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Bat mortality at wind turbines in northwestern Europe

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We reviewed published and unpublished written reports on bat mortality at wind farms in northwestern Europe. The estimated number of bats killed per turbine annually was relatively low (0–3) on flat, open farmland away from the coast, higher (2–5) in more complex agricultural landscapes, and highest (5–20) at the coast and on forested hills and ridges. The species killed almost exclusively (98%) belonged to a group (*Nyctalus*, *Pipistrellus*, *Vespertilio* and *Eptesicus* spp.) adapted for open-air foraging. The bats were killed by the moving rotor blades as they hunted insects attracted to the turbines. This occurred independently of sex and age. Peak mortality varied considerably in frequency and timing among years, but the events usually (90%) occurred on nights with low wind speeds in late July to early October and to a lesser extent (10%) also in April-June. The mortality increased with turbine tower height and rotor diameter but was independent of the distance from the ground to the lowest rotor point. It was also independent of the size of the wind park (1–18 turbines). Bat species other than the open-air suite referred to above are usually not at risk at wind turbines, because they fly below the rotors, but are still killed occasionally (2%).

Key words: aerial ecology, aeroecology, bat conservation, high-altitude feeding, killing factors, renewable energy, wind farming

INTRODUCTION

Wind turbines cause extensive mortality among birds and bats in certain situations, more so in some species than in others. This has become an important ethical problem and has resulted in serious concern about the future of some populations (Kunz *et al*., 2007*a*). For example, bats that encounter wind turbines along the Appalachian Mountains in eastern U.S. are killed at rates of 30–40 individuals per turbine annually. The estimated total mortality rate at wind turbines in this area alone in the year 2020, based on projections of installed capacity, is between 33,000 and 110,000 bats per year (Kunz *et al*., 2007*a*). Bats typically live long lives and have slow reproductive rates (Barclay and Harder, 2003) and, although the sizes of bat populations are generally unknown, it is unclear if they can sustain increased mortality of this magnitude (Kunz *et al*., 2007*a*).

Based on the North American studies reviewed by Kunz *et al*. (2007*a*, 2007*b*) and Arnett *et al*. (2008) and the European work available to us, it appears that death rates similar to that of the Appalachians are uncommon. Nevertheless, mortality figures nearly as high have been reported at wind turbines on top of forested hills and ridges in southern Germany (Brinkmann *et al*., 2006) and at the Atlantic coast of France (Dulac, 2008). These cases will be considered further below.

The purpose of this review is to summarize the present knowledge about wind turbine effects on bats, as it has developed in northwestern Europe since 1999 (Bach *et al*., 1999; Ramel *et al*., 1999). Our aims are: i) to synthesize current information from bat mortality monitoring in northwestern Europe; ii) to apply statistical analysis to data presented in the original reports, using a meta-analytical approach, to test some general hypotheses; and iii) to compare the results of our analysis with data from North America (reviewed by Kunz *et al*., 2007*a*, 2007*b* and Arnett *et al*., 2008). The overall aim is to provide an up-to-date summary of the bat and wind turbine issue with the focus on northwestern Europe.

MATERIALS AND METHODS

The main data for this review were obtained from published or unpublished technical reports of post-construction monitoring of dead bats at wind turbines in northwestern Europe (Table 1). We restricted this data set geographically by excluding the Mediterranean region, which is faunistically quite different, and eastern Europe, from which we did not find any reports. However, we included both summer and winter-grounds of the migratory northern bat species, i.e., from southern Scandinavia to northern France and Switzerland and from Great Britain to Austria.

Search protocols and statistics originally used in the studies providing our data set differ in several respects, because the methods have developed during the course of these studies (Arnett, 2005; Grünkorn *et al.*, 2005; Kunz *et al.*, 2007*b*; Niermann *et al.*, 2007; Rodrigues *et al.*, 2008). We have not attempted to control for such differences, but for statistical calculations on the main data set (Table 1), we used only reports where the most important sources of observational bias have been accounted for one way or another. These biases are: i) carcass removal by scavengers between observations; ii) variation in efficiency among observers and over time; and iii) site-specific detection differences, depending on e.g., the ground vegetation. Scavenger removal rates have been estimated using either fresh or frozen dead bats, mice, wild birds or chicken. To estimate searching efficiency, either real bats, model bats (paper or textile), mice or small birds have been used.

The total number of turbines monitored per wind park varied among the studies, as did the fraction of turbines monitored among those present. The correction factors referred to above were in some cases measured for each wind park or turbine separately but sometimes they were averaged over several parks or turbines. Perhaps most importantly, search intervals varied between 1 and 24 days. We did not account for any potential biases resulting from these differences. However, it should be remembered that the reported mortality rates may be subject to these biases, so comparisons should be made with care. We concentrate on patterns, not details.

In most cases the monitoring did not encompass the whole season but only the period from mid July to mid October. Since ca. 90% of the annual mortality at wind turbines took place during this period and 10% in spring and early summer (Figs. 1 and 2), we adjusted the estimated annual number of fatalities in all part-season-studies by dividing by 0.9. In one case (Grünkorn *et al.*, 2005) the observations did not start until September, which means that about half of the autumn peak mortality period was missed. We still decided to include this study, however, because it represents several wind farms located in intensively used, essentially flat and treeless farmland, a common and representative habitat type in much of northern Europe. In cases where the same study continued for more than one season we used the annual average. Some of the most important methodological differences between the studies are listed in Table 2.

The data were usually taken directly from the original reports. However, in some cases where altitude, distance to the coast, topographical features or percentage tree cover were not given in the reports, these were taken from Google Maps or provided by the authors on request. Technical data of the turbines such as installed capacity were occasionally obtained from the manufacuturer´s home pages or from the windpower and windfarms database (www.thewindpower.net).

For the main data, absolute estimates of bat mortality rates representing 40 European wind farms were obtained from 14 technical reports written between 2002 and 2010 (Table 1). Among these, estimates from three wind farms were omitted from the statistical analyses because the most important biases (scavenger removal and observer efficiency, see above) were not accounted for. In these cases, the given mortality rates represent minimum estimates and are lower than the real rates. The remaining 37 wind farms were treated as independent samples, which, because of frequent bimodal distribution of the data, were analysed by non-parametric statistics (Siegel and Castellan, 1988).

ESTIMATES OF MORTALITY

Estimates of absolute mortality rates appeared closely related to landscape features such as topography and vegetation but differed only marginally between countries and regions, as long as the habitats were similar (Table 1). The highest mortalities (mean 18–19 bats per turbine annually) were observed on top of forested hills in Schwarzwald in southern Germany (state of Baden-Württemberg) and at a site in a marsh area used for oyster farming at the Atlantic coast of France (Dulac, 2008).

In the flat and intensively used farmland in northwestern Germany (states of Schleswig-Holstein and Niedersachsen) the estimated mortality rate was generally low (mean 0.4 bats per turbine annually), but elevated (3.1 bats) at a site near the coast. The slightly more variable agricultural landscape of Sachsen in eastern Germany showed a mortality rate a little higher than that of the northwest (mean 1.8 bats). In this case the mortality was elevated (4.6 bats) at turbines on top of two low hills. Generally, mortality was higher than expected at turbines located less than 100 m from woodlands and lower at turbines further away (Endl *et al.*, 2004; Seiche, 2008).

The samples from the relatively flat and intensively used farmland of lower Austria showed high mortality rates at two of the three sites (mean 4.7 bats), one of them being located on top of a low hill. The highest mortality (8.8 bats) was recorded in a flat area of open farmland, but on a recognized flight route for bats (Traxler *et al.*, 2004). One of the Swiss samples, located at 1,250 m altitude in the Jura Mountains, was comparable to that of the Schwarzwald sites in terms of bat mortality (14 bats per turbine — Leuzinger *et al.*, 2008). The English locality, located on flat and open farmland, had a low mortality rate (1.2 bats), comparable to that of similar habitats in Germany.

TABLE 1. Setting of the wind farms and the estimated mortality rate of bats for each. Predominant land use and percentage tree cover refer to the area within 500 m of the turbines. The mortality rates are given per turbine and per MW of installed energy. Rates in parentheses were not corrected for differences in observer biases and carcass persistence rates and, therefore, are minimum estimates only and not included in the statistical analyses

Name of wind park	Land use	% tree cover	Topography (km from coast)	Altitude (m a.s.l.)	No. of turbines/ farm	Tower height (m)	Mortality year^{-1}		References
							turbine^{-1}	MW^{-1}	
Schwarzwald, Germany									
Lahr	forest	80	hill/ridge	430	3	90	(0.6)	(0.4)	Behr and von Helversen (2005)
Ittenschwander Horn	forest	90	hill/ridge	1,000	2	85	18.3	9.2	Behr *et al.* (2006)
Rosskopf	forest	90	hill/ridge	737	4	98	26.0	14.4	Behr and von Helversen (2006)
Mahlberg	forest	90	hill/ridge	485	3	80	10.0	4.0	Brinkmann *et al.* (2006)
Brudergarten	forest	90	hill/ridge	470	3	69	19.1	15.0	Brinkmann *et al.* (2006)
Hohe Eck	forest	80	hill/ridge	600	1	86	41.1	22.8	Brinkmann *et al.* (2006)
Schillinger Berg	forest	50	hill/ridge	715	2	86	31.6	17.6	Brinkmann *et al.* (2006)
Plattenhöfe	pasture	30	low hill	1,000	4	70	3.9	3.9	Brinkmann *et al.* (2006)
Holzschlägermatte	forest	80	hill/ridge	920	2	98	13.3	7.4	Brinkmann *et al.* (2006)
Fürstenberg	pasture	40	hill	920	1	90	0.0	0.0	Brinkmann *et al.* (2006)
Mean							18.0	10.5	
Schleswig-Holstein and Niedersachsen, northwestern Germany									
Blumendorf	crop	10	flat (40)	45	2	65	(2.0)	(3.3)	Göbel and Göttsche (2005)
Tralau	crop	0	flat (35)	40	4	60	(2.0)	(1.0)	Göttsche and Göbel (2007)
Friedrich-Wilhelm-Lübke-Koog	crop	10	flat (2.0)	1	13	60	0.0	0.0	Grünkorn *et al.* (2005)
Bosbüll	crop	10	flat (12)	1	4	47	0.0	0.0	Grünkorn *et al.* (2005)
Marienkoog	crop	10	flat (0.5)	1	15	40	0.0	0.0	Grünkorn *et al.* (2005)
Reussenköge	crop	10	flat (2.0)	1	17	98	0.0	0.0	Grünkorn *et al.* (2005)
Breklumer Koog	crop	0	flat (6.0)	1	11	98	0.0	0.0	Grünkorn *et al.* (2005)
Simonsberger Koog	crop	0	flat (1.5)	1	13	65	0.0	0.0	Grünkorn *et al.* (2005)
Uelvesbüller Koog	crop	0	flat (2.0)	1	4	60	0.0	0.0	Grünkorn *et al.* (2005)
Cappel-Neufeld	crop	2	flat (1.0)	1	5	40	3.1	9.4	Bach and Bach (2010)
Mean							0.4	1.2	
Sachsen, eastern Germany									
Puschwitz	forest	50	low hill	200	10	78	(3.8)	(1.9)	Trapp *et al.* (2002)
Puschwitz	forest	50	low hill	200	10	78	4.6	2.3	Endl *et al.* (2004)
Wendischbora	crop	20	flat	290	17	78	1.3	0.7	Endl *et al.* (2004)
Baeyerhöhe	crop	10	low hill	300	5	98	4.6	2.6	Endl *et al.* (2004)
Wachau	crop	4	flat	256	5	65	0.0	0.0	Endl *et al.* (2004)
Bernsdorf	forest	70	flat	198	3	80	0.0	0.0	Endl *et al.* (2004)
Röhrsdorf	crop	20	flat	156	4	65	0.0	0.0	Endl *et al.* (2004)
Ludwigsdorf	crop	10	low hill	238	18	86	1.1	0.6	Endl *et al.* (2004)
Thonberg	crop	20	low hill	198	12	60	1.1	0.7	Endl *et al.* (2004)
Kleinröhrsdorf	crop	15	flat	285	3	69	2.2	1.7	Endl *et al.* (2004)
Melaune	crop	1	flat	200	7	65	2.6	1.7	Endl *et al.* (2004)
Reichenbach	crop	3	flat	250	7	65	1.9	1.1	Endl *et al.* (2004)
Eckardsberg	crop	2	flat	300	5	86	2.6	1.4	Endl *et al.* (2004)
Mean							1.8	1.1	
Niederösterreich, Austria									
Oberdorf	crop	10	flat	163	5	98	0.0	0.0	Traxler *et al.* (2004)
Prellenkirchen	crop	5	flat	160	8	98	8.8	4.9	Traxler *et al.* (2004)
Steinberg	crop	10	low hill	292	9	98	5.3	2.6	Traxler *et al.* (2004)
Mean							4.7	2.5	
Switzerland									
Mont Soleil	pasture	20	low hill	1,250	3	77	13.6	16.0	Leuzinger *et al.* (2008)
Tramelan	pasture	20	low hill	1,000	1	24	0.0	0.0	Leuzinger *et al.* (2008)
Feldmos	pasture	20	low hill	800	1	86	0.0	0.0	Leuzinger *et al.* (2008)
Mean							4.5	5.3	
Cambridgeshire, England									
Coldham 1	crop	0	flat	1	8	60	1.2	0.6	Bioscan (2008)
Vendée, France									
Bouin	marsh	0	flat (0.1)	1	8	62	19.0	7.6	Dulac (2008)

Ahlén (2002) surveyed 160 wind turbines in southern Sweden from late August to early October 2002. Each turbine was searched once. The majority of the casualties (14 of 17) were found at 71 turbines located within 500 m from the coast. Mortality rate was thus five times higher at turbines placed at the coast compared to those located inland (χ^2 = 3.85, *d.f.* = 1, $P < 0.05$). In a similar survey in Thüringen in Germany, Kusenbach (2004) found five dead bats at 94 turbines located in mostly open farmland. Hence the mean mortality rate in Thüringen was the same as that of the inland localities in Sweden (0.04 bats per search).

There was no significant relationship between the mortality per turbine and the number of turbines in the farm (Table 3), so turbines in larger wind farms (up to 18 turbines) did not kill more (or fewer) bats than those operating as single units. In contrast, the mortality rate was significantly correlated with turbine tower height ($r_s = 0.49$, $P < 0.01$ — Table 3) and rotor diameter ($r_s = 0.32$, $P < 0.05$) but not with minimum distance between the rotor and the ground ($r_s = 0.18$, $P > 0.05$; in all cases $n = 37$). When calculating correlation coefficients, we used mortality rate per turbine as well as per MW of installed energy, but, for simplicity, we show

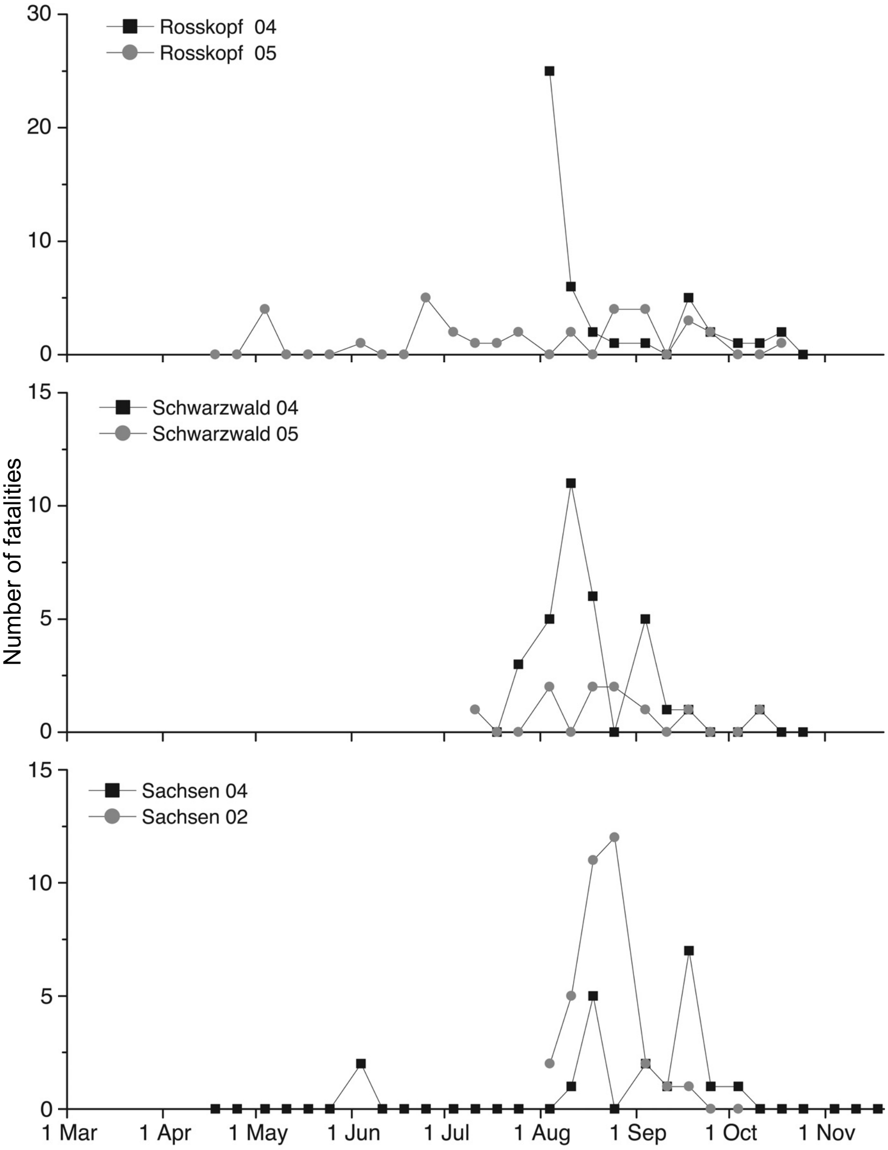

FIG. 1. Temporal patterns of bat mortality at wind turbines in Schwarzwald and Sachsen, Germany. The upper two figures are from a single Schwarzwald locality (Rosskopf) in 2004 and 2005 (Behr and von Helversen, 2006) and from several localities combined in 2004 and 2005 (Brinkmann *et al.*, 2006), respectively. The lower figure is from a single locality in Sachsen (Puschwitz) in 2002 (Trapp *et al.*, 2002) and from several localities combined in 2004 (Endl *et al.*, 2004).

TABLE 2. Some basic information on the methods used to estimate bat mortality rates (see Table 1). Search plots were either circular or rectangular, characterized by diameter (d) or side lengths, respectively. For estimates of searcher efficiency and carcass persistence, the methods (numbers and kinds of targets) used in the experiments are indicated. For details see Materials and Methods

References	Study period	Search interval (days)	Search plot (m)	Searcher efficiency (mean) and methods	Carcass persistence (mean) and methods
Behr *et al.* (2006)	31/7–30/10 2005	2–3	d = 130	mice	mice
Behr and von Helversen (2005)[1]	26/7–6/10 2005	3	d = 136	—	—
Behr and von Helversen (2006)	27/4–15/10 2005	2–3	d = 130	65%	4.0 days
				40 mice	57 mice
Brinkmann *et al.* (2006)	08–10 2004	5	d = 100	40–84%	2.0 days
	1/4–15/5 2005			60 bat models	50 mice
	15/7–15/10 2005				
Göbel and Göttsche (2005)[1]	7, 9 2005	7–14	d = 100	—	—
Göttsche and Göbel (2007)[1]	7, 9 2005, 4–6 2006	7–14	d = 100	—	—
Grünkorn *et al.* (2006)	1/9–15/11 2004	5	100 × 100	6–86%	7.5 days
				367 birds	74 birds
Bach and Bach (2010)	11/7–15/19 2008	3	d = 80	38%	6.0 days
				12 bats	12 bats
Seiche (2008)	15/5–30/9 2006	2–6		bat models	—
Endl *et al.* (2004)	2/6–4/10 2004	c. 24	90–160 =	21–79%	5.2 days
			rotor diam.	72 bat models	48 chicks
Trapp *et al.* (2002)[1]	18/8–10/10 2002	1	d = 100	—	—
Traxler *et al.* (2004)[2]	1/9 2003–1/9 2004	1	100 × 100	25–75%	—
				95 birds	
Leuzinger *et al.* (2008)	1/6–31/10 2007	15	d = 80	74%	2.0 days
				58 bat models	50 mice
Bioscan (2008)[3]	1/10 2006–30/9 2007	7	120 × 120	66%, 5 bats	—
Dulac (2008)[3]	23/7–16/12 2003	7	100 × 100	53%	8.0 days
	1/1–31/12 2004	7	100 × 100	59%	8.0 days
	1/1–31/12 2005	7	100 × 100	51%	9.7 days
	1/1–31/12 2006	7	100 × 100	84%	13.4 days

[1] — Searcher efficiency and carcass removal rate not measured; [2] — Searcher efficiency and carcass removal rate combined; [3] — Dead bats were left in situ and checked every seven days

only the former, which consistently gave the highest coefficients.

Distribution of Mortality Among Bat Species

The distribution of bat mortality was skewed to certain species. Ninety-eight percent of the recorded mortality affected either of eight 'high-risk' species in the four genera *Nyctalus*, *Pipistrellus, Vespertilio* and *Eptesicus*. The remaining 13 species may be considered 'low-risk' species, that relatively seldom are killed at wind turbines. They represent 62% of the total number of species but only 2% of the dead bats (Table 4). Bats observed flying at turbine rotor height were consistently identified as belonging to the 'high-risk' species groups (Ahlén, 2002; Endl *et al.*, 2004; Behr and von Helversen, 2005; Brinkmann *et al.*, 2006; Ahlén *et al.*, 2007; Behr *et al.*, 2007; Grünwald and Schäfer, 2007; Seiche, 2008; Bach and Bach, 2010; Bach and Niermann, 2010). The 'low-risk' species such as *Myotis*, *Plecotus* and *Barbastella* spp., some of which were among the commonest bat species in the respective areas, were usually not at risk, because they flew below the rotors (Endl *et al.*, 2004; Behr *et al.*, 2007; Grünwald and Schäfer, 2007; Seiche, 2008; Collins and Jones, 2009).

Morphological characteristics of the 'high-risk' species (*Nyctalus*, *Pipistrellus* and *Vespertilio* spp. and to some extent also *Eptesicus* spp.) include relatively long and narrow wings (Norberg and Rayner, 1987) and high-intensity echolocation calls that include a short, narrow-band component. Such echolocation pulses are used to detect moving insect wings ('glints') at relatively long distances over open air (several metres — Waters *et al.*, 1995). Clearly, these bats are morphologically and physiologically adapted for life in the open air. In contrast, the 'low-risk' bats are all relatively broad-winged and manoeuvrable species that usually feed near surfaces or within vegetation. They normally avoid open and exposed situations (Baagøe, 1987).

Generally the bat species most likely to be killed at wind farms are more or less common at least over

TABLE 3. Significance probabilities of mortality correlates calculated using data from Table 1. Sample size is the number of wind parks. For the Schleswig-Holstein sample, there was no variation in land use and topography, hence correlation coefficients could not be calculated

Region	n	Mann-Whitney U-test		Spearman's rank correlation			
		Land use	Topography	Percent tree cover	Altitude	No. of turbines	Tower height
Schwarzwald	9	< 0.05	< 0.05	ns	ns	ns	ns
Schleswig- -Holstein	9	–	–	ns	ns	ns	ns
Sachsen	12	ns	ns	ns	ns	ns	ns
All samples	37	< 0.001	< 0.001	< 0.01 $r_s = 0.49$	< 0.001 $r_s = 0.66$	ns $r_s = 0.18$	< 0.01 $r_s = 0.49$

part of their European range, although some of them are rare or may be in decline at the national or local level. This applies, for example, to the northern bat *Eptesicus nilssonii* and the parti-coloured bat *Vespertilio murinus* in parts of Germany (Petermann and Boye, 2006; Meinig *et al.*, 2009). At present, bat species that are considered endangered, vulnerable or near threatened at the European level, or that are listed in Annexes II or IV of the Habitats Directive (Temple and Terry, 2007), all belong to the 'low risk' species group (Table 4).

We applied a simple statistical analysis to the mortality data from three different regions in Germany (Table 5). Across the two lowland regions (Sachsen and Brandenburg), the species composition of the fatalities were similar and just about significantly different ($\chi^2 = 11.0$, $d.f. = 5$, $P = 0.05$). In contrast, the species composition of the bats killed in the topographically more complex region of Schwarzwald was significantly different from those in the other two regions ($\chi^2 = 388$, $d.f. = 7$, $P < 0.001$). *Nyctalus noctula* and *P. nathusii*, the species most frequently killed at turbines in the lowland regions, were replaced by *P. pipistrellus* and *N. leisleri* at higher elevations in Schwarzwald.

While *N. noctula* and *P. nathusii* as well as *N. leisleri* are long-distance migrants (Hutterer *et al.*, 2005), *P. pipistrellus*, the species most frequently killed in Schwarzwald, is believed to be resident or at most a short-distance migrant in continental Europe (Taake and Vierhaus, 2004). This also applies to *E. nilssonii*, the species most frequently killed in Scandinavia (Hutterer *et al.*, 2005).

Hence, as expected, which bat species are most frequently killed at wind turbines differ regionally and across habitats, reflecting variations in the composition of the 'high-risk' parts of the bat faunas at local or regional scales. Mortality occurs independently of whether these species are resident or migrants.

SEX AND AGE DIFFERENCES IN MORTALITY

Four European studies, representing two regions in Germany, separated dead bats according to sex and age (Table 6). The data set is limited and provides no evidence that the mortality was skewed according to sex or age. Indeed, although males were more often killed than females in eight out of 11 cases, the difference was not significant

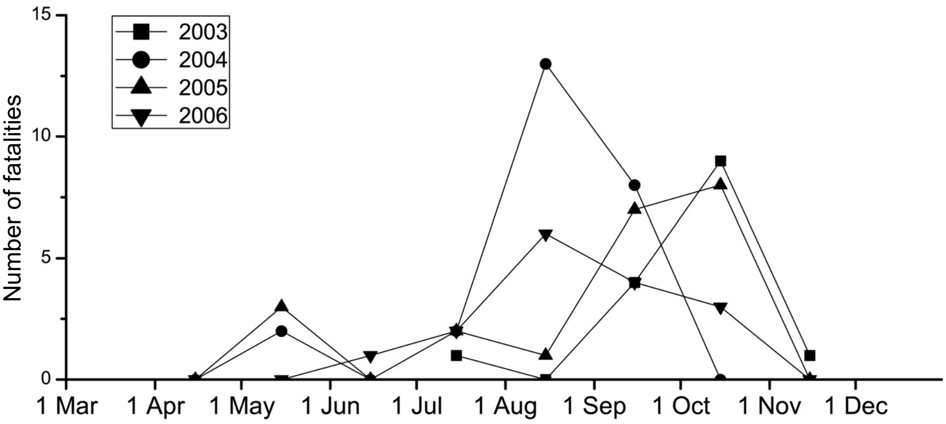

FIG. 2. Temporal patterns of bat mortality at the wind farm Bouin on the Atlantic coast of France during 2003–2006 (Dulac, 2008)

Table 4. Bat mortality at wind turbines in Europe, as recorded until December 2009. Species that regularly occur only south of Germany are not included in the table. Mortality data were taken from Dürr (2009). 'Glint detection' capability (high-intensity narrow-band FM-calls present in search phase) indicates adaptations for open-air (high-altitude) foraging (Waters *et al.*, 1995)

Bat species	Number of dead bats (%)		Glint detection
	Germany	Europe excluding Germany	
	'High-risk'		
Nyctalus noctula	374 (34.2)	16 (3.7)	Yes
N. leisleri	52 (4.8)	28 (6.4)	Yes
Pipistrellus nathusii	284 (26.0)	62 (14.2)	Yes
P. pipistrellus	230 (21.0)	140 (32.1)	Yes
P. pygmaeus	21 (1.9)	15 (3.4)	Yes
Vespertilio murinus	44 (4.0)	3 (0.7)	Yes
Eptesicus serotinus	25 (2.3)	15 (3.4)	Yes
E. nilssonii	2 (0.2)	8 (1.8)	Yes
	'Low-risk'		
*Myotis myotis**	2 (0.2)	1 (0.2)	No
*M. dasycneme**	1 (0.1)	0	No
M. daubentonii	3 (0.3)	2 (0.5)	No
M. brandtii	1 (0.1)	0	No
M. mystacinus	2 (0.2)	0	No
M. nattereri	0	0	No
*M. bechsteinii**	0	1 (0.2)	No
*M. emarginatus**	0	0	No
Plecotus austriacus	6 (0.5)	1 (0.2)	No (Yes?)
P. auritus	3 (0.3)	0	No
*Barbastella barbastellus**	0	1 (0.2)	Yes?
*Rhinolophus ferrumequinum**	0	0	No
*R. hipposideros**	0	0	No
Unidentified species	41 (3.8)	131 (30.0)	
Total	1,092 (100.0)	436 (100.0)	

* — Species that are considered endangered, vulnerable or near threatened at the European level or that are listed in Annexes II or IV of the Habitats Directive (Temple and Terry, 2007)

(Wilcoxon's signed-ranks test, $T = 26.5$, $n = 12$, $P > 0.05$). In the Sachsen studies (Endl *et al.*, 2004; Seiche, 2008), most killed *N. noctula* were juveniles (48 of 51), while at the same time, all *P. nathusii* were adults (19 of 19). In the other species the fatalities were few and distributed approximately equally between adults and young. Hence, the sex and age composition varied considerably from place to place and probably depended on the presence or absence of maternity colonies in the vicinity of the turbines. This result apparently differs from that of North America, where wind turbine mortality, regardless of species and locality, usually was dominated by adult males (Arnett *et al.*, 2008).

Temporal Patterns of Mortality

Annual mortality patterns (all species pooled) for two full season studies in Germany, and two part-season studies from the same areas are presented in Fig. 1. The whole season study from Sachsen (Endl *et al.*, 2004) indicates a minor mortality peak (10% of the annual mortality) in early June and a much larger (90%) mortality peak in August–September. The large peak is also obvious from the part-season study at the wind farm Puschwitz in Sachsen (Trapp *et al.*, 2002). The mortality affected mostly the migrants *N. noctula* and *P. nathusii*. A late summer mortality peak was also evident in the two samples from Schwarzwald in 2004, although the species most frequently killed in this case was *P. pipistrellus*. The corresponding peak was entirely missing in 2005, a year with unusually cold and windy weather (Behr and von Helversen, 2006; Brinkmann *et al.*, 2006).

The coastal locality at Bouin, France, was monitored during four successive years (2003–2006 — Dulac, 2008). This study shows a similar mortality pattern, with a small spring peak, comprising 8% of the fatalities (5/60), and a large late summer/autumn peak (Fig. 2). The peaks consisted of *P. pipistrellus*, *P. nathusii*, and relatively few *N. noctula*. Of these species, the former is believed to be resident in the area near then turbines, but the other two are long-distance migrants (Dulac, 2008).

TABLE 5. Species distribution of mortality at wind farms in various districts of Germany and in France and Sweden. Bat species acronyms: Nnoc = *Nyctalus noctula*, Nlei = *N. leisleri*, Pnat = *Pipistrellus nathusii*, Ppip = *P. pipistrellus* s.str., Vmur = *Vespertilio murinus*. The 'Others' category is mostly *Eptesicus serotinus* except in the sample from Sweden, where it was replaced by *E. nilssonii*. Carcasses that could not be identified to species were excluded. Country totals marked in bold

Study area	Predominant land features	Number of dead bats							References
		Nnoc	Nlei	Pnat	Ppip	Vmur	Others	Total	
Schwarzwald	Forested peaks and ridges	–	–	–	4	–	–	4	Behr *et al.* (2006)
		–	–	–	3	–	–	3	Behr and von Helversen (2005)
		–	8	–	63	–	–	71	Behr and von Helversen (2006)
		–	8	–	39	2	1	50	Brinkmann *et al.* (2006)
		–	16	–	109	2	1	128	
Sachsen	Farmland	3	1	8	5	–	3	20	Endl *et al.* (2004)
		87	3	63	30	12	16	211	Seiche (2008)
		12	1	8	5	–	3	20	Trapp *et al.* (2002)
		102	5	81	38	18	19	263	
Brandenburg	Farmland	228	16	140	54	17	24	479	Dürr (2009)
Germany		**330**	**37**	**221**	**201**	**37**	**44**	**948**	
France	Coastal	**6**	**–**	**35**	**15**	**–**	**4**	**60**	Dulac (2008)
Sweden	Farmland	**1**	**–**	**5**	**1**	**1**	**9**	**17**	Ahlén (2002)

BEHAVIOUR OF 'HIGH-RISK' SPECIES AT WIND TURBINES

In an American study, Horn *et al.* (2008*a*), using infrared (IR) sensitive video cameras, observed and filmed bats flying around the rotors of turbines of the Mountaineer Wind Park in West Virginia, USA, a site where hundreds of bats have been killed. The bats were actively feeding but they also 'investigated' the nacelle and the blades. They approached both moving and non-moving rotors and frequently appeared to be trapped in vortices behind moving blades (Horn *et al.*, 2008*a*). The bats observed were not identified to species.

Manual and automatic registration of bat echolocation calls in Europe has shown that 'high-risk' species (predominantly *Nyctalus*, *Pipistrellus* and *Vespertilio* spp.) regularly fly near the turbines at the height of the rotors (Ahlén, 2002; Endl *et al.*, 2004; Behr and von Helversen, 2005; Brinkmann *et al.*, 2006; Ahlén *et al.*, 2007; Behr *et al.*, 2007; Grünwald and Schäfer, 2007; Bach and Bach, 2010; Bach and Niermann, 2010). Ahlén (2003), using bat detectors and IR-cameras, observed bats (mostly *E. nilssonii*) actively feeding close to the rotor blades at wind turbines in southern Sweden. This happened both when the turbines were active and when there was no wind at all, and the rotors were stationary. Observations were also made at two marine wind parks in the Baltic Sea ca. 10 km from the Swedish coast (Ahlén *et al.*, 2007). *Nyctalus noctula* and *Pipistrellus* spp. were regularly observed there, and in both cases, the turbines attracted insects on which the bats were feeding.

In Austria, Traxler *et al.* (2004) observed a group of *N. noctula* feeding near turbine rotor blades (sometimes < 1 m) in afternoon sunlight. Brinkmann *et al.* (2006), using an IR-camera, observed *P. pipistrellus* around wind turbines in Schwarzwald, Germany. This author described the behaviour of the bats as very similar to that observed by Horn *et al.* (2008*a*) and Ahlén (2003), including 'investigation' behaviour, although he did not confirm that the bats were feeding.

Automatic registration of 'feeding-buzzes' at the height of the rotor blades (20–30 m) of wind turbines (Bach and Bach, 2010) and other towers (Collins and Jones, 2009) indicates that bats of the genera *Nyctalus* and *Pipistrellus* regularly feed at this level. Hence, the accumulated evidence suggest that bats come to wind turbines to feed on insects attracted to the turbine towers. Indeed dead insects may stick to the rotor blades in such numbers that they seriously compromize the efficiency of the turbines (Corten and Veldkamp, 2001).

EFFECT OF WEATHER

Several studies from Europe show that the activity of bats at turbine rotor height is highest during nights with relatively low wind speeds (Behr and von Helversen, 2005; Behr *et al.*, 2006; Brinkmann *et al.*, 2006; Ahlén *et al.*, 2007; Bach, 2007; Grünwald and Schäfer, 2007; Bach and Bach, 2010; Bach and Niermann, 2010) and this is also when most of the bat mortality at wind turbines occur (Traxler *et al.*, 2004; Behr and von Helversen, 2005; Seiche, 2008). The apparent wind tolerance of the bats at turbine height varied among the studies, however. Generally bat activity at rotor height and the associated mortality was usually highest at 0–2 m/s and declined in the 2–8 m/s wind speed interval. Little or no bat activity remained at higher wind speeds. The relatively large *N. noctula* was more tolerant of strong winds than the smaller *Pipistrellus* species and it was also killed at higher wind speeds on average (Seiche, 2008). A similar situation occurred at the wind farms in the Baltic sea (Ahlén, 2003; Ahlén *et al.*, 2007). Insects and bats were attracted to the turbines in abundance at low wind speeds, when the sea surface was calm or nearly so, but few if any were observed in windy weather.

There is a particularly illuminating study from the Appalachian Mountains in U.S. (Kerns *et al.*, 2005). Daily searches for dead bats were made simultaneously at two wind farms well separated in space (Mountaineer Wind Farm in West Virginia and Meyersdale Wind Farm in Pennsylvania) in August and September 2004 and 2005 (Arnett *et al.*, 2008). There was a striking temporal correlation between the two localities in the number of dead bats, which means that the daily variation in bat mortality was determined indirectly by large-scale weather patterns rather than by local conditions. Hence, Kerns *et al.* (2005) found a negative relationship between bat mortality and rainy and stormy weather. The highest mortality occurred on low and predominantly northern winds during a few nights following storms, and was also positively associated with high air pressure and low humidity. There was also a weak positive association with air temperature. Fiedler (2004) made similar observations at Mountaineer, Tennessee (Arnett *et al.*, 2008). We are not aware of any comparable study from Europe.

The observation that most bats are killed at low wind speeds has recently been successfully exploited experimentally. By increasing the turbine "cut in speed" (the wind speed at which the turbine starts to deliver electricity) from 3–4 m/s to 4–6 m/s, the bat mortality rates were reduced considerably. Since curtailment occurred only in late summer and during restricted periods at low wind speeds, when the expected power output was minimal anyway, it only reduced the annual energy output marginally (Behr and von Helversen, 2006; Arnett *et al.*, 2009*a*; Baerwald *et al.*, 2009).

HOW WIND TURBINES KILL BATS

Although bats sometimes approach non-moving turbine blades and towers to feed or perhaps roost (Ahlén, 2002; Horn *et al.*, 2008*a*), there is no evidence that they are killed in such situations (Arnett *et al.*, 2008). Unlike birds, bats rarely collide with high man-made buildings and other structures like weather towers or light houses (Gelder, 1956; Crawford and Baker, 1981). Instead, fatalities of bats at wind turbines are closely linked to the movement of the rotors, which in modern turbines approach 100–150 m/s at the tips. Objects moving at such speeds are hard for bats to detect in time and avoid, because bats typically fly relatively slowly and detect targets only at close range. Indeed, Long *et al.* (2009) showed experimentally, using synthetic echolocation calls of *P. pipistrellus*, that a bat typically will recognize the rotors of miniturbines no more than 0.5–1 m away. This means that the bat will have 1/100 s at best to avoid the tip of a rotor blade after detection, if it moves towards it! Bats colliding with moving rotor blades were filmed using IR-video by Horn *et al.* (2008*a*).

In Seiche's (2008) study in Sachsen, Germany, 76 bats of various species, found under wind turbines, were examined for injuries. Three of these were found alive with broken wings and died later. The most common injuries were fractures and haemorrhaging in the skull (11), wing fractures (32), external wounds on the thorax and abdomen (18) and internal haemorrhaging of the thorax and abdomen (27). Seven specimens (7%) did not show any obvious injuries. Brinkmann *et al.* (2006) and Behr and von Helversen (2006) collected 40 dead bats of two species (*P. pipistrellus* and *N. leisleri*) found under turbines in Schwarzwald, Germany. Six of these had broken wings and 20 had fractures or other internal damages of the skull. Twenty externally undamaged bats, which were dissected, showed more or less severe thoracic haemorrhaging, possibly caused by barotraumatic impact. At the time of death, all the dissected bats were in good physical condition and had food in their stomachs and/or intestines.

The direct cause of death in most specimens in the three German studies, regardless of species and locality, were 'impact of a blunt force', presumably moving turbine blades, but barotrauma was probably also involved in several cases (Brinkmann *et al.*, 2006). The bats were generally in good shape when killed and they died during or possibly shortly after feeding.

In a recent study in Canada, Baerwald *et al.* (2008) examined 188 bats (*Lasiurus cinereus* and *Lasionycteris noctivagans*) killed at wind turbines the previous night. About half of these bats may

TABLE 6. Age and sex distribution of wind farm mortality in four studies representing two regions in Germany

Study area	Species	Male	Female	Juvenile	Total	Reference
Sachsen	*N. noctula*	2	1	48	51	Seiche (2008)
	P. nathusii	13	6	–	19	
	P. pipistrellus s.str.	1	4	4	9	
	V. murinus	2	2	4	–	
Sachsen	*N. noctula*	2	1	–	3	Endl *et al*. (2004)
	P. nathusii	4	2	–	6	
	P. pipistrellus s.str.	2	1	–	3	
Schwarzwald	*P. pipistrellus* s.str.	12*	17*	–	29	Brinkmann *et al*. (2006)
	N. leisleri	3*	5*	–	8	
	V. murinus	1	–	–	1	
Schwarzwald	*P. pipistrellus* s.str.	16*	4*	–	20	Behr and von Helversen (2006)
	N. leisleri	2*	1*	–	3	

* — Both adults and juveniles included

have died in direct contact with the turbine blades, but 92% had haemorrhaging in internal organs and 100% showed pulmonary lesions, consistent with barotrauma. Together with the European studies cited above, this strongly suggests that the bat fatalities at wind turbines are caused by direct collisions with the moving rotor blades and/or by the pressure changes near them (Dürr and Bach, 2004; Hensen, 2004).

CONCLUDING REMARKS

The results of bat surveys at wind turbine sites usually reside in unpublished reports in various languages, rather than in peer reviewed scientific journals or on the internet, so the critical information may or may not be generally available and open to review. Frequently there is no open access to many of the reports even in jurisdictions where monitoring is required. This is the case both in North America and in Europe, but the problem varies in extent from country to country. In fact we have no information about how many reports are kept secret. Therefore, unfortunately, we cannot assume that the results reviewed here are unbiased.

Nevertheless, the results of this review suggest that a particular suite of bats (*Nyctalus*, *Pipistrellus*, *Vespertilio* and *Eptesicus* spp.), those that are morphologically and physiologically adapted for it, engage in a seasonal high-altitude feeding on insects that are attracted to the towers of wind turbines. As long as the habitats are similar and dominated by open farmland, the mortality rates are similarly low across regions and countries in northwestern Europe (Sweden — Germany — Austria — England). The rates increase considerably and consistently at turbines placed at the coastline (Sweden — Germany — France) and, in particular, on top of forested hills and ridges (Germany — Switzerland). The mortality rate may sometimes increase locally even at inland localities away from forests and hills (Austria — Germany), perhaps because turbines interfere with bats moving along established flyways (Traxler *et al*., 2004) or if the wind farms are located near important bat roosts (Baerwald and Barclay, 2009).

In North America the highest bat mortality at wind turbines occur in late summer on peaks and ridges of the Appalachian Mountains (Fiedler, 2004; Kerns and Kerlinger, 2004; Kerns *et al*., 2005; Fiedler *et al*., 2007; Jain *et al*., 2007, 2009; Arnett *et al*., 2009*b*). Because the mortality affects mostly migratory bat species and coincides temporally with the southern migration of these bats, it is usually assumed that the mortality and the migration flights are casually related (Kunz *et al*., 2007*a*; Arnett *et al*., 2008; Cryan, 2008; Horn *et al*., 2008*a*; Cryan and Barclay, 2009).

However, we believe that the evidence from Europe suggests otherwise. The mortality patterns of bats at wind farms in the European mountains (e.g., Schwarzwald) are generally the same as in North America, although the European mountains run east–west rather than north–south, and therefore are not followed by bats during migration. Indeed, the long-distance migrants *N. noctula* and *P. nathusii* avoid the Schwarzwald mountains and rather follow routes along the river Rhein to the west (Dieterlein, 1997; Bach *et al*., 2005). Accordingly, the fatalities at wind turbines in Schwarzwald are dominated by the locally common and presumed non-migratory species *P. pipistrellus* (Behr and von Helversen, 2006; Brinkmann *et al*., 2006).

Migrating bats are known to follow rivers (Jarzembowski, 2003; Furmankiewicz and Kucharska, 2009) and coastlines (Ahlén, 1997; Petersons, 2003; Ahlén *et al*., 2009; Bach and Bach, 2010), perhaps including corridors inland (Bach *et al*., 2009) as well as on the seaward side (Sjollema and Gates, 2009). With the important exception of the study of Dulac (2008), we are not aware of any mortality estimates at wind farms located along such flyways, and this also applies to potential stop-over sites on peninsulas and islands (Walther *et al*., 2004; Bach *et al*., 2009; Dzal *et al*., 2009). This is a most serious gap in our knowledge.

We found that taller turbines kill more bats. This result, which agrees with previous studies (Barclay *et al*., 2007; Seiche, 2008), is a bit worrying, because there is a clear trend towards taller and taller turbines. When old turbines are modernized or repowered, which usually means that they are replaced by taller ones, the danger to bats will increase (Hötker, 2006; Smallwood and Karas, 2009).

On the positive side, periods with high bat mortality at wind turbines are predictable, being mainly restricted to relatively calm nights in August–September. The problem with excessive bat mortality at wind turbines can therefore be mitigated relatively easily by increasing the cut in speed of the turbines (Behr and von Helversen, 2006; Arnett *et al*., 2009*a*; Baerwald *et al*., 2009). Otherwise, solving the problem by use of technical innovations, that prevent bats from approaching the turbines, have proven difficult, although bat discouraging radar or emission of ultrasonic noise could possibly be solutions for the future (Nicholls and Racey, 2007, 2009; Horn *et al*., 2008*b*).

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