending on changes in vegetation (also see Appendix I).

# 6 Landscape parameters

The habitat surrounding a wind farm is likely to affect the number of bats that visit a wind farm. Insect abundance differs between habitats. Potential roost sites for bats can be found in forests or urban areas, and their availability in the surroundings will influence bat activity and abundance. Different habitats are used by bats in relation to specific behaviour, in different parts of the season, e.g. as foraging habitat during maternity, or as guiding structures or foraging areas during migration.

In theory, type and structure of landscape or habitat surrounding a wind farm or specific turbine, are possible risk factors (Brinkmann *et al.* 2011, Limpens *et al.* 2007, Niermann *et al.* 2011b).

Therefore landscape factors were assessed in a standardized way. Used were the European CORINE Database (CLC2000) and Google Earth.

## 6.1 Distance to surrounding key habitats for bats;

The first category describes the distance between the turbine and the nearest key habitat. The key habitats taken into the analysis are:

A: nearest smaller bush or tree line, hedge row, group of trees or smaller forest plot (with minimum length of 300 m or minimum size of 0,5 ha)
A1: nearest forest (with minimum size of 1 ha)
B: nearest water (with minimum size of 1 ha or minimum width of 10 m)
C: nearest wetland

Within these categories, forest (A1) is a sub category of (A) the bush or treelike vegetation.

### 6.2 Area of different habitat types

The second category describes the relative area of specific habitats within a 250, 500, 1.000, 5.000 and 10.000 m radius around the turbine.

First choice of habitat types for analysis, were based on the expert judgement of their suitability as a hunting or roosting habitat (Brinkmann *et al.* 2011, Niermann *et al.* 2011b):

| CLC-Code | Short description | Description |
|---|---|---|
| 211 | Dry arable land not irrigated | Arable land with cereals, leguminosae, animal food crops, root crops and bare fields. Includes vegetables and flowers, orchards and tree nurseries. |
| 231 | Meadows and pastures | Dense grassland dominated vegetation, predominantly pasture, but also meadows. Includes hedge rows. |
| 242 | Complex plot structures | Complex structures of smaller plots of different agricultural, green lands. Includes gardens and holiday parks. |
| 312 | Coniferous forest | Forest with high (>75%) coniferous trees. Includes lower tree levels and shrub layer. |
| 313 | Mixed forest | Forest with no domination of deciduous or coniferous trees. Includes lower tree levels and shrub layer. |
| 321 | Natural grass and green lands | Natural grass and green lands with low productivity, often in areas with rough terrain, including stony areas, thorn bushes and heathlands. |
| 512 | Water areas | Al artificial or natural water bodies |

Excluded were strong anthropogenic types like industrial areas, car- and railway infrastructure, harbours, airfields, open quarries, dump sites, building areas, sporting areas, and areas where low bat activity may be expected, like vineyards, bare areas, peat bogs, salt meadows and tidal zones.

### 6.3 Natural-geographical area

The third category describes the larger ‘natural-geographical area’ in which the wind farm is located. Here it is used in the sense of the Dutch ‘fysisch geografische regio’ or the German ‘Naturraum’.

We have complemented the typology of the German ‘Naturraum’ in two different ways. We have worked with the assumption that the typical Dutch open lowland landscape type, in which the investigated turbines were situated, can be seen as part of, or equal to the ‘Naturraum Norddeutsche Tiefebene’ or ‘north German lowlands’. And we have worked with the assumption that the ‘northwest Dutch lowlands’ can be seen as an independent natural geographical area.

# 7 Models for estimation of number of casualties

## 7.1 Estimation based on found carcasses

The number of casualties in the research period can be estimated on the basis of the actually found carcasses and injured bats and the probability 'p' of actually finding casualties by using the theorem of Bayes (see e.g. Korner-Nievergelt *et al.* 2011 J Wildlife Biology). This theorem gives a mathematical description of the probability of the number of casualties being M given the number of carcasses found C and the carcass detection probability p: $P(M|C) = P(C|M)P(M)/P(C)$. Also see Niermann *et al.* 2011, but note that there are some typos in the algebraic derivation in this publication.

Where
M = number of casualties occurring within the search period i.e. estimated real number of casualties;
C = number of found casualties;
p = probability of spotting, or actually finding a casualty that has occurred.

In order to assess the probability 'p' of spotting a casualty that has occurred, it is necessary to determine the following probabilities and/or comprising parameters:

*p* = probability of finding a casualty that occurred within the search period, which is dependent on:

n = the number of searches per search site,

d = search interval i.e. number of days between searches,

f = the searcher efficiency, i.e. relative share of casualties that is found within one search event of the casualties that lay in the searched area and remained until the search event, with confidence intervals and taking into account the relative area of the three searchability / visibility classes.

a = probability that the casualty has dropped into the searchable area, within the circular search plot. This probability was based on the relative area within the <10, 10–20, 20–30, 30–40 and 40–50 m radius circle searched and a theoretical spatial distribution of bat carcasses.

s = probability of a casualty persisting in the area, from the time it has occurred until the search even, with confidence intervals and per search site. This will be used in the form of the 'one day persistence rate', i.e. the relative share of casualties that persist 24 hours.

I = search period ($I = n * d$); the period for which the estimation / extrapolation is valid.

These probabilities, or parameters to calculate these probabilities, are assessed through field observations and experiments as described earlier.

There are different ways to use the described probabilities and parameters to estimate the real number of casualties (e.g. Niermann *et al.*, 2011a). Where estimation/calculation of probabilities *a,* is relatively straight forward, combining persistence time s, searcher efficiency f and search interval d into p, is more complex. We use the formula described by Korner-Nievergelt *et al.* 2011, which at this stage in the development of such models, seem to render the best estimate for central European conditions (Niermann *et al.*, 2011a)[2]. This approach is described in the following text.

***Probability (p) of finding a casualty that occurred within the search period.***
The probability of finding a casualty can be described as a function of different relevant aspects:

p = function (a, s, f, d)

The relative rate of casualties falling into the searchable area (a) in the function is a multiplication factor, where s and f are dependent on the search interval (d). This allows the formula to be written as

p = a * function (s, f, d)

where,

p = (a * p‘) = a * function(s, f, d)

As a function for

p‘ = function(s, f, d)

We use the formula proposed by Korner-Nievergelt *et al.* (2011).

This formula takes into account that a casualty that was not found in a specific search event can be found in a following search event. And, that at all nights, including those which are not followed directly by a search event, bats fatalities do occur and persist with probability ***s***.

In table 7 the deduction of a formula for the probability *p* of finding a fatality is described, following Niermann *et al.* (2011a). The table shows the expected number of found bats in the $1^{st}$ to $4^{th}$ night, up to the $n^{th}$ night, given that an average number of ***m*** bats are hit in any night of the ***(n*d***) nights in the research period.

[2] Note: A model or formula always needs to be adapted to study specific characteristics and available data!

To be able to develop and use such a new formula, different assumptions were made to simplify the process:

- There is no history; there are no (persisting) casualties in the period before the start of the research period. Therefore casualties found during the first search event, which were already heavily decayed were not included in the calculation
- There is a clustering of occurrence of casualty in time; casualties occur only once every night at the exact same time. This assumption will be relatively valid, due to the peak in observed casualties around sunset.
- The time interval between occurrence of casualties, and the search for casualties, is always the same (search interval d), for the first search as well as following searches. Since casualties are most likely to occur in the first halve of the night (e.g. Behr *et al.* 2011a) and casualties are most likely to be removed in the second halve (Ott 2009), this assumption will be relatively valid. Therefore, the fact that the interval between the occurrence of casualties and the first search is less than 24 hours may be ignored.
- The observations in searches, finding of a casualty, are independent. In successive search events the probability of finding a casualty (if still persisting) is always equal. There are no non-findable casualties. It is, however, possible to enhance the formula, through using an on average lower probability of finding for persisting bats, which were not found in the first search event after occurrence of that casualty.
- There is a constant persistence time for a specific site during the research period. Persistence time can vary between research sites.

Using carcass detection probability *p* and number of carcasses found, the Theorem of Bayes was applied to obtain the posterior distribution of the number of fatalities (see e.g. Korner-Nievergelt *et al.* 2011). From this posterior distribution of the number of fatalities, the mean, and the interval within which we expect the true number of fatalities with a probability of 0.95 were extracted.

To account for uncertainties in the estimates for persistence probability s and search efficiency f, Monte Carlo simulations were used. Calculations were repeated 5000 times, each time using different values from distributions of wind farm specific persistence times and random values drawn from a Beta-distribution for searcher efficiency. This distribution was parameterized aligning its mean and 95% interval to the experimentally determined searcher efficiency (see Korner-Nievergelt *et al.* [2013]). The calculations generated 5000 different posterior distributions of fatality numbers. These were averaged to produce the final posterior distribution that describes what we know about the number of fatalities (also Appendix I).

*Table 7a*

| Search event | night | Actual casualties | Found casualties |
|---|---|---|---|
| | 1 | $\overline{m}$ s | |
| | 2 | $\overline{m}$ (s + s$^2$) | |
| | …. | $\overline{m}$ | |
| 1st | d | $\overline{m}\ ( s + s^2 + \ldots + s^{\sigma}) =$<br>$\overline{m}\ s \frac{1 - s^d}{1 - s} = \overline{m}\ A$<br>Where<br>$A = s \frac{1 - s^d}{1 - s}$ | $\overline{m}\ A\ f$ |
| | d+1 | $\overline{m}\ (A(1-f)s + s)$ | |
| | d+2 | $\overline{m}\ (A(1-f)s^2 + s + s^2)$ | |
| 2nd | 2d | $\overline{m}\ (A(1-f)s^d + s + s^2 + \ldots + s^d) =$<br>$\overline{m}(A(1-f)s^d + A) = \overline{m}\ A\ [(1-f)s^d + 1])$ | $\overline{m}\ A[(1-f)s^d + 1]f$ |
| | 2d+1 | $\overline{m}\ (A[(1-f)s^d + 1](1-f)s + s)$ | |
| | 2d+2 | $\overline{m}(A[(1-f)s^d + 1](1-f)s^2 + s + s^2)$ | |
| | …. | | |
| 3rd | 3d | $\overline{m}\ (A[(1-f)s^d + 1)(1-f)s^d + A) =$<br>$\overline{m}(A(x+1)x + A)$<br>$= \overline{m}\ A((x+1)x + 1)$<br>$= \overline{m}\ A(x^2 + x + 1)$<br>Where<br>$x = (1-f)s^d$ | $\overline{m}\ A(x^2 + x + 1)f$ |
| | 3d+1 | $\overline{m}\ (A(x^2 + x + 1)(1-f)s + s)$ | |
| | 3d+2 | $\overline{m}\ (A(x^2 + x + 1)(1-f)s^2 + s + s^2)$ | |
| | ….. | | |
| 4th | 4d | $\overline{m}\ (A(x^2 + x + 1)(1-f)s^d + A) =$<br>$\overline{m}\ A(x^3 + x^2 + x + 1)$ | $\overline{m}\ A(x^3 + x^2 + x + 1)f$ |

∑n describes the expected number in the whole of the research period.

*Table 7b*

| Search event | night | Actual casualties | Found casualties |
|---|---|---|---|
| n^th | nd=I | $\bar{m}\,A(x^{(n-1)}+x^{(n-2)}+\ldots+x+1)$ | $\bar{m}\,A(x^{(n-1)}+x^{(n-2)}+\ldots+x+1)f$ |
| | | | |
| Σ n | I | $\bar{m}\,A(1+(1+x)+(1+x+x^2)+\cdots+(1+x+\ldots+x^{(n-1)}))$ $\bar{m}\,A(n+(n-1)x+(n-2)x^2+\ldots+(n-n)x^n)$ $=\bar{m}\,A\sum_{i=0}^{n}(n-i)x^i$ | $\bar{m}\,Af\sum_{i=0}^{n}(n-i)x^i$ |

The next step is the deduction of a formula for the probability p that during the research period a fatality that has fallen in the searchable area will be found. This is the formula for the expected number for the whole research period divided by I = n*d.

*Table 7c*

| Search event | night | Actual casualties | Found casualties |
|---|---|---|---|
| | | $p=\frac{Af}{I}\sum_{i=0}^{n}(n-i)\,x^i$ where $A=s\frac{1-s^d}{1-s}$ and $x=(1-f)s^d$ | |

Using carcass detection probability *p* and number of carcasses found, the Theorem of Bayes was applied to obtain the posterior distribution of the number of fatalities (see e.g. Korner-Nievergelt *et al.* 2011). From this posterior distribution of the number of fatalities, the mean, and the interval within which we expect the true number of fatalities with a probability of 0.95 were extracted.

To account for uncertainties in the estimates for persistence probability s and search efficiency f, Monte Carlo simulations were used. Calculations were repeated 5000 times, each time using different values from distributions of wind farm specific persistence times and random values drawn from a Beta-distribution for searcher efficiency. This distribution was parameterized aligning its mean and 95% interval to the experimentally determined searcher efficiency (see Korner-Nievergelt *et al.* [2013]). The calculations generated 5000 different posterior distributions of fatality numbers. These were averaged to produce the final posterior distribution that describes what we know about the number of fatalities (also see Appendix I).

## 7.2 Aligning the Dutch data to the German BMU model

To apply the German BMU model[3,4] to the Dutch data, it is assumed that the conditions in the Netherlands are similar to those in the BMU-project. Concrete assumptions are 1) correlation between wind speed and activity are similar, 2) species composition is similar, 3) daily and seasonal activity patterns of bats are similar, 4) wind turbines types are similar (rotor diameter, nacelle heights) resulting in similar risks, 5) acoustic equipment (bat detectors and microphones) have comparable sensitivity and are placed in a similar way.

Given all the above assumptions, the average collision rate (number of collisions per turbine and night) can be estimated from the acoustic activity (number of bat recordings per turbine $i$ and night $t$, $A_{it}$) and the median of the wind speed over the night ($W_{it}$), using the following relationship/model (Brinkmann *et al.* 2011, Table 5 p. 340):

$$\hat{\lambda}_{it} = \exp(-2.811 + 0.662 zA_{it} - 0.277 zW_{it} - 0.231 zW_{it}^{2})$$

$zA_{it}$ and $zW_{it}$ are the standardized activity and wind measurements. Standardizing is transforming the variable, by taking off the mean and dividing by the standard deviation resulting in a variable with a mean of zero and a standard deviation of one.

There are considerations to make before applying the German model to other than German data, as is intended here. One important question is which standard deviations and means should be used to standardize activity and wind measurements: the means and deviations from the BMU-project or those resulting from the Dutch project? In this study both possibilities are tried. The observed variability of the outcome will reflect one aspect of the uncertainty of prediction from one project to another.

[3] The model was developed in a research project financed by the German Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit / BMU.

[4] In fact two models were developed 1) Estimation of number of collisions based on carcass search data alone (Brinkmann *et al.* 2011, Korner-Nievergelt *et al.* 2011) and 2) estimation of number of collisions based on combination of carcass search and acoustic activity. This model, once established, can also be used to predict collisions at turbines without carcass searches (Brinkmann *et al.* 2011, Korner-Nievergelt *et al.* 2013).

# 8 Results from bat fatality searches

In the five wind farms in the present study only 2 fatalities were found, during the whole of the search period. Both casualties were found in the wind farms in the Wieringermeer area. The first, a Nathusius' pipistrelle (*Pipistrellus nathusii*) was found on the August 6th 2012 at Wieringermeer-Waardtocht, and the second, a common pipistrelle (*Pipistrellus pipistrellus*) on September 9th 2012 at Wieringermeer-Waterkaaptocht.

Results on searcher efficiency and carcass persistence were statistically analysed by Dr. Fränzi Korner-Nievergelt and Dr. Pius Korner-Nievergelt (2013, Appendix I).

## 8.1 Results carcass persistence time

To estimate wind farm specific persistence probabilities, persistence was modelled as an autoregressive Bernoulli-process. Average daily persistence probability $\hat{s}_{it}$ varied from 0.186 to 0.884 (Table 8).

*Table 8 Estimated daily persistence probabilities $s_i$ of carcasses with the lower and upper limit of the 95% confidence interval.*

| Wind farm$_i$ | $s_i$ | lower | upper |
|---|---|---|---|
| Almere | 0.468 | 0.290 | 0.648 |
| Burgervlotbrug | 0.884 | 0.812 | 0.941 |
| Herkingen | 0.748 | 0.637 | 0.844 |
| Wieringermeer-Kolhorn-Waardtocht | 0.735 | 0.619 | 0.835 |
| Wieringermeer-Waterkaaptocht | 0.186 | 0.051 | 0.383 |

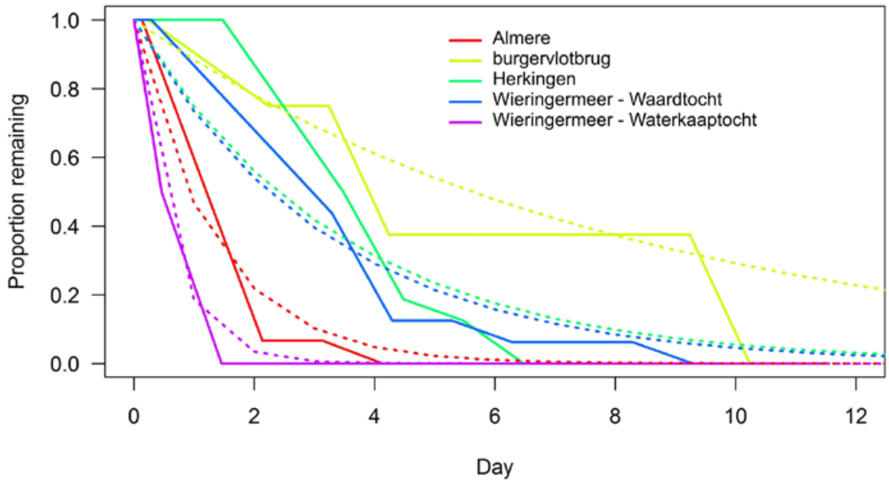


*Figure 8.1: Proportion of remaining experimental mice carcasses in relation to time (in days). Solid lines depict the data, dotted lines are the model.*

## 8.2 Results searcher efficiency

Sample size in the present study is – from a statistical view point – relatively low (n = 33, 43, and 8 number of laid out items for the three visibility classes). Therefore, the Dutch data were pooled with the data from the German study (Niermann *et al.*, 2011). Because the necessity of pooling of data was anticipated, the present study used the same classification of the visibility as the German study, allowing combining of data sets.
The pooling of the data sets results in searcher efficiency estimates, which are weighted averages between the independent person-specific estimates and the average over all the persons, where the German data set, being larger, has a larger influence on the outcome (also see Appendix I).

Based on the Dutch data alone, the average searcher efficiency was 0.942 (95% confidence interval: 0.739-0.989) for visibility class 1 (Type=1), 0.637 (0.39-0.827) for visibility class 2 (Type=2) and 0.915 (0.502-0.991) for visibility class 3 (Type=3). The location-specific searcher efficiency estimates based on the Dutch data are presented in Table 9.

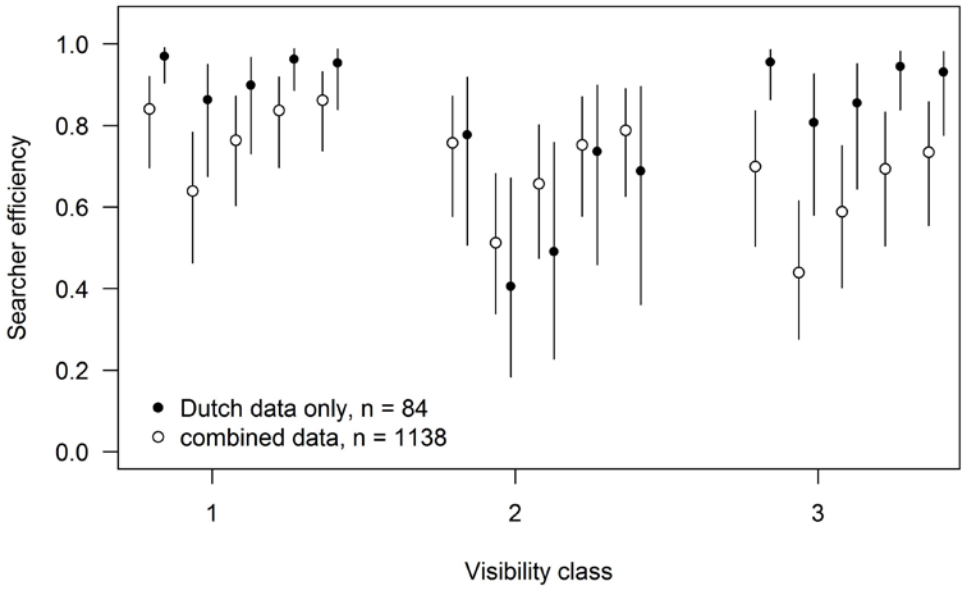


*Figure 8.2: Estimated searcher efficiency f based on the Dutch data, as well as on a combined data set from the German study. The 5 estimates per visibility class are for the 5 different locations (from left to right: Almere (3 search turbines), Burgervlotbrug (4), Herkingen (3), W.-Waardtocht (5), W.-Waterkaaptocht(10)).*

*Table 9: Estimated searcher efficiency for each location and visibility class with the lower and upper limit of the 95% confidence interval. These estimates are based on the Dutch data alone.*

| Visibility class | Location | f | lower | upper |
|---|---|---|---|---|
| 1 | Almere | 0.970 | 0.905 | 0.990 |
| 2 | Almere | 0.777 | 0.507 | 0.918 |
| 3 | Almere | 0.955 | 0.863 | 0.986 |
| 1 | Burgervlotbrug | 0.863 | 0.675 | 0.949 |
| 2 | Burgervlotbrug | 0.405 | 0.184 | 0.671 |
| 3 | Burgervlotbrug | 0.807 | 0.580 | 0.926 |
| 1 | Herkingen | 0.899 | 0.731 | 0.966 |
| 2 | Herkingen | 0.490 | 0.228 | 0.758 |
| 3 | Herkingen | 0.855 | 0.644 | 0.950 |
| 1 | Wieringermeer-Waardtocht | 0.963 | 0.886 | 0.988 |
| 2 | Wieringermeer-Waardtocht | 0.736 | 0.459 | 0.899 |
| 3 | Wieringermeer-Waardtocht | 0.945 | 0.839 | 0.982 |
| 1 | Wieringermeer-Waterkaaptocht | 0.953 | 0.839 | 0.987 |
| 2 | Wieringermeer-Waterkaaptocht | 0.688 | 0.361 | 0.895 |
| 3 | Wieringermeer-Waterkaaptocht | 0.931 | 0.776 | 0.981 |

The combined estimates of the Netherlands and German study are given in Table 10. These estimates are shrunk towards the population mean which is dominated by the German data (Figure 8.2). For visibility class 3, the sample size in the Netherlands data was very low (8) and the estimates surprisingly high. Therefore, for this group, the shrinkage was large (Figure 8.2). In the subsequent analyses and modelling, we used the estimates based on the combined data (Table 10).

*Table 10: Estimates for searcher efficiencies f for each location and visibility class, combining the data from [Niermann et al., 2011] with the Dutch data. The last two columns give the lower and upper limit of the 95% confidence interval.*

| Visibility class | Location | f | lower | upper |
|---|---|---|---|---|
| 1 | Almere | 0.840 | 0.697 | 0.920 |
| 2 | Almere | 0.758 | 0.577 | 0.872 |
| 3 | Almere | 0.700 | 0.504 | 0.835 |
| 1 | Burgervlotbrug | 0.640 | 0.463 | 0.783 |
| 2 | Burgervlotbrug | 0.513 | 0.338 | 0.682 |
| 3 | Burgervlotbrug | 0.440 | 0.276 | 0.615 |
| 1 | Herkingen | 0.764 | 0.604 | 0.872 |
| 2 | Herkingen | 0.658 | 0.475 | 0.801 |
| 3 | Herkingen | 0.589 | 0.402 | 0.750 |
| 1 | Wieringermeer-Waardtocht | 0.837 | 0.697 | 0.919 |
| 2 | Wieringermeer-Waardtocht | 0.752 | 0.577 | 0.870 |
| 3 | Wieringermeer-Waardtocht | 0.694 | 0.505 | 0.833 |
| 1 | Wieringermeer-Waterkaaptocht | 0.862 | 0.738 | 0.932 |
| 2 | Wieringermeer-Waterkaaptocht | 0.788 | 0.626 | 0.890 |
| 3 | Wieringermeer-Waterkaaptocht | 0.735 | 0.555 | 0.858 |

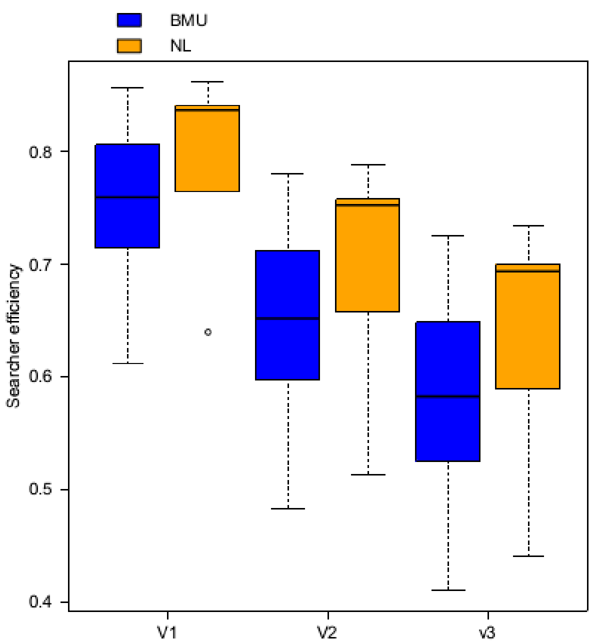


*Fig 8.3 The searchers in the Dutch project have scored somewhat better on finding the dummies than those in the German project.*

### 8.3 Results regarding proportion of carcasses in the searched area

To estimate the proportion of carcasses that have fallen into the search area, we used the proportion of area searched per 10 m distance ring for each wind farm.

Calculation of the proportion of carcasses lying in the searched area takes into account that carcasses are not homogeneously distributed. The distribution of bat carcasses beneath a wind turbine depends on the height of the turbine and the rotor diameter [Hull and Muir, 2010]. The turbines in the Dutch study were relatively small except the ones at Herkingen. We used the results from three studies that presented information about the spatial distribution of bat carcasses beneath wind turbines with rotor diameter of less than 80 m: Niermann *et al.* 2011, Arnett *et al.* 2005 and Hull and Muir 2010. We averaged the spatial distribution of bat carcasses over the three studies We assumed that no bat carcass was further than 50 m away from the turbine. In this way, we obtained the following theoretical distribution of bat carcasses among the 10 m distance rings: 0-10m: 17%, 10 – 20m: 28%, 20-30m: 26%, 30-40m: 21%, and 40-50m: 8%. For each distance ring, we multiplied the theoretical proportion of bat carcasses with the proportion of area searched within the specific distance ring. At last, these products were summed over the 5 distance rings to obtain the proportion of bat carcasses that have fallen into the area that was searched.

*Table 11 Tower height and rotor diameter (m) in the 5 wind farms*

| location | tower height | rotor diameter |
|---|---|---|
| Almere | 67 | 66 |
| Burgervlotbrug | 65 | 52 |
| Herkingen | 80 | 80 |
| Wieringermeer-Kolhorn-Waardtocht | 78 | 66 |
| Wieringermeer-Waterkaaptocht | 78 | 66 |

The results show that the proportion of carcasses lying in the search area can be considered constant over time in all wind farms. Visibility classes also remained constant over the course of the data collection, with very slight changes in Almere (also see Appendix I).

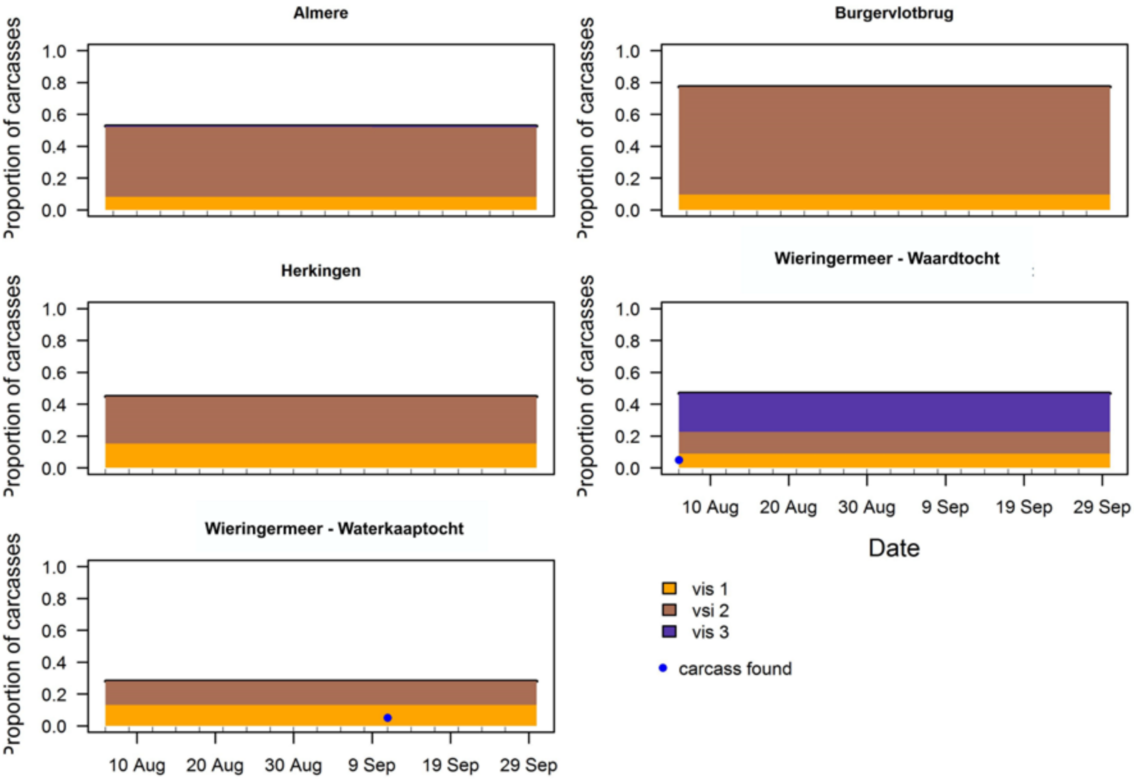


*Figure 8.4: Proportion of carcasses expected to lie in the search area (based on the proportion of area that could be searched per 10 m distance ring and a theoretical spatial distribution of the bat carcasses. Colours indicate visibility classes. The black tick marks inside the plot indicate days with searches.*

# 9 Outcome of estimating fatalities and modelling

## 9.1 Estimation of the number of fatalities based on carcass search data alone

The low number of carcasses found in the present study (c = 2) would lead to a very imprecise estimation of the number of fatalities for a specific site, when based on carcass data alone (Korner-Nievergelt *et al.*, 2011). Therefore wind farm-specific estimates on carcass data alone are not calculated.

Here, we first estimate the number of fatalities for all five sites, during the whole study period based on carcass search data. Three different methods to combine the estimates for carcass persistence probability *s*, searcher efficiency *f*, and proportion of carcasses laying in the search area *a* to establish the probability p that a bat killed during the study period was found by a searcher (carcass detection probability *p*) were used (also see Appendix I, Bernardino *et al.* 2013).

At each wind farm, 18 searches took place with a search interval of 3 days. The average daily carcass persistence probability (averaged over the 5 wind farms) was 0.604 (95% CI: 0.547 - 0.667). The average searcher efficiency (averaged over the persons and weighted average over the visibility classes) was 0.677 (95% CI: 0.639 - 0.715). The average proportion of carcasses lying in the search area was 0.499. These statistics lead to a carcass detection probability of 0.277 to 0.349 depending on the method used (Korner-Nievergelt *et al.* 2011: 1) formula assuming constant s and constant f, 2) formula assuming constant s but decreasing f over time, and Huso 2010: 3) different model, assuming constant s with not explicit assumption about f).

The lowest detection probability is estimated using the method of Korner-Nievergelt *et al.* (2011) assuming that the searcher efficiency decreases with the number of searches because it is more difficult to detect carcasses the longer they remain on the ground. The highest detection probability is obtained by the method of Huso.

Given a carcass detection probability and the number of carcasses found (which was 2), we calculated that with a probability of 95% the true number of fatalities was between 4 and 50 with means of 14 to 18 depending on the method used (Table 12). These estimates are totals for all 25 wind turbines[5] where searches have been done, and for the whole of the study period (6 August to 30 September, i.e. 3*18=54 days).

Thus, the average daily fatality rate per turbine was between 14/25/54 =0.01 ([N = number of estimated casualties] / [number of turbines] / [n*d = search period]) and 18/25/54 =0.013 with an approximated 95% confidence interval of 0.003 to 0.037.

[5] Note: see paragraph 5.3: Searching at 2 turbines per site with 100% searchable area within the 50 m radius from the turbine foot, is needed for the statistical modelling. In practice the available turbines showed clearly smaller searchable areas. Therefore the available search time was used on searches at a larger number of turbines per site, with a total area up to approximately 2 x 100 % per site. We searched at 3 turbines at Almere, 4 at Burgervlotbrug, 3 at Herkingen, 5 at Wieringermeer-Waardtocht and 10 at Wieringermeer-Waterkaaptocht.

*Table 12 Estimated carcass detection probability p and total number of fatalities $\hat{N}$, during 54 nights, between August 6th and September 30th, at the combined 5 wind farms, with the lower and upper limit of the 95% confidence interval. These estimates are based on carcass search data alone.*

| Method | P | N | Lower | Upper |
|---|---|---|---|---|
| **Korner *et al.* 2011, 1** | 0.287 | 18 | 5 | 48 |
| **Korner *et al.* 2011, 2** | 0.277 | 18 | 5 | 50 |
| **Huso 2010** | 0.349 | 14 | 4 | 39 |

## 9.2 Estimation of fatality rates based on combined carcass search data and acoustic activity data at the nacelle

The uncertainty of the parameter estimates is very high (large standard errors in Table 13). When the data from the carcass searches (carcass detection probabilities, number of carcasses found) are combined with the acoustic activity and wind speed data, using the n-mixture model for the Dutch data only (see chapter 3.6 in Appendix I), an estimate is generated for the total number of fatalities at the 5 wind farms, with 95% probability, between 3 and 227. The median of the posterior distribution was 15 and its mean 35. The posterior distributions of the number of fatalities per wind farm are given in Figure 7.5.

*Table 13 Estimated coefficients of the linear predictor for the logarithm of daily collision rates from the n-mixture model, with the standard error (SE) and the r_hat value. The r hat value should be smaller than 1.02 otherwise the Markov chains have not converged.*

| parameter | estimate | SE | r_hat |
|---|---|---|---|
| intercept | -8.727 | 3.082 | 1.001 |
| activity | -3.907 | 2.874 | 1.002 |
| wind | -4.820 | 6.820 | 1.001 |
| $wind^2$ | -4.769 | 4.111 | 1.001 |

*Table 14 Estimated number of fatalities (N) from the combined data on carcass searches, acoustic activity and wind speed in the study period between August 3rd and September 30th at the 5 wind farms, with the lower and upper limit of the 95% confidence interval. Q = number of turbines, searches = number of searches, c = number of carcasses found, T = number of days (August 3rd - September 30th = 59 days), A = acoustic activity in number of recorded files with bat calls.*

| windfarm | Q | searches | c | T | A | N | lower | upper |
|---|---|---|---|---|---|---|---|---|
| Almere | 3 | 18 | 0 | 59 | 1647 | 4 | 0 | 24 |
| Burgervlotbrug | 4 | 18 | 0 | 59 | 47 | 1 | 0 | 4 |
| Herkingen | 3 | 18 | 0 | 59 | 92 | 14 | 0 | 92 |
| Waardtocht | 5 | 18 | 1 | 59 | 86 | 6 | 1 | 21 |
| Waterkaaptocht | 10 | 18 | 1 | 59 | 52 | 10 | 1 | 44 |

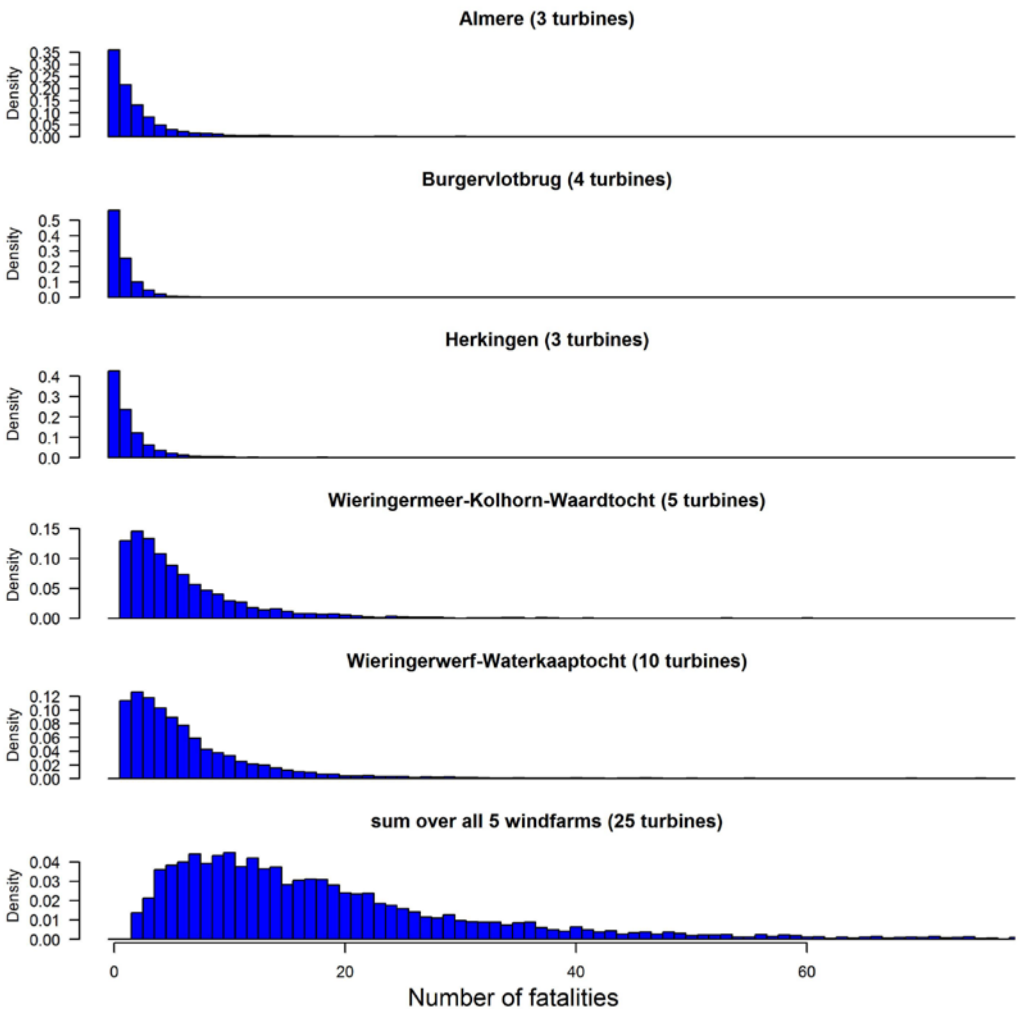


*Figure 9.1 Posterior distributions of the number of fatalities during the study period (3rd Aug. – 30th Sept.) at each wind farm and the total number of fatalities over the 5 wind farms.*

### 9.3 Estimation of fatality numbers based on the BMU-model 2010

The statistical relations between acoustic activity and wind on one side and collision risk on the other side that were present in the German data are the basis of the so called BMU model. The fatality estimations presented in this chapter are based only on the acoustic activity and wind speed measurements. In the present analysis we worked on the basis of the assumption that the relationship between acoustic activity and wind speed on one side and collision rate on the other is equal to the one in the German study (Brinkmann *et al.*, 2011). In the German study, this relationship was calculated based on the standardized acoustic activity and wind speed measurements (transformed so that their means were zero and their standard deviations one). When the BMU formula is applied to new activity and wind speed measurements, these new measurements have to be transformed in a similar way as in the German study, i.e.

zA = (log(A + 1) - mean(log(A + 1))) = sd(log(A + 1)) and zW = (W - mean(W))=sd(W).

Since it is still unclear whether means and standard deviations from the original BMU data, or the data from our study should be used, both transformations are tried.

Using this model, using these statistical relationships, there seems to be little difference whether the means and standard deviations from the BMU data or the Dutch data are used for calculations: Using the means and standard deviations from the Dutch data, with the fatalities and acoustic activity and weather from the Dutch data, in the German model, generates an estimate for the real number of fatalities of 142 (83-253). Using the transformation exactly as used in the BMU-project, with the fatalities and acoustic activity and weather from the Dutch data, generates an estimate of 135 (77-259).

However, in both cases, using means and standard deviations from the Dutch or German data, the estimates based on the statistical relations in the BMU model alone, were almost 4 times higher than estimates based on the Dutch data alone (Table 15).

When we combine the information from the BMU-project regarding the relationship between acoustic activity and wind speed on one the hand and collision rate on the other hand with the Dutch data, we obtain an estimate of 54.7 (95% CrI: 33-82) fatalities during the study period of 59 days at the 25 wind turbines[6].

*Table 15: Estimated number of fatalities between August 3rd and September 30th at the 5 wind farms with the lower (l) and upper (u) limit of the 95% confidence interval. Q = number of searched turbines, NL = based on the Dutch data alone, BMU = based on the BMU-model alone using the transformations as used in the BMU-project, BMU NL = based on the combination of the Dutch data with the BMU-data*

| Windfarm | Q | NL | NL.l | NL.u | BMU_NL | BMU_NL.l | BMU_NL.u | BMU | BMU.l | BMU.u |
|---|---|---|---|---|---|---|---|---|---|---|
| **Almere** | 3 | 4 | 0 | 24 | 13 | 5 | 28 | 43 | 20 | 89 |
| **Bu.brug** | 4 | 1 | 0 | 4 | 4 | 0 | 9 | 13 | 7 | 23 |
| **Herk.** | 3 | 14 | 0 | 92 | 6 | 1 | 12 | 14 | 8 | 26 |
| **W.tocht** | 5 | 6 | 1 | 21 | 9 | 4 | 18 | 35 | 13 | 99 |
| **W.kaapt.** | 10 | 10 | 1 | 44 | 20 | 11 | 33 | 30 | 19 | 48 |
| **All 5** | 25 | 35 | 3 | 227 | 54 | 33 | 82 | 135 | 17 | 259 |

The acoustic data from Almere are 10 times higher than at the other sites (table 14), and at this site no fatalities were found. All equipment was checked again and the fatality searches and searcher efficiency and carcass persistence tests were performed as they should be performed. Therefore the data from Almere are accepted as real and we process the data in a version with and without these Almere data.

[6] Note: 2 times 100% searchable area in 50 m radius, approximated through searching at 3 turbines at Almere, 4 at Burgervlotbrug, 3 at Herkingen, 5 at Wieringermeer-Waardtocht and 10 at Wieringermeer-Waterkaaptocht.

When the model is fitted to the Dutch data alone, and the data from Almere are excluded, the fatality estimates increased by more than a factor 2 (table 16). When the model was fitted to both the Dutch and the German data, excluding the data from Almere had no substantial effect on the estimate of the daily collision rate per turbine (54/25 turbines/59 nights = 0.037, vs. 43/22 turbines/59 nights = 0.033).

*Table 16 Estimated number of fatalities between 3 Aug and 30 Sept at the 4 wind farms (Almere excluded) with the lower (l) and upper (u) limit of the 95% confidence interval. Q = number of turbines, NL = based on the Dutch data without Almere, BMU NL = based on the combination of the Dutch data (without Almere) with the BMU-data.*

| Windfarm | Q | NL | NL.l | NL.u | BMU_NL | BMU_NL.l | BMU_NL.u |
|---|---|---|---|---|---|---|---|
| **Almere** | 3 | | | | | | |
| **Bu.brug** | 4 | 1 | 0 | 5 | 4 | 1 | 9 |
| **Herk.** | 3 | 47 | 0 | 239 | 6 | 2 | 13 |
| **W.tocht** | 5 | 7 | 1 | 23 | 10 | 4 | 19 |
| **W.kaapt.** | 10 | 21 | 1 | 112 | 22 | 11 | 36 |
| **All 5** | 25 | 75 | 3 | 432 | 43 | 25 | 66 |

## 9.4 Curtailment algorithm

As a result of the low sample size, high variation in acoustic activity and extremely low number of found casualties, calculation of a curtailment algorithm based on Dutch data alone is not yet reliable. To develop a curtailment algorithm for the Dutch wind turbines, more data and subsequent analysis is needed on the prediction of bat activity.

# 10 Conclusion and discussion

## 10.1 Estimation of fatality numbers

The total number of fatalities at the 25 wind turbines[7] was estimated using different methods and different sources of data.

The lowest estimate of 15 fatalities in 54 days at 25 wind turbines was obtained through correcting the number of carcasses found by the carcass detection probability (table 12).

When data on acoustic activity were used to enhance the carcass search data, an estimate of 35 casualties in 59 days at 25 wind turbines was obtained from data including Almere. At the site Almere recorded acoustic activity was extraordinary high and no fatalities were found (table 14). Running the model excluding these extraordinary data generated an estimate of 75 casualties in 59 days at 22 wind turbines.

When combining the entire data from the Netherlands (inclusive Almere) with the BMU-data, we estimate a total number of bats of 54 killed during the 59 days at the 25 Dutch wind turbines.

These large differences between the different fatality estimators reflect the low number of casualties found in this specific research at 5 sites in the Netherlands. Only 2 carcasses were found, and at the same time the ratio between the number of carcasses found and the number of recorded bat calls (acoustic activity) was extremely variable between the wind farms. This impedes the description of a clear relationship between acoustic activity and collision rate. This can be tackled by collecting more data at wind farms in the Netherlands.

*Estimation of 'true fatality numbers' based on only fatality searches, is possible, in the Dutch situation and estimation formula used here (Niermann et al. 2012) are valid and functional. However a reasonable precision of the estimate can only be achieved when higher (> 10) numbers of carcasses are be found.*

## 10.2 Combining carcass search data with acoustic activity

We have to be aware that we are testing the functionality of the model(s) on the basis of the assumption that the relationship between acoustic activity and wind speed on one side and collision rate on the other is equal to the one in the German study. We should be well aware that there will be differences e.g. as a result of differences in landscape and species composition. Given the frail information about fatality rates in the now available Dutch data, we nonetheless recommend to use the estimates based on the model that combines the Dutch data with the German data (BMU NL in table 15). In this estimate, we have - up to now - included the data from Almere. Higher fatality estimates may be expected when Almere is excluded.

[7] Because the searchable area per turbine was smaller than 100%, using the available time and budget, searches were done at a total number of 25 different turbines.

The high numbers of bat calls recorded at Almere, where no carcasses have been found are extraordinary. At both of the turbines where a carcass was found each, the total number of bat calls did not exceed 100. Based on such observations, one would expect more than one carcass at a turbine with over 1600 bat calls, especially since given carcass detection probability at Almere was similar to that at the other farms. Therefore, we suspect that something is different with Almere.

The data from Almere may cause the model to estimate much smaller collision rates in relation to acoustic activity, than those generated with the German data. We, therefore, fitted the model to the Dutch data excluding data from Almere. Indeed, the generated fatality estimates based on the Dutch data, ignoring data from Almere, were twice as high as those generated including Almere (NL1 in table 15). This exercise is, however, only intended to explore the differences. It is statistically not legitimate to exclude data. Maybe in reality the spatial and temporal variance in the ratio between collision rate and recorded bat calls is much larger than we think. The only answer to this uncertainty can be found in collecting more data to keep on improving the model ability to reliably predict collision rate. None the less, in exploring the spatial and temporal relations between bats, (a)biotic parameters and collision risk, it may be valuable searching for (other than stochastic) reasons why no carcass has been found at Almere despite the large number of recorded bat calls.

In order to give this phenomenon a closer look, the probability of finding only 2 or less carcasses was calculated, given the acoustic activity and wind speed measurements and assuming the same relationship between acoustic and wind speed on one side and collision rate on the other side as in Germany and a carcass detection probability of 0.3 (as measured in the current study). This generates a probability of 2.2% of finding 2 or less carcasses. It would be expected to find 9 carcasses, and in 95% of the cases we would have expected the number of carcasses found to be within 3 and 21.

The low number of casualties in combination with high differences in acoustic activity renders the process in the model vulnerable for small deviation from the protocol. We assume e.g. that when spending search time on small areas at 10 turbines instead of 100% at two turbines could lead to some ‘’loss of search time’’ to traveling between turbines. Fieldworkers however estimate that this time can be neglected. Small differences between the German and Dutch data in the ratio of time spend searching and on searcher efficiency tests may have an effect. Differences in visibility classes between the two data sets might have an impact. It is therefore important to try and enhance the Dutch data set through using the approach and protocols from the current study in new site studies.

### 10.3 Using the BMU model based on German data for estimating the fatality numbers

Using the model build on the German data (Brinkmann *et al.* 2011, Korner-Nievergelt *et al.* 2011) and Dutch acoustic activity data alone, higher numbers of fatalities were predicted than when looking at the carcass search data. This means that the ratio between activity and fatalities in the Dutch data is higher than in the

German data. Reasons for this overestimation using the German model with just the Dutch acoustic data may point to less harmful turbine types in the Netherlands, a species composition less susceptible to collisions or more recorded bat calls per flying bat.

We have to be aware that e.g. 'northern' sites in the German project include both north eastern and north western sites, where the north western sites are more alike the Dutch sites, and also showed below average activity and fatalities (Behr *et al.* 2011, Brinkmann *et al.* 2011). This supports the conclusion that the fatality risk in the studied Dutch sites is low. At this point we refrained from modelling only using German data from the northern sites in combination with Dutch data. Since the total number of sites used for modelling would be lower, the 95% confidence interval would be larger and estimates less accurate. In future, with more Dutch data and data from northern Germany, this will probably become an approach to enhance estimates for these landscapes.

Since the assessed landscape parameters at the five sites in the Netherlands were all from open lowland areas, and thus not very discriminative, it will be of interest to test how adding data from different Dutch landscapes might aid the model predictions. Possibilities for further enhancement could lie in analysis of characteristics of turbines and differences with respect to the turbines in the Dutch and German project, as well as to compare activity data between both projects to establish how similar or different conditions were and how this influence the reliability of the predictions from the BMU-model are. This, however, lies outside the scope of the current project.

*Using the German model (Korner-Nievergelt et al. 2011), i.e. using the combination of carcass searches, acoustic activity and weather, for estimation of 'true fatality numbers', is possible in the Dutch situation, and can be statistically meaningful on the level of individual wind farm sites. Enhancing the model with more standardised data from Dutch Wind farm sites, is important to decrease uncertainty, gain prediction power and to validate the underlying model assumptions.*

### 10.4 Model for acoustic activity

The model presented here can potentially be used to predict average acoustic activity for 10 min intervals based on time, date and weather parameters. The prediction from such a model can be used in curtailment algorithms based on collision risk estimates for the real time. This is important e.g. for estimating risks and mitigation at off shore wind farms or wind farms in fresh water lakes, where bats are present (Ahlen *et al.* 2007, Jansen *et al.* 2013, Jonge Poerink *et al.* 2013), but fatality searches are not possible.

Due to the low sample size in the current research, model fit is poor as will be the predictive power. Future steps for the development of the model lie in more detailed analysis of and inclusion of landscape parameters as predictors, accounting for temporal autocorrelation (10min intervals close together in time are more similar to each other than 10min intervals far away in time), using cross-validation to assess predictive power, trying a model that accounts for zero-inflation (when there are many zero's a distinction should be made between true zero's and excess zero's. Bats can be absent altogether [excess zero] or can be absent because of unfavourable conditions [strong wind; true zero]), aligning the Dutch data with the German lowland data.

Since the possibility of predicting data for sites where no fatality searches are possible, e.g. sites in water, or to be able to calculate curtailment algorithms without having to do the time consuming fatality searches is extremely valuable, it is of great importance to collect more data on activity and fatalities on Dutch wind farms. Therefore a policy to stimulate the use of the approach and protocols from the current study – based on the German study – resulting in a larger set of data representative for the Netherlands would be of great importance.

*Using the German model (Korner-Nievergelt et al. 2011), i.e. using the combination of only acoustic activity and weather data, for estimation of 'true fatality numbers' in situations where no carcass searches are possible (Behr et al. 2011), is achievable in the Dutch situation. The registered activity in this study, however, showed a large variance making predictions unreliable. This needs more input of standardised Dutch data to produce stronger prediction power.*

## 10.5 Curtailment algorithm

From German and American research (Arnett *et al.* 2009a, b, 2010; Brinkmann *et al.* 2011) it is clear that curtailment of the turbines can be a powerful mitigation of collision risk, at those parts of the night and season, and at wind speeds at which collision risk is high. The challenge is to optimize the prevention of fatalities and energy production.

An important future step for the Netherlands would be to develop a curtailment algorithm specific for the Netherlands and specific sites, which would help to decide at what times in the season and night curtailing of turbines will lead to a maximum of fatality prevention at a minimum loss of energy production.

A curtailment algorithm requires powerful models to predict bat activity and to estimate collision rate based on estimated activity. However, for the moment, the data base may be too scarce for the development of precise curtailment algorithms for the Netherlands based on Dutch data. It is possible to use the combined Dutch and German data, but given the higher incidence of fatalities in the German study compared to those in the current study, this will probably lead to unnecessary curtailment.

*Using the German model (Korner-Nievergelt et al. 2011), i.e. using the combination of fatality searches, acoustic activity and weather and landscape data, or a combination without fatality searches, as a basis for curtailment algorithms optimizing prevention of fatality risk and energy production (Bearwald et al. 2009, Behr et al. 2011c), is possible in the Dutch situation. In order not to curtail turbines when this is not necessary, it is of importance to get more input of standardised Dutch data.*

*An important step towards a more reliable and effective curtailment algorithm, in terms of mitigation effectiveness as well as minimizing loss in produces energy,* *would be to pool all available data from central Europe. Such modelling however, would need an extensive computer (supercomputer) as well as more time for statisticians. This is not possible within a "standard data analysis".*

### 10.6 General conclusion

It proved to be possible to assess acoustic activity, fatalities, searcher efficiency, carcass persistence, searchable area and searchability classes, and weather and landscape parameters, using the protocols.

Found carcasses were very few (2) and the acoustic activity showed a large variance. The explanatory power of landscape parameters from Dutch sites is poor since data were assessed at five sites with rather similar landscape parameters.

Fitting and aligning the data from the 5 Dutch wind farms to the German model resulted in workable estimates. Since the volume of Dutch data is small compared to the German data, the German data, for now, will have the larger impact on the generated estimates and most probably overestimate fatalities. Generating estimates based on Dutch data only is possible, but will lead to greater deviances. Estimates of collision risks based on combined German and Dutch data are possible but will be dominated by the German data and might be less accurate for the Dutch situation.

Estimates of collision risks based on only the Dutch data are possible, but they still have a large spread and thus are not very precise.

In general, the protocols and models work, but due to the small Dutch sample size and large variance, estimates and predictions are too imprecise. It is, therefore, of utmost importance to enlarge the number of study sites, and to use the protocols for assessing acoustic data and data on fatalities (incl. search efficiency and persistence) and on weather, landscape, et cetera in the Netherlands, and make these data available, to be able to use these in improving the reliability of the predictions with the model.

We have to acknowledge that the possibility to use the protocols and models from the German project was tested, with positive results, but that estimates and predictions presented in this study are not yet precise estimates for the study sites.

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# Appendices

## Appendix I. Statistiscal analyses Dr. Fränzi Korner-Nievergelt

# Analyses of bat collision data at wind farms in the Netherlands

Report data analysis, June 26, 2013



| | |
|---|---|
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# Contents



# 1 Aims and general procedure

The aims of the project are:

1. Quantification of bat collision rate at 6 wind farms (Almere, Burgervlotbrug, Herkingen, Waardtocht and Waterkaaptocht) during the study period.

2. Contribution to the development of a model for the prediction of bat collision risk at wind towers.

3. Development of a mitigation method (curtailment algorithm).

Specific points to be done by oikostat:

1. Estimate carcass persistence probabilities for the five wind farms where carcass searches have been performed.

2. Estimate searcher efficiency based on data and, if necessary, on estimates from the literature or other studies such as the German BMU-project.
3. Estimate proportion of bat fatalities lying in the search area.
4. Combine the estimates on carcass removal rates, searcher efficiency, proportion of fatalities lying in the search area with the numbers of found fatalities to get an estimate of the absolute number of fatalities.
5. Model acoustic bat activity based on weather data, time of the night and date.
6. Combine all information from carcass searches with acoustic activity to obtain a more precise estimate of the number of fatalities and to predict bat collision rates.
7. If necessary, combine activity model of the Netherlands with the one from Germany.
8. If possible, develop a curtailment algorithm.

## 2 Data

We have received the following data files:

1. "**Locaties dode muizen-def130121.xls**" (e-mail 3. 4. 2013 from Maurice de Haye) containing the data from the carcass removal experiment
2. "**Vindkansproef-search-efficiency-130403-def.xlsx**" (e-mail 3. 4. 2013 from Maurice de Haye) with the data from the search efficiency experiment.
3. "**10-481 Landschap oppervlaktes per park.xlsx**" (e-mail 12. 4. 2013 from Maurice de Haye) with landscape parameters as well as characteristics of the turbines for each wind farm
4. "**10-481 search area and vegetation.xlsx**" (e-mail 12. 4. 2013 from Maurice de Haye) with proportions of vegetation types and area searched for each 10 m-distance ring for each turbine
5. "**10-481 turbine details-def.xlsx**" (e-mail 12. 4. 2013 from Maurice de Haye) with details for each turbine
6. "**10-481 Landscape distances key habitats.xlsx**" (e-mail 16. 4. 2013 from Maurice de Haye) with geographical coordinates and distances to nearest forest and waterbodies for each of the 5 wind farms
7. "**bat-fatality-nr1-PipNat-120806.xls**" (e-mail 16. 4. 2013 from Maurice de Haye) with the following information: One *Pipistrellus nathusii* was found at turbine nr. 5 in Waardtocht wind farm, 1.5 m from the tower in NW direction. Estimated age of carcass: 1-2 days. Finding date is 6. 8. 2012. It was laying on the basement of the turbine.
8. "**Bat-fatality-Nr2-Pipi-120911.xls**" (e-mail 16. 4. 2013 from Maurice de Haye) with the following information: One *Pipistrellus pipistrellus* was found at turbine nr. 4 in Waterkaaptocht wind farm, 32 m from the tower in S direction. Estimated age of carcass: 1 day. Finding date is 11. 9. 2012. It was laying on a path way.
9. "**Planning search activity.xls**" (e-mail 17. 4. 2013 from Maurice de Haye) with the date of searches for each wind farm.
10. "**Totaal bestand 22052013.xlsx**" (e-mail 22. 5. 2013 from Herman Limpens) with acoustic activity data.

The data on persistence times contained histories of 79 carcasses that were laid out at 5 wind farms. They were controlled over 12 days. For each day and each individual carcass it was indicated whether the carcass was still present. There were some missing values for days without controls.

The data on searcher efficiency contained the information which of the 84 objects laid out in 5 wind farms was found by the searcher during one search or which not. For each object the visibility class of its location was indicated. At each wind farm a different person has done all the searches. Therefore, we estimated, for each wind farm, one searcher efficiency per visibility class.

The search area data file contained for all turbines and for each 10 m distance ring the area of each visibility class and the area that could not be searched (in $m^2$ and as proportion). In Almere searches were done at 3 turbines, in Burgervlotbrug at 4, in Herkingen at 3, in Wieringermeer-Kolhorn-Waardtocht at 5, and in Wieringerwerf-Waterkaaptocht at 10 turbines. In total, carcass searches were done at 25 turbines.

We rearranged the data with the days of the searches so that for each wind farm and day the variable "searches" indicated whether there was a search or not. Further, the variable "dayofstudy" gave the number of days since 5 August (i.e. 1 = 6 August).

Acoustic activity data has been measured on the ground and at the nacelle of six wind turbines. Here, we will use the activity measures at the nacelle only, because acoustic activity measured at the ground is only very weakly correlated with acoustic activity measured at the nacelle, where the bats are exposed to collision [Behr et al., 2011].

All data sets were analysed using the software R 3.0.0 [R Core Team, 2012].

# 3 Methods

## 3.1 Persistence time

To estimate wind farm specific persistence probabilities, we modeled persistence as an autoregressive Bernoulli-process. The state $z$ of a mouse carcass indicates whether it is still present (1 = presence, 0 = removed), and the state $z$ of mouse $i$ at time $t$ is $z_{i,t} \sim$Bernoulli$(\phi_{park} * z_{i,t-1})$. Note that the index $i$ is here used for the mouse, whereas it is used as the id of the turbine in the rest of the report. The parameter $\phi_{park}$ is the daily persistence probability and $park$ the indicator for the wind farm. Daily persistence probability was assumed to be constant. This seems to be a reasonable assumption for this data set as assessed from comparing the data with the model fit (Figure 4). We allowed daily persistence probability to vary between the wind farms by including wind farm as a random factor in the linear predictor for $\phi$.

The mice carcasses were deposited during the night before the first search at different times. The subsequent controls have taken place at 9 a.m. every day, except for the first day at 'Wieringerwerf-Waterkaaptocht' where it was 11.45. Therefore, time spans between deposition and first search varied between 3.25 and 11.5 hour. Between the subsequent controls, time span was around 24 h. In the model, we took into account the varying time span between deposition and first search by using a persistence probability of $\phi^{x/24}$, where $x$ is the wind farm-specific time span between deposition and first search. The bugs-code of the model is given in the grey box.

We fitted the model to the data using Bayesian methods, i.e. Markov chain Monte Carlo simulations in WinBUGS [Lunn et al., 2009]. WinBUGS was accessed from R via the package R2WinBUGS [Sturtz et al., 2005]. We simulated 2 Markov chains of length $10^6$. The first $10^4$ iterations were discarded as burnin and of the remaining iterations each 50 simulations were used to describe the posterior distributions of the model parameters.

```
# bugs-code of the model to estimate persistence probability
sink("surivalmod.txt")
cat("
    model{
```

```
    # priors and constraints
    for(i in 1:nind){
      for(t in 1:nocc-1){
            logit(phi[i,t]) <- beta + rpark[park[i]]
      }# close t
    }# close i
    beta~dnorm(0, 0.001) # flat prior for beta
    for(p in 1:nparks){
      rpark[p]~dnorm(0, taupark) # random factor park
    } # close p
    taupark~dgamma(0.01, 0.01) # flat prior for taupark

    # likelihood
    for(i in 1:nind){
      # for the first search
      z[i,2] ~ dbern(mu1[i,2])
      mu1[i,2] <- pow(phi[i,1], durfirst[i]/24)*z[i,1]
      for(t in 3:nocc){
        # state process
        z[i,t] ~ dbern(mu1[i,t])
        mu1[i,t] <- phi[i,t-1]*z[i,t-1]
        # observation process
      } # close t
    } # close i
    } # close model
 ",fill=TRUE)
sink()
```

Convergence was assessed based on the r-hat value [Brooks and Gelman, 1998] and on visual inspection of the Markov chains (plots not shown).

### 3.2 Searcher efficiency

We used a generalized linear mixed model (GLMM) to estimate searcher efficiency for each person (wind farm) and visibility class. The combined numbers of detected and not detected items were used as outcome variable assuming the binomial error distribution. We used the logit-link function. Visibility class was included as a fixed effect and person (location) as random effect. The function glmer from the package lme4 [Bates, 2005] was used to fit the model to the data. Bayesian credible intervals for the estimated searcher efficiency values were obtained from the joint posterior distribution of the model parameters by simulating 5000 random sets of model parameters using the function sim from the package arm [Gelman and Hill, 2007]. From these 5000 sets of model parameters, 5000 fitted values were calculated and their 2.5% and 97.5% quantiles used as lower and upper limit of the credible interval.

Since sample size was low in the Dutch data (n = 33, 43, and 8 number of laid out items for the three visibility classes), we combined the Dutch data with the data from a German study [Niermann et al., 2011]. The present study used the same classification of the visibility as the German study which allows combining the two data sets. We matched the German visibility class "offen" to Type=1, "überwachsen" to Type=2 and "stark überwachsen" to Type=3. The average searcher efficiency for the three visibility classes in the German study are given in Table 1.

The pooling of the Dutch and German data in the way we have done it (GLMM) results in searcher efficiency estimates that are weighted averages between the independent person-specific estimates and the average over all the persons with weights equal to the precision (inverse of variances) of the estimates. As a consequence, the resulting estimates will be shrunk towards the average over all the persons. The amount of shrinkage is determined by the precision of the independent person-specific estimate (e.g. estimates that are based on a low sample size will be shrunk to a higher degree than estimates based on a large sample size).

Table 1: Searcher efficiencies from [Niermann et al., 2011] with the lower and upper limit of the 95% credible interval.

| visibility_dt | visibility_class | f | lower | upper |
|---|---|---|---|---|
| offen | 1.00 | 0.75 | 0.67 | 0.86 |
| überwachsen | 2.00 | 0.66 | 0.60 | 0.73 |
| stark überwachsen | 3.00 | 0.58 | 0.48 | 0.67 |

## 3.3 Proportion of carcasses in the searched area

We first merged the data with the dates of the searches per wind farm with the data of the proportion of the area searched per visibility class and distance ring.

Then, we calculated the proportion of carcasses lying in the search area taking into account that the carcasses are not homogeneously distributed. The distribution of bat carcasses beneath a wind turbine depends on the height of the turbine and the rotor diameter [Hull and Muir, 2010]. The turbines in the study were relatively small except the ones at Herkingen (Table 2). Up to now, there is not much (accessible) information about spatial distribution of bat carcasses beneath wind turbines. We found two studies that empirically estimated carcass distribution based on carcass searches [Arnett et al., 2005, Niermann et al., 2011] and one study that estimated this distribution based on a ballistic model [Hull and Muir, 2010]. The turbines investigated by these studies were slightly larger than the ones in the present study (Table 3). We choose the studies given in Table 3 with a rotor diameter smaller than 80 m and averaged the distributions. We assumed that no bat carcass was further than 50 m away from the turbine.

Table 2: Tower height and rotor diameter (m) in the 5 wind farms

| location | tower height | rotor diameter |
|---|---|---|
| Almere | 67 | 66 |
| Burgervlotbrug | 65 | 52 |
| Herkingen | 80 | 80 |
| Wieringermeer-Kolhorn-Waardtocht | 78 | 66 |
| Wieringerwerf-Waterkaaptocht | 78 | 66 |

Table 3: Proportions of bat carcasses in different distance rings from different studies. The proportions for the present study were derived from the first 4 lines of the table. n = number of bat carcasses.

| study | diameter | height | n | method | 10m | 20m | 30m | 40m | 50m | 50m+ |
|---|---|---|---|---|---|---|---|---|---|---|
| niermann2011 | 70 | 98 | 100 | empirical | 0.21 | 0.39 | 0.27 | 0.11 | 0.02 | 0 |
| arnett2005 | 72 | 80 | 398 | empirical | 0.1 | 0.26 | 0.28 | 0.26 | 0.07 | 0.03 |
| arnett2005 | 72 | 80 | 262 | empirical | 0.04 | 0.19 | 0.28 | 0.31 | 0.14 | 0.04 |
| hull2010AJEM | 66 | 65 | | physical_model | 0.3 | 0.26 | 0.2 | 0.15 | 0.07 | 0.02 |
| hull2010AJEM | 90 | 80 | | physical_model | 0.24 | 0.23 | 0.19 | 0.15 | 0.12 | 0.07 |
| hull2010AJEM | 110 | 94 | | physical_model | 0.21 | 0.2 | 0.18 | 0.15 | 0.12 | 0.14 |
| this study | 66 | 74 | | | 0.17 | 0.28 | 0.26 | 0.21 | 0.08 | 0 |

## 3.4 Estimation of the number of fatalities based on carcass search data alone

Because of the low number of carcasses found in total ($c = 2$) estimation of the number of fatalities based on carcass search data alone will be imprecise [Korner-Nievergelt et al., 2011]. We, therefore, do not give wind farm-specific estimates based on carcass search data alone. We will do this based on a combination of carcass search data with acoustic activity data later. Here, we first estimate the total number of fatalities during the study period at the 5 wind farms together based on carcass search data alone. To do so, we used three different methods to combine the estimates for carcass persistence probability $s$, searcher efficiency $f$, and proportion of carcasses laying in the search area $a$ to get the probability $p$ that a bat killed during the study period was found by a searcher (henceforth called carcass detection probability $p$): 1) The method described in Korner-Nievergelt et al. [2011] that assumes constant persistence probability and constant searcher efficiency, 2) a version of 1) assuming decreasing searcher efficiency with the number of searches. This accounts for the fact that easy to find carcasses (e.g. such fallen on the top of a stone) will be found faster than hard to find ones (e.g. such fallen into a hole). We assumed, as suggested by Huso, that average searcher efficiency decreased to $1/4$ after each search. 3) The method described by Huso. Huso's estimator is based on the same assumptions but it uses a different underlying model. The different methods are reviewed and compared in Bernardino et al. [2013].

Given the carcass detection probability $p$ and the number of carcasses found, the Theorem of Bayes can be applied to obtain the posterior distribution of the number of fatalities (see e.g. Korner-Nievergelt et al. [2011]). From this posterior distribution of the number of fatalities we can extract the mean and a 95% credible interval, i.e. the interval within which we expect the true number of fatalities with a probability of 0.95.

The uncertainties in the estimates for persistence probability $s$ and search efficiency $f$ were taken into account by using Monte Carlo simulations. To do so, we repeated the whole calculations 5000 times, each time with different values from the posterior distributions of the wind farm specific persistence times (Table 4) and, for searcher efficiency, random values drawn from a Beta-distribution. This Beta-distribution was parameterized so that its mean and 95% interval corresponded to the experimentally determined searcher efficiency (see Korner-Nievergelt et al. [2013]). We so obtained 5000 different posterior distributions of the number of fatalities. At last we averaged the 5000 posterior distributions to obtain the final posterior distribution that described what we know about the number of fatalities after having looked at the data.

## 3.5 Acoustic activity

We first explore the acoustic activity data before combining them with the carcass search data. First, we describe the overall activity at the different wind turbines and the species composition. Then we construct a model to predict acoustic activity from weather, date and time.

Bat activity was recorded as the number of files containing bat calls per 10 minute interval for the nighttime. 0 means that no bats were recorded although the equipment was operational. -1 means that the equipment was not operational. Bats could not have been recorded. 5 means that 5 files were recorded containing bats calls. The equipment was not installed on the same day at each wind farm (documentation of activity data from Martijn Boonman).

The output of several Anabat filters was used. Double identification of bat calls was subsequently reduced per file by using a set of rules (separate documentation not given to oikostat).

The sum of all bats is not equal to the sum of all species (as seen in Fig. 1). Some files contain more than one species. In rare cases, a file containing all bats is not identified to a certain species (social calls, feeding buzzes).

Nyctaloid should contain all nycnocCF. The nycnocCF only provides extra information about the presence of noctules. NycnocCF only contains the typical qCF calls of the noctule bat, FM noctule bat calls are not picked up by this filter. Myotis only contains myotid FM calls. MyotisDasCF only identifies the typical qCF calls of the pond bat. Myotis does not contain MyotisDasCF. The sum of all myotids is thus better described by the sum of both Myotis and MyotisdasCF (documentation of activity data from Martijn Boonman).

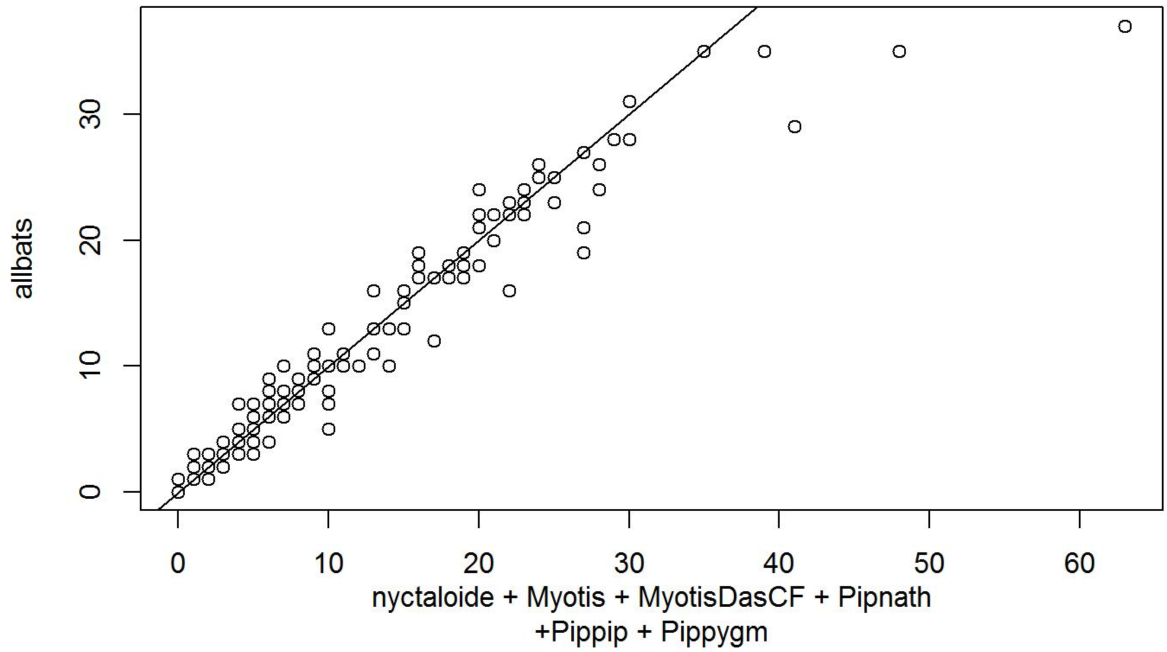


Figure 1: The number of recorded bat calls "Allbats" vs. the sum of all the identified categories.

Bat activity was higher in August than in September, especially at Jaap Rodenburg (Almere) and Waardtocht. *P. nathusii* was more abundant in September than in August, whereas *P. pipistrellus* was more abundant in August than in September (Figure 2). At Waterkaaptocht only Nyctaloids were recorded (this was checked by MB: even though a Pipipstrellus was found dead at this wind farm, no Pipistrellus call has been recorded there).

In the subsequent analyses, we will only look at the "allbats" data. The aim is to first use these activity measurements to more precisely estimate the number of fatalities during the study period. The second aim is to develop a model to predict the total number of bat calls from date, time, weather and maybe other explanatory variables. The final goal is to combine the two models above in order to be able to predict collision rate based on date, time, weather and maybe other predictors. This model could be used as a curtailment algorithm to reduce the number of bat collisions at wind farms while minimizing the loss of energy production. However, we will not reach the final goal yet because the model to predict bat activity will need more work and/or more data (see discussion).

The final goal, a curtailment algorithm, would involve the following three steps:

1. Prediction of bat activity from time, date, weather and maybe other explanatory variables.
2. Inference of collision rate from predicted bat activity.
3. Decision (stop or go) based on the ratio between collision rate and energy production according to a (political) decision on how many dead bats are tolerated on average.

We only estimate the number of fatalities for the actual study period. To develop a curtailment algorithm we would need to be able to extrapolate the prediction of fatalities to the whole range of dates, time and weather situations and the predictive power of the model would have to be assessed carefully. To reach a satisfactory predictive power, the model has to be based on sufficient and representative data. In the discussion section, we suggest a number of further points that have to be addressed before the model may be used in a curtailment algorithm.

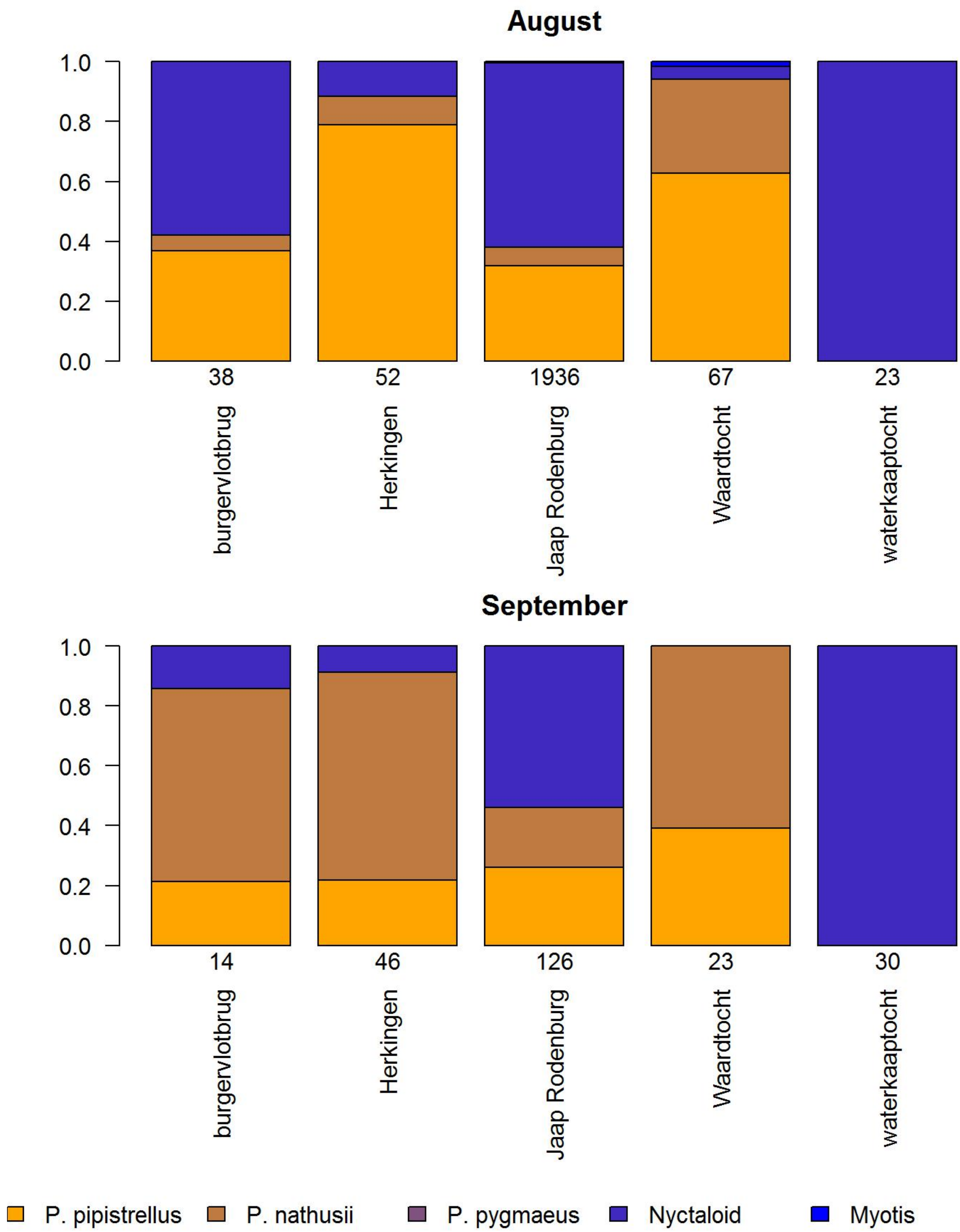


Figure 2: Composition of the identified bat calls per wind turbine and month. The numbers below the bars give the absolute number of identified bat recordings.

We used generalized linear mixed models (GLMM) to predict the number of bat calls per 10 min interval from date, time, and weather. The Poisson error distribution was assumed and the logarithm link function used. We included the wind farm as a random factor to account for between-wind farm variance in overall bat activity. In the full model, we included the following fixed effects: proportion of the night up to the 5th polynomial (i.e. time in relation to sunset and sunrise), day of the year up to the 2nd polynomial, wind speed up to the 2nd polynomial, the sinus and cosine of wind direction as well as the sinus and cosine of twice the wind direction, and a binary variable indicating whether there was rain or not. Since we expected that the influence of wind direction on bat activity may differ between different locations due to differences in topography, we allowed the effect of wind direction to vary between the wind farms.

We tested whether overdispersion was present by including an observation level random factor [Gelman and Hill, 2007]. Whether the overdispersion parameter was important was assessed by the BIC [Burnham and Anderson, 2002]. Then, the following parameters were stepwise, in the given order, deleted from the model if they were not important according to the Bayesian information criterion BIC [Schwarz, 1978]: 1. wind farm-specific second order sinus and cosine of wind direction, 2. wind farm-specific sinus and cosine of wind direction, 3. 5h polynomial of proportion of night, 4. second order of sinus and cosine of wind direction. We expect all other terms to be biologically important. For this, and to prevent overestimation of effect sizes [Whittingham et al., 2006], these terms remained in the model independent of their significance. To test whether a zero-inflation is present we used posterior predictive model checking [Gelman et al., 2004]. Temporal autocorrelation is measured but not accounted for here. Since unaccounted autocorrelation results in the underestimation of uncertainty, we do not give uncertainty estimates.

```
# model fit and model selection
mod <- glmer(allbats ~ propnight.z + I(propnight.z^2) +
    I(propnight.z^3) + I(propnight.z^4) + I(propnight.z^5) +
    day.z + I(day.z^2) + windspeed.z + I(windspeed.z^2) +
    winddir.sin + winddir.cos + winddir.sin2 + winddir.cos2 +
    rain.bin + (winddir.sin + winddir.cos + winddir.sin2 +
    winddir.cos2 | windfarm), data = d.actc, family = poisson)
save("mod", file = "modactfull.RData")

# include overdispersion
modod <- glmer(allbats ~ propnight.z + I(propnight.z^2) +
    I(propnight.z^3) + I(propnight.z^4) + I(propnight.z^5) +
    day.z + I(day.z^2) + windspeed.z + I(windspeed.z^2) +
    winddir.sin + winddir.cos + winddir.sin2 + winddir.cos2 +
    rain.bin + (winddir.sin + winddir.cos + winddir.sin2 +
    winddir.cos2 | windfarm) + (1 | obsid), data = d.actc,
    family = poisson)
save("modod", file = "modactfullod.RData")

# delete farm-specific
# sin(2*winddir)+cos(2*winddir)
modod1 <- glmer(allbats ~ propnight.z + I(propnight.z^2) +
    I(propnight.z^3) + I(propnight.z^4) + I(propnight.z^5) +
    day.z + I(day.z^2) + windspeed.z + I(windspeed.z^2) +
    winddir.sin + winddir.cos + winddir.sin2 + winddir.cos2 +
    rain.bin + (winddir.sin + winddir.cos | windfarm) +
    (1 | obsid), data = d.actc, family = poisson)
save("modod1", file = "modactfullod1.RData")


# delete farm-specific sin(winddir)+cos(winddir)
```

```r
modod2 <- glmer(allbats ~ propnight.z + I(propnight.z^2) +
    I(propnight.z^3) + I(propnight.z^4) + I(propnight.z^5) +
    day.z + I(day.z^2) + windspeed.z + I(windspeed.z^2) +
    winddir.sin + winddir.cos + winddir.sin2 + winddir.cos2 +
    rain.bin + (1 | windfarm) + (1 | obsid), data = d.actc,
    family = poisson)
save("modod2", file = "modactfullod2.RData")

# delete propnight^5
modod3 <- glmer(allbats ~ propnight.z + I(propnight.z^2) +
    I(propnight.z^3) + I(propnight.z^4) + day.z + I(day.z^2) +
    windspeed.z + I(windspeed.z^2) + winddir.sin +
    winddir.cos + winddir.sin2 + winddir.cos2 + rain.bin +
    (1 | windfarm) + (1 | obsid), data = d.actc, family = poisson)
save("modod3", file = "modactfullod3.RData")

# delete sin(winddir*2) + cos(winddir*2)
modod4 <- glmer(allbats ~ propnight.z + I(propnight.z^2) +
    I(propnight.z^3) + I(propnight.z^4) + day.z + I(day.z^2) +
    windspeed.z + I(windspeed.z^2) + winddir.sin +
    winddir.cos + rain.bin + (1 | windfarm) + (1 |
    obsid), data = d.actc, family = poisson)
save("modod4", file = "modactfullod4.RData")
```

```r
# the smaller the BIC the better the model

# rule: if a parameter reduces BIC by at least 2,
# when it is included in the model, it is
# important.
BIC(mod, modod, modod1, modod2, modod3, modod4)

##        df  BIC
## mod    30 6838
## modod  31 3777
## modod1 22 3688
## modod2 17 3642
## modod3 16 3632
## modod4 14 3615
```

### 3.6 Combining carcass search data with acoustic activity

For the combination of carcass search data and acoustic activity data, we aggregated the activity data from 10 min measurements into measurements per night. To do this, we used the sum of the bat calls over the night. We used the median wind speed for each night. Nights with more than 20% of acoustic activity data missing were treated as missing values. We used multiple imputation to treat the missing activity data.

The aim is to estimate the number of bats killed per night given the acoustic activity and wind speed. Korner-Nievergelt et al. [2013] developed a model to relate acoustic activity and wind speed to collision rate while using the information from carcasses searches taking into account the carcass detection probability. We adapted this model to allow for search intervals larger than one day.

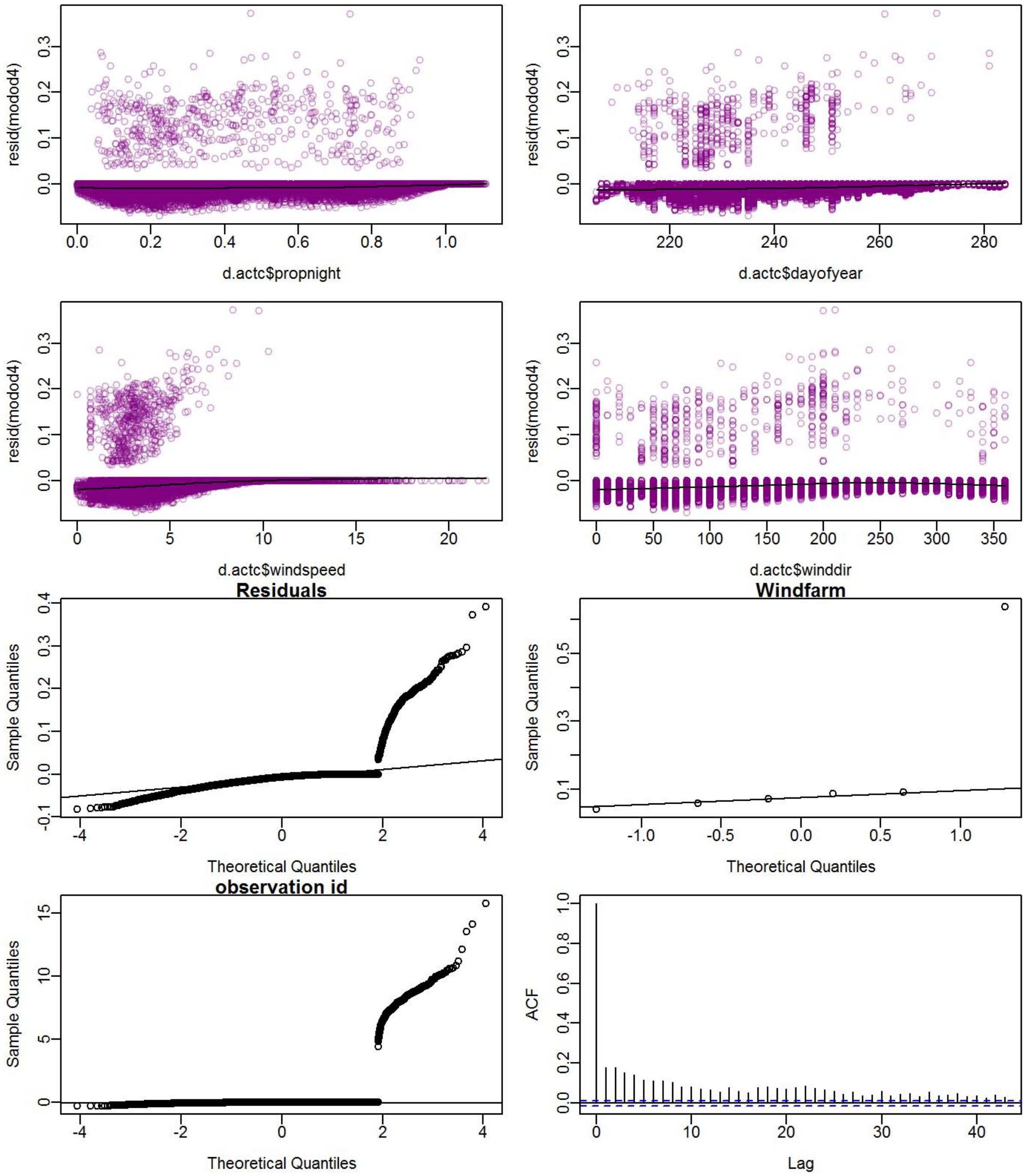


Figure 3: Diagnostic plots of the residuals for the activity model. In the upper four plots, the residuals are plotted against each predictor variable. The black line is a Loess-smoother. The qq-plots are of the residuals, the random effects for wind farm and the additional variance parameter accounting for overdispersion. The last panel shows the temporal autocorrelations.

We used the three-level sub-model for the observation process. This model contains a stochastic part for each of the three steps involved from the collision event to the finding of the carcass: 1) falling into the searched area, 2) remaining on the ground (i.e. not being scavenged), and 3) being found by a searcher. The model formulation takes into account that carcasses that have not been found during search $t$ may be found during a subsequent search.
First, the number of fresh carcasses falling into the area that was searched during night $t$ at wind farm $i$, $N_i^{fa}{}_t$, was modeled as a binomial distributed variable with the (unknown) number of collisions, $N_{it}$, as the size parameter and $a_{it}$ as the success probability, where $a_{it}$ was the proportion of the carcasses falling into the search area.

$$N_i^{fa}{}_t \sim Binom(N_{it}, a_{it}).$$

The number of carcasses present in the search area before removal by scavengers was the number of carcasses that have remained on the search area from the past, $N_i^{re}{}_{t-1}$, minus the number of carcasses found during the last search, $c_{it-1}$ (since they were removed by the searcher), plus the new carcasses killed during night $t$, $N_i^{fa}{}_t$.

$$N_i^a{}_t = N_i^{re}{}_{t-1} - c_{it-1} + N_i^{fa}{}_t$$

with $N_i^a{}_1 = N_i^{fa}{}_1$, assuming that no carcasses were present at the beginning of the study.
Second, the number of carcasses remaining until search $t$ was modeled as a binomial random variable with the persistence probability $s_{it}$ as the probability parameter:

$$N_i^{re}{}_t \sim Binom(N_i^a{}_t, s_{it})$$

Third, the number of carcasses found during day $t$ was modeled as a binomial random variable:

$$c_{it} \sim Binom(N_i^{re}{}_t, f_{it})$$

with $N_i^{re}{}_t$ being the number of carcasses present in the search area until the start of the search on day $t$ and $f_{it}$ the searcher efficiency, i.e. the probability that a carcass lying in the search area is found by the searcher during one search. Searcher efficiency $f_{it}$ was set to zero during days without carcass searches. The estimates for $s$ and $f$ from the corresponding experiments (chapters 4.1 and 4.2) were used as prior distributions for these parameters. The estimates and their standard errors were transformed into beta-distributions as described in chapter 3.4: $s_{it} \sim Beta(\alpha_i^s, \beta_i^s)$ and $f_{it} \sim Beta(\alpha_i^f, \beta_i^f)$. The proportion of carcasses lying in the search area $a_{it}$ was assumed to be known without error (see chapter 3.3).

Thus, we had a first sub-model (with three levels) to model collision rate from the numbers of carcasses found, the persistence probability and the searcher efficiency. The second sub-model described the collision process: The number of bat collisions during day $t$ at wind farm $i$, $N_{it}$ was modeled as a Poisson distributed variable with $\lambda_{it}$ as expected value,

$$N_{it} \sim Pois(\lambda_{it} Q_i) \text{ with } log(\lambda_{it}) = \alpha_0 + \alpha_1 zA_{it} + \alpha_2 zW_{it} + \alpha_3 zW_{it}^2$$

and $zA$ and $zW$ being the standardized (z-transformed) activity and wind speed measurements, respectively. We standardized these variables to increase the speed of model fitting. Activity was increased by one and log-transformed before standardizing: $zA_{it} = (log(A_{it} + 1) - 0.6747)/1.1132$ and $zW_{it} = (W_{it} - 5.667)/2.527$.

The number of turbines at wind farm $i$, $Q_i$, was used as an offset, i.e. we multiplied $\lambda_{it}$ by the number of turbines to get the expected value of the number of collisions. In this way we accounted for the different number of turbines sampled per wind farm.

The natural logarithm was used as the link function. For the model coefficients $\alpha_k$ flat normal distributions with a mean of zero and variance of 100 were used as prior distributions.

We used Markov chains Monte Carlo simulations to fit the model to the data in WinBUGS [Lunn et al., 2009]. We simulated 2 Markov chains each of length $5 \times 10^5$. The first 5000 simulations were discarded as burn-in and of the remaining values each 180$^{th}$ value was used to describe the posterior distribution of the model parameters. Convergence was assessed graphically and by the r-hat value [Brooks and Gelman, 1998].

During 40 nights (14% of all nights) the activity was measured in less than 80% of the 10 min intervals. In these nights the activity data was treated as missing. Missing $zA$-values were handled by multiple imputation using wind speed as predictor and assuming a variance of 1 (see bugs-code).

```
# bugs code of the n-mixture model
sink("nmixmod.txt")
cat("
    model{
for(i in 1:nfarms){

    N[1,i] ~ dpois(lambdastar[1,i])   # first night
    Nfar[1,i]~dbin(a[1,i], N[1,i])    # number of carcasses falling in search area
    Narea[1,i] <- Nfar[1,i]           # number of carcasses being in search area
    Nrem[1,i]~dbin(s[1,i], Narea[1,i])    # number of carcasses remaining in search area
    fstar[1,i] <- f[1,i]*search[1,i]
    y[1,i]~dbin(fstar[1,i], Nrem[1,i])


    f1[1,i] ~ dbeta(f1a[1,i], f1b[1,i]) # f visibility 1
    f2[1,i] ~ dbeta(f2a[1,i], f2b[1,i]) # f visibility 2
    f3[1,i] ~ dbeta(f3a[1,i], f3b[1,i]) # f visibility 3
    #weighted mean
    f[1,i] <- (a1[1,i]*f1[1,i] + a2[1,i]*f2[1,i] +
                  a3[1,i]*f3[1,i])/(a1[1,i]+a2[1,i]+a3[1,i])
    s[1,i] ~ dbeta(sa[1,i], sb[1,i]) # persistence probability



for(t in 2:ndays){

    f1[t,i] ~ dbeta(f1a[t,i], f1b[t,i]) # f visibility 1
    f2[t,i] ~ dbeta(f2a[t,i], f2b[t,i]) # f visibility 2
    f3[t,i] ~ dbeta(f3a[t,i], f3b[t,i]) # f visibility 3
    #weighted mean
    f[t,i] <- (a1[t,i]*f1[t,i] + a2[t,i]*f2[t,i] + a3[t,i]*f3[t,i])/
                (a1[t,i]+a2[t,i]+a3[t,i])
    s[t,i] ~ dbeta(sa[t,i], sb[t,i]) # persistence probability


    N[t,i] ~ dpois(lambdastar[t,i])
    Nfar[t,i]~dbin(a[t,i], N[t,i])   # number  of carcasses  falling in searched area
    Narea[t,i] <- Nfar[t,i] + Nrem[t-1,i]-y[t-1,i] # no of carcasses in searched area
    Nrem[t,i]~dbin(s[t,i], Narea[t,i])  # number of carcasses remaining in searched area
    fstar[t,i] <- f[t,i]*search[t,i] # counts are only possible when searched
```

```
    y[t,i]~dbin(fstar[t,i], Nrem[t,i])
   } # close ndays
   } # close nfarms
for(i in 1:nfarms){
    for(t in 1:ndays){
    lambdastar[t,i] <- exp(b[1]+b[2]*act[t,i] + b[3]*wind[t,i] +
                              b[4]*pow(wind[t,i],2))*nturbinespfarm[i]
    # impute missing activity data
    act[t,i]~dnorm(mu[t,i], 1)
    mu[t,i] <- delta[1]+delta[2]*wind[t,i]
} # close ndays
} # close nfarms

# priors
for(k in 1:4){
b[k] ~ dnorm(0, 0.01)
}
delta[1]~dnorm(0,0.01)
delta[2]~dnorm(0,0.01)
# derived parameters
for(i in 1:nfarms){
   sumN[i]<-sum(N[1:ndays,i])  # total number of collisions per farm
   }
totN <- sum(sumN[1:nfarms])
}# close model

 ",fill=TRUE)
sink()
```

### 3.7 Estimation of fatality numbers based on the BMU-model 2010

Because the information in the Dutch data is sparse (only 2 carcasses found, activity measurements at only 5 turbines), we also used analogous data from a larger German study (BMU-model, Brinkmann et al. [2011]) to parameterize the model. We first estimated the number of fatalities by applying the BMU-model to the Dutch activity data and then we combined the BMU-model with the Dutch data to obtain a new model.

To apply the BMU-model to the Dutch data, we had to assume that the conditions in the Netherlands are similar to the ones in the BMU-project. Particularly, we assumed that 1) the correlation between wind speed and activity was similar, 2) species composition was similar, 3) daily and seasonal activity patterns of the bats were similar, 4) type of wind turbines were similar, i.e. similar rotor diameter and nacelle heights, 5) acoustic bat detector should had comparable sensitivity and were installed in the same way.

If we can make all the above assumptions, we can estimate the average collision rate (number of collisions per turbine and night) from the acoustic activity (number of bat recordings per turbine $i$ and night $t$, $A_{it}$) and the median of the wind speed over the night ($W_{it}$) as follows:

$\hat{\lambda}_{it} = exp(-2.811 + 0.662zA_{it} - 0.277zW_{it} - 0.231zW_{it}^2)$
(from Table 5, p.340, Brinkmann et al. 2011)

$zA_{it}$ and $zW_{it}$ are the standardized activity and wind measurements. Standardizing is transforming the variable by taking off the mean and dividing by the standard deviation so that the resulting variable has a mean of zero and a standard deviation of one. There are still some open questions for the application of the BMU-model to other than the German data. One is which means and standard deviations we should use to standardize the activity and wind speed measurements: the one from the BMU-project or the one from the Dutch data. Here, we use both possibilities and report both results. The variability of the results will reflect the uncertainty in the prediction from one project to another.

To combine the information from the BMU-project with the Dutch data, we used the estimates for the model parameters $\alpha_k$ (Table. 5 in Brinkmann et al. [2011]) as prior distributions in the n-mixture model that is fitted to the Dutch data. In this way, the information of the German data is combined with the Dutch data without the necessity to re-fit the model to the German data. The bugs-code for this model is given below.

```
# n-mixture model combining information from BMU and Netherlands
sink("nmixmodbmu.txt")
cat("
    model{
for(i in 1:nfarms){

    N[1,i] ~ dpois(lambdastar[1,i])   # first night
    Nfar[1,i]~dbin(a[1,i], N[1,i])    # number of carcasses falling in searched area
    Narea[1,i] <- Nfar[1,i]           # number of carcasses being in searched area
    Nrem[1,i]~dbin(s[1,i], Narea[1,i])    # number of carcasses remaining in searched area
    fstar[1,i] <- f[1,i]*search[1,i]
    y[1,i]~dbin(fstar[1,i], Nrem[1,i])


    f1[1,i] ~ dbeta(f1a[1,i], f1b[1,i]) # f visibility 1
    f2[1,i] ~ dbeta(f2a[1,i], f2b[1,i]) # f visibility 2
    f3[1,i] ~ dbeta(f3a[1,i], f3b[1,i]) # f visibility 3
    #weighted mean
    f[1,i] <- (a1[1,i]*f1[1,i] + a2[1,i]*f2[1,i] + a3[1,i]*f3[1,i])/
                  (a1[1,i]+a2[1,i]+a3[1,i])
    s[1,i] ~ dbeta(sa[1,i], sb[1,i]) # persistence probability



for(t in 2:ndays){

    f1[t,i] ~ dbeta(f1a[t,i], f1b[t,i]) # f visibility 1
    f2[t,i] ~ dbeta(f2a[t,i], f2b[t,i]) # f visibility 2
    f3[t,i] ~ dbeta(f3a[t,i], f3b[t,i]) # f visibility 3
    #weighted mean
    f[t,i] <- (a1[t,i]*f1[t,i] + a2[t,i]*f2[t,i] + a3[t,i]*f3[t,i])/
                  (a1[t,i]+a2[t,i]+a3[t,i])
    s[t,i] ~ dbeta(sa[t,i], sb[t,i]) # persistence probability


    N[t,i] ~ dpois(lambdastar[t,i])
    Nfar[t,i]~dbin(a[t,i], N[t,i])   # number  of carcasses  falling in searched area
    Narea[t,i] <- Nfar[t,i] + Nrem[t-1,i]-y[t-1,i] # no of carcasses in searched area
    Nrem[t,i]~dbin(s[t,i], Narea[t,i])  # number of carcasses remaining in searched area
    fstar[t,i] <- f[t,i]*search[t,i] # counts are only possible when searched
```

```
    y[t,i]~dbin(fstar[t,i], Nrem[t,i])
   } # close ndays
   } # close nfarms
for(i in 1:nfarms){
    for(t in 1:ndays){
    lambdastar[t,i] <- exp(b[1]+b[2]*act[t,i] + b[3]*wind[t,i] +
                        b[4]*pow(wind[t,i],2))*nturbinespfarm[i]
    # impute missing activity data
    act[t,i]~dnorm(mu[t,i], 1)
    mu[t,i] <- delta[1]+delta[2]*wind[t,i]
} # close ndays
} # close nfarms

# priors
b[1] ~ dnorm(-2.81, 22.59) # information from BMU
b[2] ~ dnorm(0.66, 58.4)
b[3] ~ dnorm(-0.28, 14.55)
b[4] ~ dnorm(-0.23, 39.05)

delta[1]~dnorm(0,0.01)
delta[2]~dnorm(0,0.01)
# derived parameters
for(i in 1:nfarms){
   sumN[i]<-sum(N[1:ndays,i])  # total number of collisions per farm
   }
totN <- sum(sumN[1:nfarms])
}# close model

 ",fill=TRUE)
sink()
```

### 3.8 Curtailment algorithm

Can be done after having found a reliable model to predict acoustic activity.

## 4 Results

### 4.1 Persistence time

After one to seven days only 50% of the mouse carcasses remained on the ground (Figure 4). Average daily persistence probability $\hat{s}_{it}$ varied from 0.186 to 0.884 between the different wind farms (Table 4).

### 4.2 Searcher efficiency

From the Dutch data alone, the average searcher efficiency was 0.942 (95% credible interval: 0.739-0.989) for visibility class 1 (Type=1), 0.637 (0.39-0.827) for visibility class 2 (Type=2) and 0.915 (0.502-0.991) for visibility class 3 (Type=3). The location-specific searcher efficiency estimates that

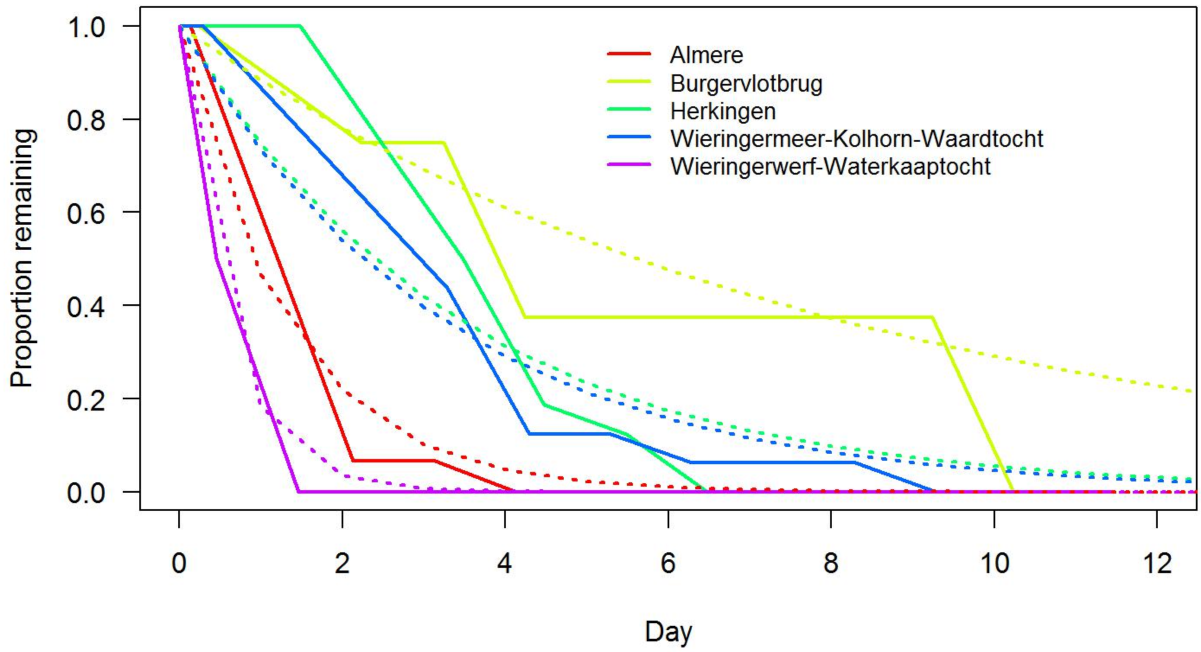


Figure 4: Proportion of remaining experimental mice carcasses in relation to time (in days). Solid lines depict the data, dotted lines are the model.

Table 4: Estimated daily persistence probabilities $s_i$ of carcasses with the lower and upper limits of the 95% credible interval.

| Park_i | s_i | lower | upper |
|---|---|---|---|
| Almere | 0.468 | 0.290 | 0.648 |
| Burgervlotbrug | 0.884 | 0.812 | 0.941 |
| Herkingen | 0.748 | 0.637 | 0.844 |
| Wieringermeer-Kolhorn-Waardtocht | 0.735 | 0.619 | 0.835 |
| Wieringerwerf-Waterkaaptocht | 0.186 | 0.051 | 0.383 |

are based on the Dutch data only are given in Table 5.

The combined estimates of the Dutch and German study are given in Table 6. These estimates are shrunk towards the population mean which is dominated by the German data (Figure 5). For visibility class 3, the sample size in the Dutch data was very low (8) and the estimates surprisingly high. Therefore, for this group, the shrinkage was large (Figure 5). In the subsequent analyses, we used the estimates based on the combined data (Table 6).

### 4.3 Proportion of carcasses in the searched area

The proportion of carcasses lying in the search area was constant over time in all wind farms (Fig. 6). Visibility classes also remained constant over the course of the data collection (very slight changes in Almere).

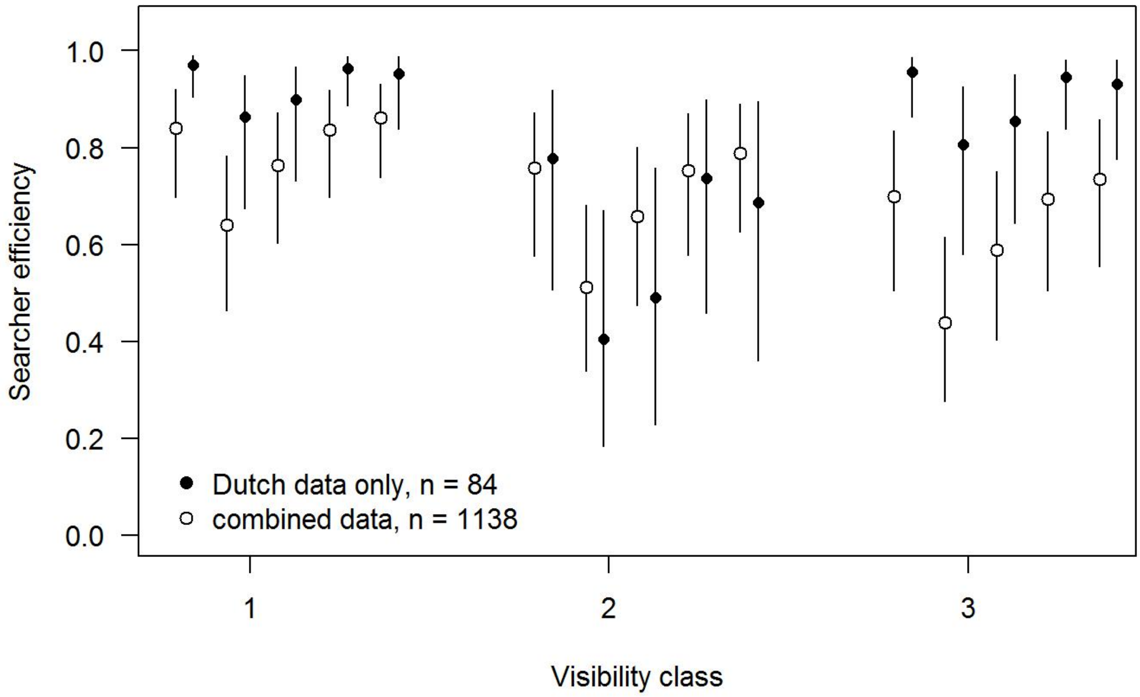


Figure 5: Estimated searcher efficiency $f$ based on the Dutch data alone and based on a combined data set with the German study. The 5 estimates per visibility class are for the 5 different locations (from left to right: Almere, Burgervlotbrug, Herkingen, W.-Waardtocht, W.-Waterkaaptocht).

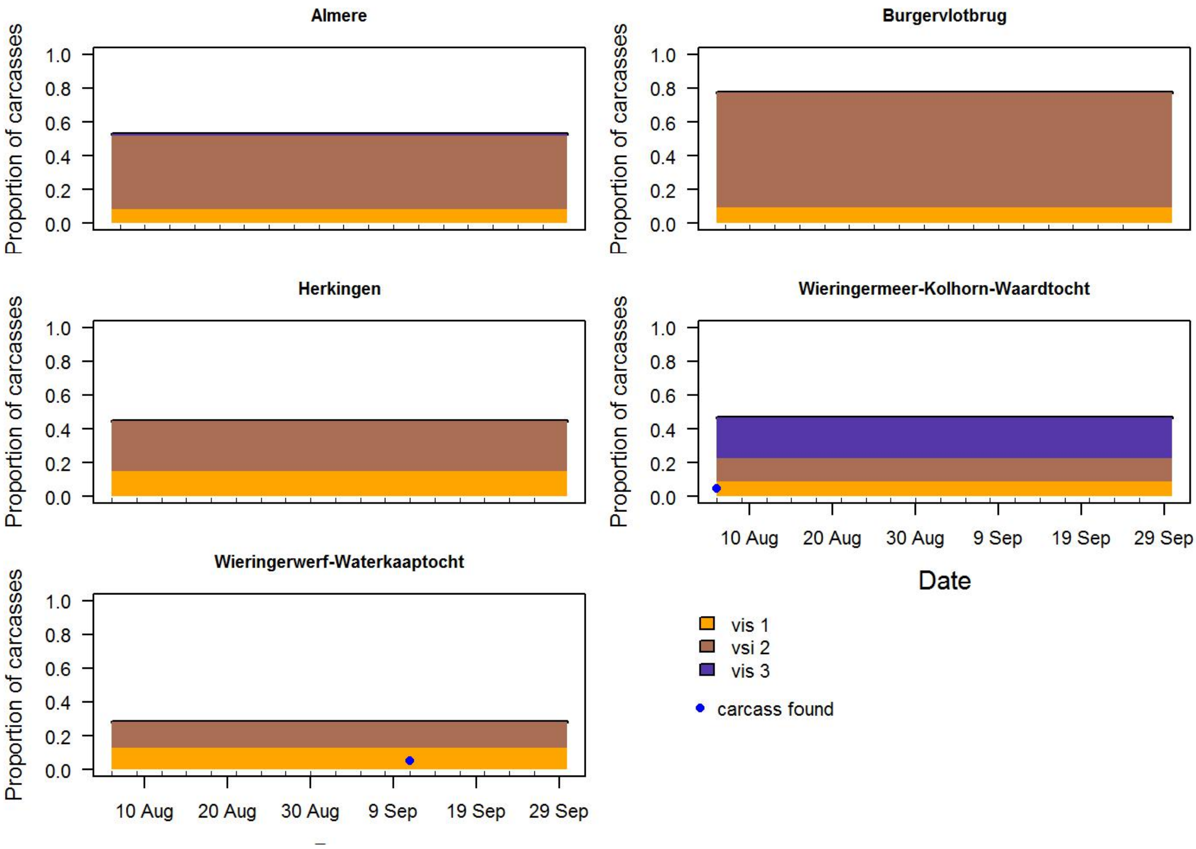


Figure 6: Proportion of carcasses expected to lay in the search area (based on the proportion of area that could be searched per 10 m distance ring and a theoretical spatial distribution of the bat carcasses. Colors indicate visibility classes. The black tick marks inside the plot indicate days with searches.

Table 5: Estimated searcher efficiency for each location and visibility class with the lower and upper limit of the 95% credible interval. These estimates are based on the Dutch data alone.

| Visibility class | Location | f | lower | upper |
|---|---|---|---|---|
| 1 | Almere | 0.970 | 0.905 | 0.990 |
| 2 | Almere | 0.777 | 0.507 | 0.918 |
| 3 | Almere | 0.955 | 0.863 | 0.986 |
| 1 | Burgervlotbrug | 0.863 | 0.675 | 0.949 |
| 2 | Burgervlotbrug | 0.405 | 0.184 | 0.671 |
| 3 | Burgervlotbrug | 0.807 | 0.580 | 0.926 |
| 1 | Herkingen | 0.899 | 0.731 | 0.966 |
| 2 | Herkingen | 0.490 | 0.228 | 0.758 |
| 3 | Herkingen | 0.855 | 0.644 | 0.950 |
| 1 | Wieringermeer-Kolhorn-Waardtocht | 0.963 | 0.886 | 0.988 |
| 2 | Wieringermeer-Kolhorn-Waardtocht | 0.736 | 0.459 | 0.899 |
| 3 | Wieringermeer-Kolhorn-Waardtocht | 0.945 | 0.839 | 0.982 |
| 1 | Wieringerwerf-Waterkaaptocht | 0.953 | 0.839 | 0.987 |
| 2 | Wieringerwerf-Waterkaaptocht | 0.688 | 0.361 | 0.895 |
| 3 | Wieringerwerf-Waterkaaptocht | 0.931 | 0.776 | 0.981 |

### 4.4 Estimation of the number of fatalities based on carcass search data only

At each wind farm, 18 searches took place with a search interval of 3 days. The average daily persistence probability (averaged over the 5 wind farms) was 0.604 (95% CI: 0.547 - 0.667). The average searcher efficiency (averaged over the persons and weighted average over the visibility classes) was 0.677 (95% CI: 0.639 - 0.715). The average proportion of carcasses lying in the search area was 0.499. These statistics lead to an average carcass detection probability of 0.277 to 0.349 depending on the method used. The lowest detection probability is estimated using the method of Korner-Nievergelt et al. [2011] assuming that the searcher efficiency decreases with the number of searches because difficult to detect carcasses remain longer on the ground. The highest detection probability is obtained by the method of Huso.

Given a carcass detection probability and the number of carcasses found (which was 2), we calculated that with a probability of 95% the true number of fatalities was between 4 and 50 with means of 14 to 18 depending on the method used (Table 7). These estimates are totals over all 25 wind turbines during the study period (6 August to 30 September, i.e 3*18=54 days). Thus, the average daily fatality rate per turbine was between $14/25/54$ =0.01 (25 turbines, 54 nights) and $18/25/54$ =0.013 with an approximated 95% credible interval of 0.003 to 0.037.

### 4.5 Estimation of fatality rates based on combined carcass search data and acoustic activity data at the nacelle

The uncertainty of the parameter estimates is very high (large standard errors in Table 8).

When we combine the information from the carcass searches (carcass detection probabilities, number of carcasses found) with the acoustic activity and wind speed data using the n-mixture model for the Dutch data only (see chapter 3.6), we estimate that the total number of fatalities at the 5 wind farms was with 95% chance within 3 and 227. The median of the posterior distribution was 15. The posterior distributions of the number of fatalities per wind farm are given in Figure 7.

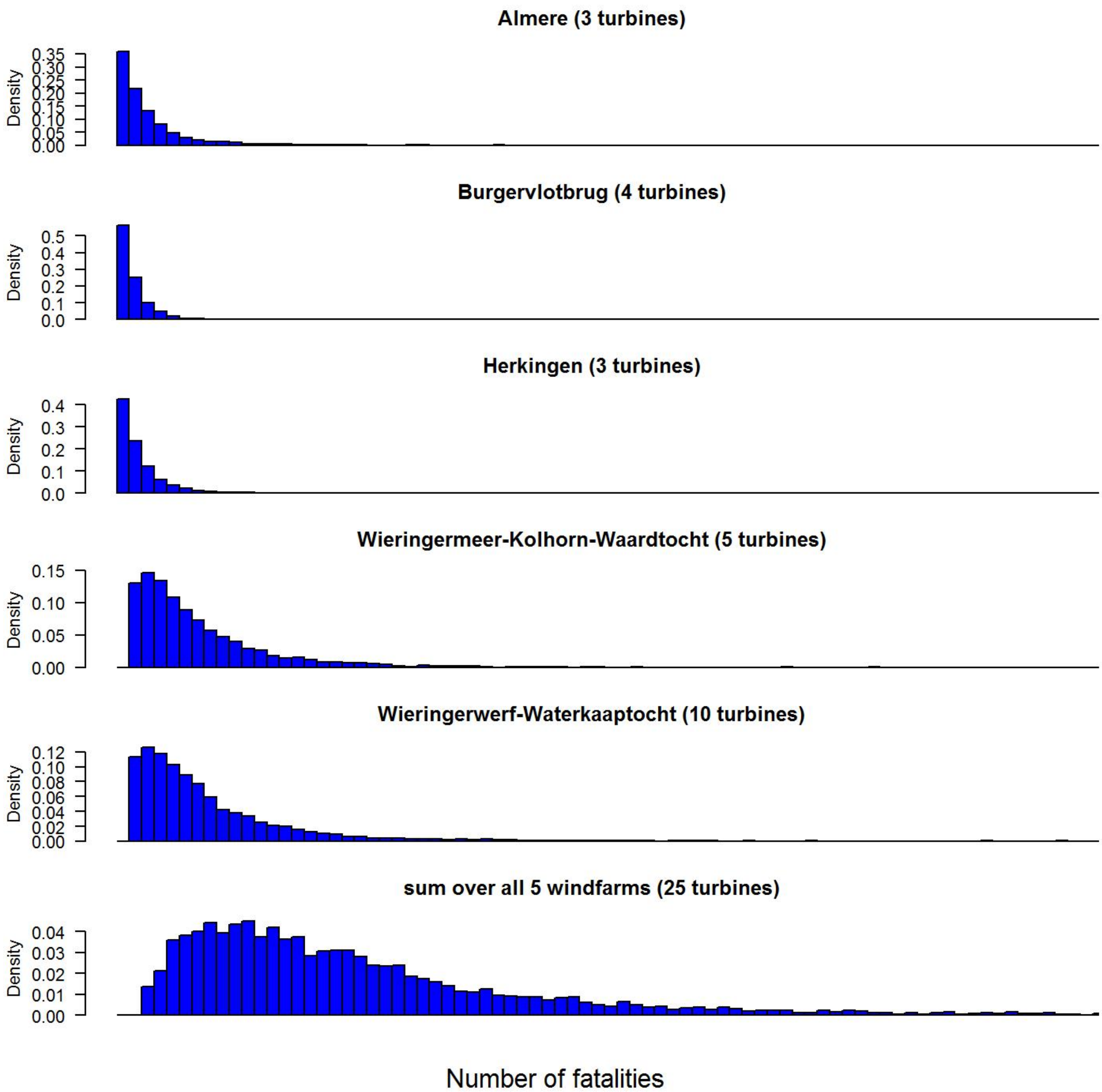


Figure 7: Posterior distributions of the number of fatalities during the study period (3 August - 30 September) at each wind farm and the total number of fatalities over the 5 wind farms.

Table 6: Estimates for searcher efficiencies $f$ for each location and visibility class when combining the information from Niermann et al. [2011] with the Dutch data. The wind-farm specific estimates for Germany are not given because they are not relevant in this study. The last two columns give the lower and upper limits of the 95% credible interval.

| visibility | location | f | lower | upper |
|---|---|---|---|---|
| 1 | Almere | 0.840 | 0.697 | 0.920 |
| 2 | Almere | 0.758 | 0.577 | 0.872 |
| 3 | Almere | 0.700 | 0.504 | 0.835 |
| 1 | Burgervlotbrug | 0.640 | 0.463 | 0.783 |
| 2 | Burgervlotbrug | 0.513 | 0.338 | 0.682 |
| 3 | Burgervlotbrug | 0.440 | 0.276 | 0.615 |
| 1 | Herkingen | 0.764 | 0.604 | 0.872 |
| 2 | Herkingen | 0.658 | 0.475 | 0.801 |
| 3 | Herkingen | 0.589 | 0.402 | 0.750 |
| 1 | Wieringermeer-Kolhorn-Waardtocht | 0.837 | 0.697 | 0.919 |
| 2 | Wieringermeer-Kolhorn-Waardtocht | 0.752 | 0.577 | 0.870 |
| 3 | Wieringermeer-Kolhorn-Waardtocht | 0.694 | 0.505 | 0.833 |
| 1 | Wieringerwerf-Waterkaaptocht | 0.862 | 0.738 | 0.932 |
| 2 | Wieringerwerf-Waterkaaptocht | 0.788 | 0.626 | 0.890 |
| 3 | Wieringerwerf-Waterkaaptocht | 0.735 | 0.555 | 0.858 |

Table 7: Estimated carcass detection probability $p$ and total number of fatalities $\hat{N}$ during 54 nights between 6 Aug and 30 Sept at each of the 5 wind farms with the lower and upper limit of the 95% credible interval. These estimates are based on carcass search data alone.

| method | p | N | lower | upper |
|---|---|---|---|---|
| Korner et al. 2011, 1 | 0.287 | 18 | 5 | 48 |
| Korner et al. 2011, 2 | 0.277 | 18 | 5 | 50 |
| Huso 2010 | 0.349 | 14 | 4 | 39 |

## 4.6 Estimation of fatality numbers based on the BMU-model 2010

The fatality estimations presented in this chapter are based only on the acoustic activity and wind speed measurements. We assume that the relationship between acoustic activity and wind speed on one side and collision rate on the other is equal to the one in the German study [Brinkmann et al., 2011]. In the German study, this relationship was calculated based on the standardized acoustic activity and wind speed measurements (transformed so that their means were zero and their standard deviations one). When we apply the BMU formula to new activity and wind speed measurements, these new measurements have to be transformed in a similar way as in the German study, i.e. $zA = (log(A+1) - mean(log(A+1)))/sd(log(A+1))$ and $zW = (W - mean(W))/sd(W)$. However, it is still unclear which means and standard deviations we should use, the one from the original BMU data or the one from the new data. Therefore, we did both transformations.

It does not seem to matter whether we use the means and standard deviations from the BMU data or the Dutch data: When using the means and standard deviations from the Dutch data, the estimated total number of fatalities was 142 (83-253), when using the transformation exactly as used in the BMU-project the estimate was 135 (77-259). However, in both cases the estimates based on the BMU model alone were almost 4 times higher than estimates based on the Dutch data alone (Table 10). When we combine the information from the BMU-project regarding the relationship between acoustic activity and wind speed on one the hand and collision rate on the other hand with the Dutch data, we obtain an estimate of 54.7 (95% CrI: 33-82) fatalities during the study period of 59 days at the 25 wind turbines.

Table 8: Estimated coefficients of the linear predictor for the logarithm of daily collision rates from the n-mixture model fitted to the Dutch data only, with the standard error (SE) and the r_hat value. The r_hat value should be smaller than 1.02 otherwise the Markov chains have not converged.

| | estimate | SE | r_hat |
|---|---|---|---|
| intercept | -8.727 | 3.082 | 1.001 |
| activity | -3.907 | 2.874 | 1.002 |
| wind | -4.820 | 6.820 | 1.001 |
| wind quared | -4.769 | 4.111 | 1.001 |

Table 9: Estimated number of fatalities (N) from the combination of carcass searches with the acoustic activity and wind speed data between 3 Aug and 30 Sept at the 5 wind farms with the lower and upper limit of the 95% credible interval. Q = number of turbines, searches = number of searches, c = number of carcasses found, T = number of days, A = acoustic activity in number of recorded files with bat calls.

| windfarm | Q | searches | c | T | A | N | lower | upper |
|---|---|---|---|---|---|---|---|---|
| Almere | 3 | 18 | 0 | 59 | 1647 | 4 | 0 | 24 |
| Burgervlotbrug | 4 | 18 | 0 | 59 | 47 | 1 | 0 | 4 |
| Herkingen | 3 | 18 | 0 | 59 | 92 | 14 | 0 | 92 |
| Waardtocht | 5 | 18 | 1 | 59 | 86 | 6 | 1 | 21 |
| Waterkaaptocht | 10 | 18 | 1 | 59 | 52 | 10 | 1 | 44 |

When we fitted the model solely to the Dutch data while excluded the data from Almere, where acoustic activity was more than 10 times higher than at the other wind farms but no carcass was found, the fatality estimates increased by more than a factor 2 (Table 11). In the model that was fitted to both the Dutch and the German data, the exclusion of the data from Almere had no substantial effect on the estimate of the daily collision rate per turbine (54/25 turbines/59 nights = 0.037, vs. 43/22 turbines/59 nights = 0.033).

## 4.7 Model for acoustic activity

The diagnostic plots of the residuals show that the model fit deserves improvements (Fig. 3). Particularly, for low wind speeds average residuals seems to be smaller than zero, i.e. the model seems to overestimate activity for low wind speeds. We see in the qq-plots of the variance parameters (residuals, wind farm and additional variance) a distinct bend which may be an indication of zero-inflation. Further, significant positive temporal autocorrelation is present. Autocorrelation needs to be taken into account when constructing uncertainty intervals.

The proportion of 10 min intervals with zero bat calls in the real data was 0.972. In 95% of the data sets simulated from the model, this proportion was between 0.978 and 0.98. Thus, the model even overestimated the proportion of zeros. The maximal number of bat calls seems to be appropriately modeled: the 95% interval was 34.975 - 51 and the observed maximum was 37 bat calls.

Overall, the model fit to the Dutch data needs to be improved. It can not yet be used to reliably predict bat activity which would be needed to construct a curtailment algorithm.

In Figure 8 we show the relationship between the explanatory variables and the raw data graphically. During 10 min intervals with rain the probability of recording bat activity was lower than during 10 min intervals without rain (Table 12).

The model selection based on the BIC revealed that the overdispersion parameter is very important. This means that the acoustic activity data have a much higher variance than assumed by the Poisson-distribution. In fact, the estimated additional variance parameter was 44.7. This was

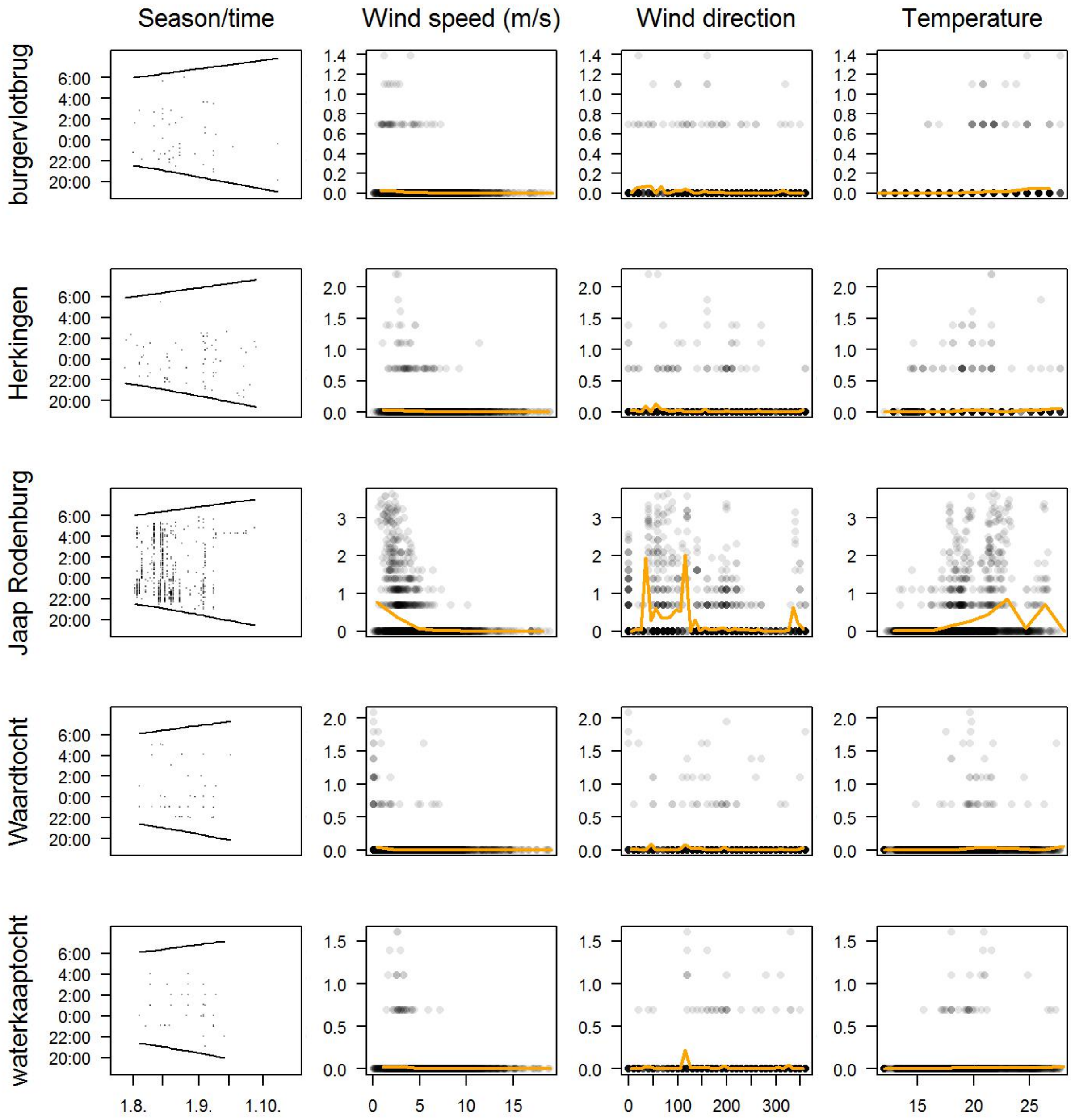


Figure 8: Activity measurements vs. all predictor variables. The orange lines give the means. In the first column, darker points mean more activity. In columns 2-4, the y-axis is the activity measure (logarithm transformed).

Table 10: Estimated number of fatalities between 3 Aug and 30 Sept at the 5 wind farms with the lower (l) and upper (u) limit of the 95% credible interval. Q = number of turbines, NL = based on the Dutch data alone, BMU = based on the BMU-model alone using the transformations as used in the BMU-project, BMU_NL = based on the combination of the Dutch data with the BMU-data.

| Windfarm | Q | NL | NL.l | NL.u | BMU | BMU.l | BMU.u | BMU_NL | BMU_NL.l | BMU_NL.u |
|---|---|---|---|---|---|---|---|---|---|---|
| Almere | 3 | 4 | 0 | 24 | 43 | 20 | 89 | 13 | 5 | 28 |
| Bu.brug | 4 | 1 | 0 | 4 | 13 | 7 | 23 | 4 | 0 | 9 |
| Herk. | 3 | 14 | 0 | 92 | 14 | 8 | 26 | 6 | 1 | 12 |
| W.tocht | 5 | 6 | 1 | 21 | 35 | 13 | 99 | 9 | 4 | 18 |
| W.kaapt. | 10 | 10 | 1 | 44 | 30 | 19 | 48 | 20 | 11 | 33 |
| all 5 | 25 | 35 | 3 | 227 | 135 | 77 | 259 | 54 | 33 | 82 |

Table 11: Estimated number of fatalities between 3 Aug and 30 Sept at the 4 wind farms (Almere excluded) with the lower (l) and upper (u) limit of the 95% credible interval. Q = number of turbines, NL = based on the Dutch data without Almere, BMU_NL = based on the combination of the Dutch data (without Almere) with the BMU-data.

| Windfarm | Q | NL | NL.l | NL.u | BMU_NL | BMU_NL.l | BMU_NL.u |
|---|---|---|---|---|---|---|---|
| Bu.brug | 4 | 1 | 0 | 5 | 4 | 1 | 9 |
| Herk. | 3 | 47 | 0 | 239 | 6 | 2 | 13 |
| W.tocht | 5 | 7 | 1 | 23 | 10 | 4 | 19 |
| W.kaapt. | 10 | 21 | 1 | 112 | 22 | 11 | 36 |
| all 4 | 22 | 75 | 3 | 432 | 43 | 25 | 66 |

much higher than the between-turbine variance which was 0. A wind-farm specific effect of the wind direction was not important and could be excluded from the model. Similarly, the 5th polynomial of time (measured as proportion of the night) and the sinus and cosine of twice the wind direction could be excluded from the fixed part of the model. The parameter estimates of the fixed effects are given in Table 13.

### 4.8 Curtailment algorithm

To develop a curtailment algorithm for the Dutch wind turbines, more work is needed on the prediction of bat activity.

## 5 Discussion

### 5.1 Estimation of fatality numbers

We estimated the total number of fatalities at the 25 wind turbines during the study period using different methods and different sources of data. The lowest estimate was 15 fatalities in 54 days at 25 wind turbines. This estimate was obtained when correcting the number of carcasses found by the carcass detection probability (Table 7). When acoustic activity data was used in addition to the carcass search data, we obtained an estimate of 35 in 59 days at 25 wind turbines when the data from Almere was included or 75 in 59 days at 22 wind turbines when the data from Almere was excluded. If we use the relationship between acoustic activity and collision rate that was developed in the BMU-project based on German data and assume the same relationship for the Dutch data we would predict 135 collisions at the 25 Dutch wind turbines during the 59 days. When combining the entire data from the Netherlands (inclusive Almere) with the BMU-data to establish the relationship between acoustic activity and collision rate, we estimate for the Dutch turbines a total number of

Table 12: Proportions of 10 min intervals with bat activity with (rain=1) and without (rain=0) rain. n= number of 10 min intervals.

| rain | windfarm | Proportion of intervals with bat activity | n |
|---|---|---|---|
| 0.00 | burgervlotbrug | 0.01 | 3480 |
| 1.00 | burgervlotbrug | 0.01 | 598 |
| 0.00 | Herkingen | 0.02 | 3221 |
| 1.00 | Herkingen | 0.01 | 272 |
| 0.00 | Jaap Rodenburg | 0.12 | 2649 |
| 1.00 | Jaap Rodenburg | 0.07 | 297 |
| 0.00 | Waardtocht | 0.01 | 3141 |
| 1.00 | Waardtocht | 0.00 | 515 |
| 0.00 | waterkaaptocht | 0.01 | 3141 |
| 1.00 | waterkaaptocht | 0.00 | 515 |

Table 13: Model estimates of the GLMM to predict activity for each 10-min interval. Note: because temporal autocorrelation has not been corrected for, uncertainty estimates are not reliable and therefore no standard errors are shown here.

| | estimate |
|---|---|
| (Intercept) | -9.397 |
| propnight.z | -0.038 |
| I(propnight.z^2) | 1.303 |
| I(propnight.z^3) | -0.492 |
| I(propnight.z^4) | -0.842 |
| day.z | -0.910 |
| I(day.z^2) | -0.463 |
| windspeed.z | -2.054 |
| I(windspeed.z^2) | -0.758 |
| winddir.sin | 0.789 |
| winddir.cos | 0.279 |
| rain.bin | -0.203 |

bats killed during the 59 days at the 25 wind turbines of 54.

This large differences between the different fatality estimators reflect that the information in the Dutch data on the number of fatality is weak. One the one hand, we have only 2 carcasses found. On the other hand, the ratio between the number of carcasses found and the number of recorded bat calls (acoustic activity) is extremely variable between the wind farms. Particularly, it is surprising that the acoustic activity at Almere is more than 10 time higher while no carcass was found there, even if the carcass detection probability was similar at this farm as at the others. This impedes the description of a clear relationship between acoustic activity and collision rate.

In the next subsection, we shortly discuss some technical aspects that may be important to take into account in future analyses.

### 5.1.1 Persistence time

Constant persistence probability: According to Fig. 4 it does not look as if the carcasses are removed faster than predicted by the model at the beginning of the experiment. Therefore, we think it is quite reasonable to assume constant persistence probabilities.

### 5.1.2 Searcher efficiency

Estimated searcher efficiency for the Dutch searchers were in average higher than in the German data. Especially in visibility class 3, the Dutch searcher seemed to find a much higher proportion of dummies than the German ones. This could be due to the small sample size for this visibility class in the Dutch data maybe coupled with a higher motivation of the searcher to search for dummies in the hardest visibility class (?).

Even if average carcass detection probability was lower in the Dutch data (due to larger search intervals, see below) than in the German data, the much lower ratio between the number of carcasses found to the acoustic activity recorded is surprising. Brinkmann et al. [2011] found 45 carcasses while 3854 recordings of Chiroptera (all bats) were done by the Anabat. This is a ratio of 45:3854 = 0.012. In the Dutch data, this ratio was 2 to (1647*3+47*4+92*3+86*5+52*10) when we assume that the turbine where acoustic activity was measured was representative for the wind farm. This is a ratio of $3.1 \times 10^{-4}$. If Almere is excluded the ratio becomes 0.0014, but is still almost 10 times smaller than in the German study. One (of many others) potential cause of this difference might be that the searcher efficiency for real bat carcasses might have been much smaller than the ones measured by the efficiency trials using dummies. Such a difference could appear when the trials were done on a small area during a short time whereas the real searches have been conducted on a much bigger area so that at the searches for real carcasses were done at a higher speed (area per min) or over a much longer time resulting in exhaustion of the searcher (e.g. at Waterkaaptocht one person searched at 10 turbines during one morning (!)).

### 5.1.3 Proportion of carcasses in the searched area

It may be valuable to assess the influence of the assumed spatial distribution of the carcasses by a sensitivity analysis.

### 5.1.4 Estimation of the number of fatalities

Average detection probability was around half the one obtained in the German study. This was mainly because searches were done every third day, whereas in the German study, daily searches were done. Persistence time, searcher efficiency and proportion of carcasses in the search area were comparable between the Dutch and the German study.

### 5.1.5 Combining carcass search data with acoustic activity

To formally combine the information in the carcass search data with the acoustic activity data, we used the model presented by Korner-Nievergelt et al. [2013]. This model has successfully been applied to German data sets with relatively high sample sizes (number of carcasses found >30 and number of sampled turbines >10). Given the weak information about fatality rates in the Dutch data alone, we recommend to use the estimates based on the model that combines the Dutch data with the information from the BMU-project (BMU_NL in Tables 10 and 11).

The very high number of bat calls recorded at Almere where no carcasses have been found is surprising. At the two turbines where one carcass was found each, the total number of bat calls did not exceed 100. Thus, we would highly expect more than one carcass at a turbine with over 1600 bat calls given the similar carcass detection probability. Carcass detection probability at Almere was not lower than at the other farms. Therefore, we suspect that something is different with Almere. The data from Almere may cause the model to estimate much smaller collision rates in relation to acoustic activity than were obtained in the German (BMU-)data. We, therefore, fitted the model to the Dutch data without the data from Almere. Indeed, when the data from Almere was ignored, the fatality estimates based on the Dutch data alone were twice as high as when the data of Almere were used (compare Tables 10 and 11).

However, it is not legitimate to exclude data that does not fit to our conception. Maybe, in reality the spatial and temporal variance in the ratio between collision rate and recorded bat calls is much larger than we think. This would mean that we need much more data to develop a model that can reliably predict collision rate from acoustic activity. But, we think it may be valuable searching for (other than stochastic) reasons why no carcass has been found at Almere despite the large number of recorded bat calls.

#### 5.1.6 Using the BMU-model for estimating the fatality numbers

When the BMU-model was applied to the Dutch acoustic activity data alone, we predicted higher numbers of fatalities than when we looked at the Dutch carcass search data (either carcass search data alone or using carcass search data together with acoustic activity data). Reasons could be because less harmful turbine types may have been used, or because, the species were less susceptible to collisions, or because acoustic detector recorded more bat calls per flying bat.

Possible further steps:

1. describe characteristics of turbines and differences between the Dutch project and the BMU project
2. compare activity data between the Dutch and the BMU data to assess how similar the conditions are and how reliable the predictions from the BMU-model are.

### 5.2 Model for acoustic activity

The model presented here can potentially be used to predict average acoustic activity for 10 min intervals based on time, date and weather parameters. Such a model is used in curtailment algorithms that are based on collision risk estimates for the real time.

However, model fit is poor and the predictive power of the model has not yet been assessed.

Possible further steps:

1. merge the data with the lowland German data
2. include landscape parameters as predictors
3. account for temporal autocorrelation
4. use cross-validation to assess predictive power
5. consider a model that accounts for zero-inflation

It may be worth to discuss how representative the data set with n = 5 turbines is before starting to develop a model for the prediction of bat activity per 10 min interval at Dutch wind turbines. Given the large between-turbine variance (e.g. Almere being completely different from the other turbines with respect to the number of recordings and Waterkaaptocht with respect to species composition), it will be extremely valuable to collect data from further turbines.

An alternative to collecting more Dutch data may be to merge the Dutch data with the German (lowland) data in order to develop a more representative model.

We would like to stimulate people who collected similar data to share them so that a collection of acoustic data representative for the Netherlands will be available.

## 5.3 Curtailment algorithm

The curtailment algorithms requires a powerful model to predict bat activity and a model to estimate collision rate based on estimated activity. We, here, present a start towards both of these models. However, for the moment, the Dutch data base may be too scarce for the development of a precise curtailment algorithms for the Netherlands.

## 5.4 General conclusions

Since the volume of Dutch data in general is small compared to the German data, the German data dominate the estimates on fatality rates in the analyses based on the combined data sets.

Predictions of collision rates for new turbines or new dates are possible, but at the moment these predictions are not very precise because the carcass search data and the acoustic activity data used to develop a model allowing for such predictions is scarce.

It is, therefore, of utmost importance to use the standard protocols for assessing acoustic data and for performing carcass searches (and e.g. also assess search efficiency, persistence and proportion of carcasses falling into the search area). Landscape and weather should also be recorded in a standard way, to enable these data to be used in improving the models for the predictions of bat activity and collision rates. Once such models are reliable, an efficient curtailment algorithm could be developed that allows saving the maximum number of bats while minimizing the loss of energy production.

## 6 Notations, abbreviations and glossary

| Abbreviation | Description |
|---|---|
| *Variables* | |
| $c$ | count; number of carcasses found |
| $N$ | number of fatalities |
| *Parameters* | |
| $s$ | daily persistence probability; probability that a carcass remains on the ground for 24 hours |
| $f$ | searcher efficiency; probability that a carcass that is lying on the ground is found by a searcher during one search |
| $a$ | proportion of fatalities that have fallen into the search area |
| $p$ | carcass detection probability; probability that a bat that has been killed during the study period is found by a searcher |
| $d$ | search interval; number of days between two searches |
| $n$ | total number of searches per wind farm |
| *Indices* | |
| $i$ | wind farm, $i = 1, ..., I$ |
| $q$ | wind turbine within a wind farm, $q = 1, ..., Q$ |
| $t$ | day, $t = 1, ..., T$ |
| $I$ | number of wind farms |
| $Q$ | number of turbines within a wind farm |
| $T$ | number of days (study period) |
| *Glossary* | |
| credible interval | Bayesian equivalent to the frequentist confidence interval. The Bayesian credible interval (CrI) gives the range of parameter values within which we expect the true parameter value to be with a defined probability (here, we always use 95%) given the data. |
| posterior distribution | The probability distribution that expresses what we know about a parameter after having looked at the data. It is a combination of the prior distribution with the information in the data. |
| prior distribution | The probability distribution that expresses what we know about a parameter before collecting the data |

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## Appendix II. Description of Anabat filters

All bats:
calls: smoothness: 20, highstart
frequencies Fmin (kHz) min: 16
times: Dur (ms) Min: 1, Max: 20

Nyctaloid:
body: Fc (kHz) Min: 15; Max: 80
body: Fk (kHz) Min: 12; Max: 38
calls: smoothness: 60, highstart
frequencies Fmin (kHz) Min: 15, Max: 30
times: Dur (ms) Min: 2, Max: 35

Nyctalus noctula (qCF calls):
body: Fc (kHz) Min: 17; Max: 20
calls: smoothness: 20, highstart
frequencies Fmin (kHz) Min: 17, Max: 20
frequencies: Sweep (kHz) Min: 1.5
times: Dur (ms) Min: 5

Myotis (FM calls):
body: Fc (kHz) Min: 35; Max: 80
calls: smoothness: 20, highstart
frequencies: Sweep (kHz) Min: 15
times: Dur (ms) Min: 2, Max: 7

Myotis dasycneme (qCF calls):
body: Fc (kHz) Min: 30; Max: 60
calls: smoothness: 40, highstart
frequencies: Fmin (kHz) Min: 30, Max: 35
frequencies: Sweep (kHz) Min: 2
frequencies: Fmean (kHz) Min: 30, Max: 42
times: Dur (ms) Min: 4, Max: 18

Pipistrellus nathusii:
body: Fc (kHz) Min: 35; Max: 41
calls: smoothness: 20, highstart
frequencies Fmin (kHz) Min: 35, Max: 41
frequencies: Sweep (kHz) not used
times: Dur (ms) Min: 2, Max: 15

Pipistrellus pipistrellus:
body: Fc (kHz) Min: 40; Max: 49
calls: smoothness: 20, highstart
frequencies Fmin (kHz) Min: 40
frequencies: Sweep (kHz) Min: 1.5
times: Dur (ms) Min: 2, Max: 15

Pipistrellus pygmaeus:
body: Fc (kHz) Min: 50; Max: 60
calls: smoothness: 20, highstart
frequencies Fmin (kHz) Min: 16
frequencies: Sweep (kHz) Min: 1.5
times: Dur (ms) Min: 2, Max: 15

## Appendix III. Set of rules to reduce multiple identification of single files

Every file is scanned using different filters. Since the file length is very short (up to a few seconds depending on the amount of information per ms) one file usually contains only one species. The occurrence of several species that are relatively rare within a single file is unlikely. Additionally, when many calls of one species and a couple of calls of another similar species are detected within a file, it is more likely that a few unusual calls (e.g. feeding buzz) of the commonest species were present instead of two species at the same time.
The following rules were applied to the filter output to reduce multiple identification of the same calls (in this specific order).

1. Only accept Myotis if the number of calls exceeds P. pipistrellus.
2. Only accept P. pipistrellus if the number of calls is equal to or exceeds Myotis.
3. Only accept Myotis if the number of calls exceeds P. nathusii.
4. Only accept P. nathusii if the number of calls is equal to or exceeds Myotis.
5. Only accept Myotis if the number of calls exceeds Nyctaloid.
6. Only accept Nyctaloid if the number of calls is equal to or exceeds Myotis.
7. Only accept Myotis dasycneme if the number of calls exceeds Nyctaloid.
8. Only accept Nyctaloid if the number of calls is equal to or exceeds M. dasycneme.
9. Decline Myotis dasycneme if the number of calls < 4 while P. nathusii exceeds 9.
10. Decline Myotis dasycneme if the number of calls < 2 while P. pipistrellus exceeds 9.
11. Decline Nyctaloid if the number of calls < 4 while P. nathusii exceeds 9.
12. Decline Nyctaloid if the number of calls < 2 while P. pipistrellus exceeds 9.
13. Decline P. nathusii if the number of calls < 4 while P. pipistrellus exceeds 9.
14. Decline P. pipistrellus if the number of calls < 4 while P. nathusii exceeds 9.

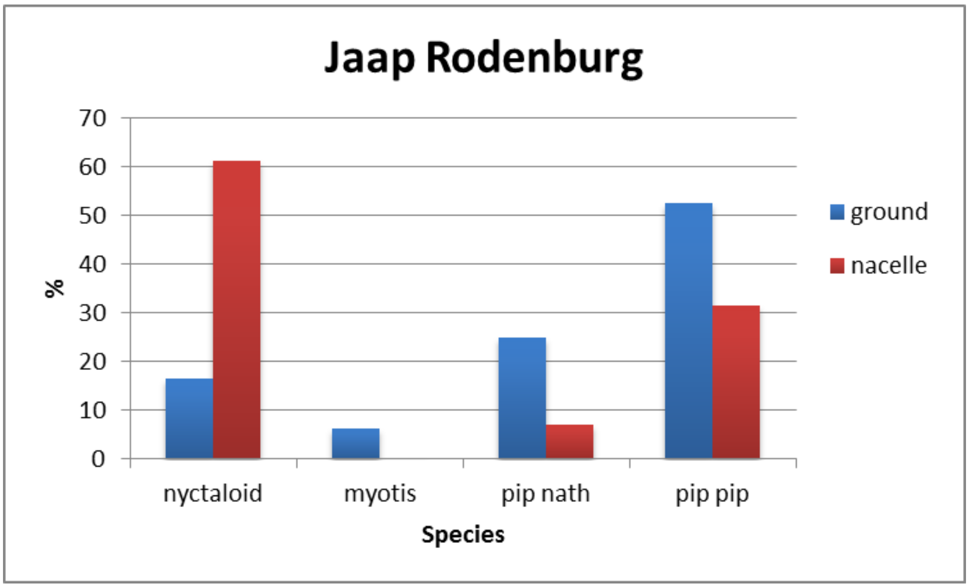
Note that none of these rules apply to the all bats output and that all combinations of nyctaloid : Nyctalus noctula and Myotis : Myotis dasycneme were accepted.

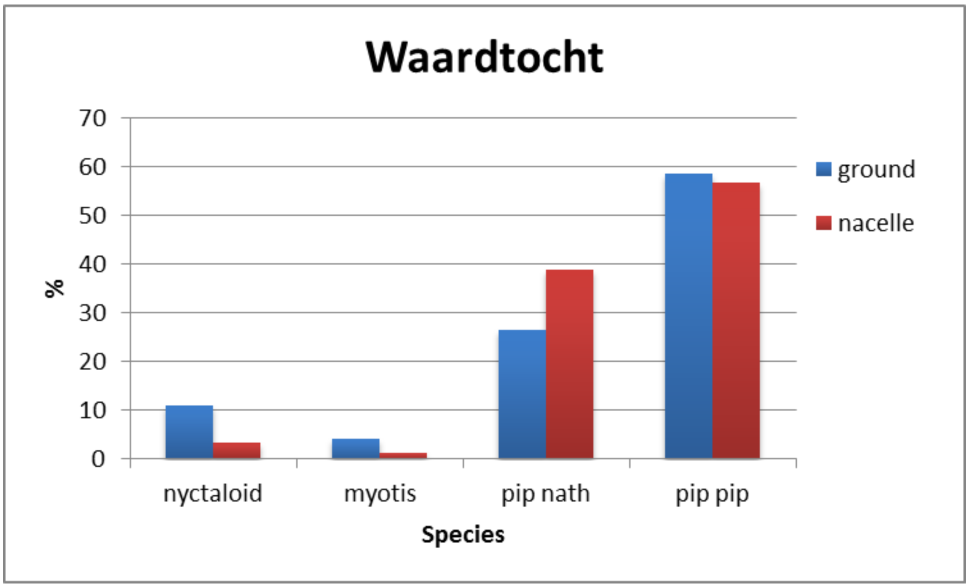
**Appendix IV. R-code statistical analyses acoustic activity**

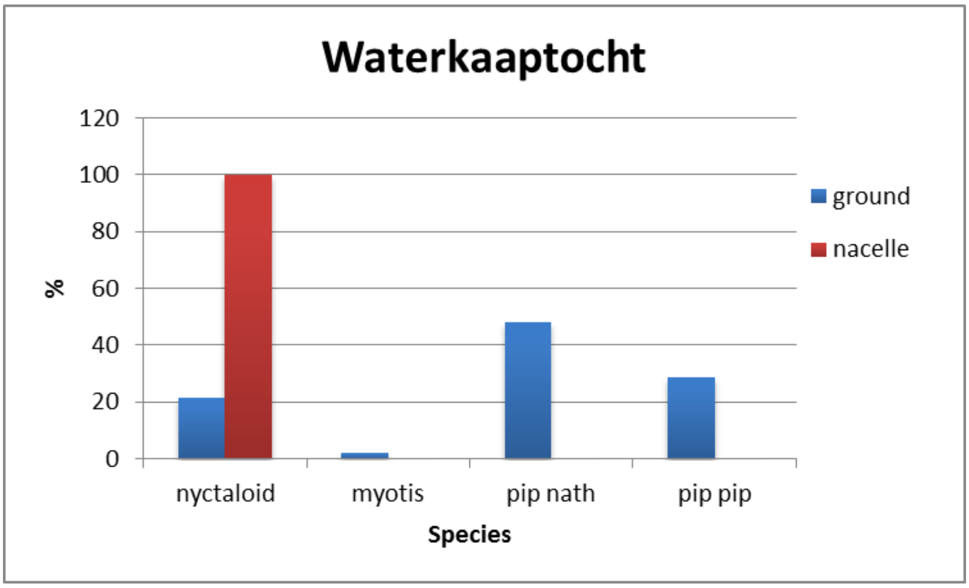
```
# transformation of explanatory variables
d.act$propnight <- (d.act$nighttime -
d.act$sunset.nighttime)/(d.act$sunrise.nighttime - d.act$sunset.nighttime)
d.act$propnight.z <- (d.act$propnight -
mean(d.act$propnight))/sd(d.act$propnight) d.act$day.z <- (d.act$dayofyear -
mean(d.act$dayofyear))/sd(d.act$dayofyear) d.act$windspeed.z <-
(d.act$windspeed - mean(d.act$windspeed,
na.rm = TRUE))/sd(d.act$windspeed, na.rm = TRUE) d.act$winddir.rad <-
d.act$winddir/180 * pi d.act$winddir.sin <- sin(d.act$winddir.rad)
d.act$winddir.cos <- cos(d.act$winddir.rad) d.act$winddir.sin2 <- sin(2 *
d.act$winddir.rad) d.act$winddir.cos2 <- cos(2 * d.act$winddir.rad) d.act$temp.z
<- (d.act$temp - mean(d.act$temp, na.rm = TRUE))/sd(d.act$temp,
na.rm = TRUE)

# select complete observations for the model
d.actc <- d.act[complete.cases(d.act), ] d.actc$obsid <- factor(1:nrow(d.actc))

# model fit and model selection
mod <- glmer(allbats ~ propnight.z + I(propnight.z^2) + I(propnight.z^3) +
I(propnight.z^4) + I(propnight.z^5) + day.z + I(day.z^2) + windspeed.z +
I(windspeed.z^2) + winddir.sin + winddir.cos + winddir.sin2 + winddir.cos2 +
(winddir.sin + winddir.cos + winddir.sin2 + winddir.cos2 |
windfarm), data = d.actc, family = poisson) save("mod", file = "modactfull.RData")

# include overdispersion
modod <- glmer(allbats ~ propnight.z + I(propnight.z^2) + I(propnight.z^3) +
I(propnight.z^4) + I(propnight.z^5) + day.z + I(day.z^2) + windspeed.z +
I(windspeed.z^2) + winddir.sin + winddir.cos + winddir.sin2 + winddir.cos2 +
(winddir.sin + winddir.cos + winddir.sin2 + winddir.cos2 |
windfarm) + (1 | obsid), data = d.actc, family = poisson) save("modod", file =
"modactfullod.RData")

# delete farm-specific
# sin(2*winddir)+cos(2*winddir)
modod1 <- glmer(allbats ~ propnight.z + I(propnight.z^2) +I(propnight.z^3) +
I(propnight.z^4) + I(propnight.z^5) + day.z + I(day.z^2) + windspeed.z +
I(windspeed.z^2) + winddir.sin + winddir.cos + winddir.sin2 + winddir.cos2 +
(winddir.sin + winddir.cos | windfarm) + (1 | obsid), data = d.actc, family =
poisson)
save("modod1", file = "modactfullod1.RData")

# delete farm-specific sin(winddir)+cos(winddir)
modod2 <- glmer(allbats ~ propnight.z + I(propnight.z^2) + I(propnight.z^3) +
I(propnight.z^4) + I(propnight.z^5) + day.z + I(day.z^2) + windspeed.z +
I(windspeed.z^2) + winddir.sin + winddir.cos + winddir.sin2 + winddir.cos2 + (1 |
windfarm) + (1 | obsid), data = d.actc, family = poisson)
save("modod2", file = "modactfullod2.RData")
```

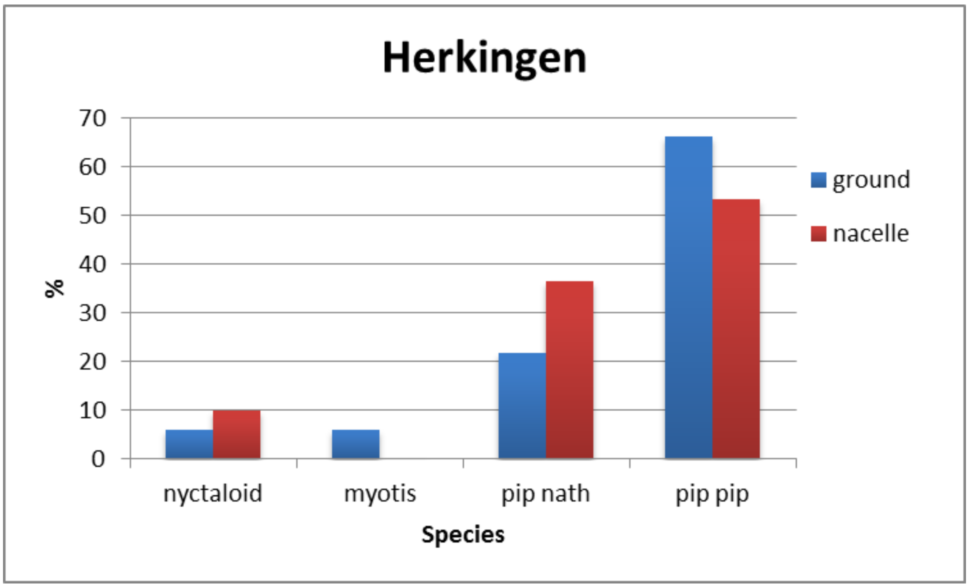
```
# delete propnight^5
modod3 <- glmer(allbats ~ propnight.z + I(propnight.z^2) + I(propnight.z^3) +
I(propnight.z^4) + day.z + I(day.z^2) + windspeed.z + I(windspeed.z^2) +
winddir.sin + winddir.cos + winddir.sin2 + winddir.cos2 + (1 |
windfarm) + (1 | obsid), data = d.actc, family = poisson) save("modod3", file =
"modactfullod3.RData")

# delete sin(winddir*2) + cos(winddir*2)
modod4 <- glmer(allbats ~ propnight.z + I(propnight.z^2) + I(propnight.z^3) +
I(propnight.z^4) + day.z + I(day.z^2) + windspeed.z + I(windspeed.z^2) +
winddir.sin + winddir.cos + (1 | windfarm) + (1 | obsid), data = d.actc, family =
poisson)
save("modod4", file = "modactfullod4.RData")
```

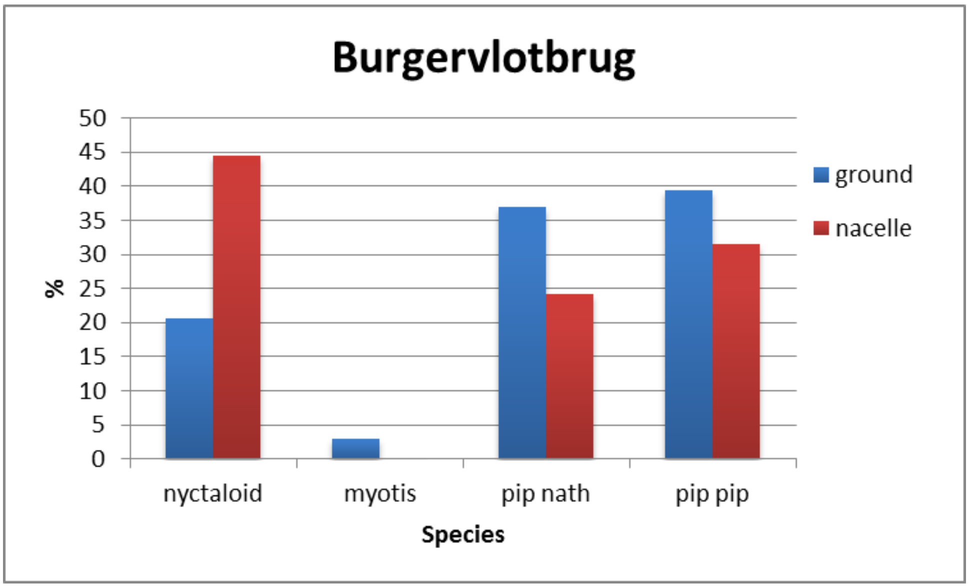
**Appendix V. Species composition per wind farm**




Waterkaaptocht
120
100
80
60
40
20
0
%
ground
nacelle
nyctaloid
myotis
pip nath
pip pip
Species


Herkingen
70
60
50
40
30
20
10
0
%
ground
nacelle
nyctaloid
myotis
pip nath
pip pip
Species


Burgervlotbrug
50
45
40
35
30
25
20
15
10
5
0
%
ground
nacelle
nyctaloid
myotis
pip nath
pip pip
Species

## Appendix VI. Maximum theoretical detection distance

Maximum theoretical detection distance is calculated for sound of 20 en 40 kHz using the way sound is attenuated and spreads from a point source in all directions (Holderied & von Helversen 2003).

Assumptions:
Sound intensity: 130 dB SPL
Atmospheric attenuation: 0.7dB/m for 20kHz; 1.4 dB/m for 40 kHz
Spreading from 0.2 m in front of beak: 6 dB doubling distance
Reception detector: 30 dB SPL

30 dB SPL is needed for reception, reduction of sound can therefore be maximal:
130 - 30 = 100 dB

Sound van 20 kHz:

$x*0.7+\log2(x/0.2)*6=100$ (x = maximal detection distance)

x=70

Sound of 40kHz:
$x*1.4+\log2(x/0.2)*6=100$

x=38

The result is dependent on the sensitivity of the equipment for each frequency and the exact intensity of the bat sound. The sensitivity of bat detectors is not the same for every frequency. This can therefore only be seen as a rough estimate.

## Appendix VII. Observed bat species

Species found in fatality searches

| English name | Dutch name | Scientific name |
|---|---|---|
| Nathusius' pipistrelle | ruige dwergvleermuis | *Pipistrellus nathusii* |
| Common pipistrelle | gewone dwergvleermuis | *Pipistrellus pipistrellus* |

Species observed in Anabat recordings, based on the used filters

| English name | Dutch name | Scientific name |
|---|---|---|
| All bats | vleermuizen | Chiroptera |
| Nyctaloids<br>group of species consisting predominantly of Noctules, serotines and particoloured bats. | Nyctaloiden<br>niet nader te determineren groep van vooral rosse vleermuis, laatvlieger en twee kleurige vleermuis | group of species consisting predominantly of *Nyctalus noctula, Eptesicus serotinus* and *Vespertilio murinus*. |
| Noctule indentified to species level | Rosse vleermuis tot op soort gedetermineerd | *Nyctalus noctula* CF:<br>typical qCF calls of the noctule bat on 16-20 kHz. |
| Common pipistrelle. | Gewone dwergvleermuis | *Pipistrellus pipistrellus* |
| Nathusius' pipistrelle. | Ruige dwergvleermuis | *Pipistrellus nathusii* |
| Myotis: group of species consisting predominantly of Daubenton's bat and pond bat | Myotis-groep' (niet nader te determineren groep van vooral Watervleermuis daubentonii en meervleermuis | Myotis: group of species consisting predominantly of *Myotis daubentonii* and *Myotis dasycneme* |
| Pond bat identified to species level | Meervleermuis tot op soort gedetermineerd | *Myotis dasycneme*:<br>typical qCF calls of pond bat of 10-18 ms and Fmax 35 kHz. |