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Mortality of bats at wind turbines links to nocturnal insect migration?

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Abstract This note is based on a literature search and a recent review of bat mortality data from wind farms in Europe (published elsewhere). We suggest that mortality of bats at wind turbines may be linked to high-altitude feeding on migrating insects that accumulate at the turbine towers. Modern wind turbines seem to reach high enough into the airspace to interfere with the migratory movements of insects. The hypothesis is consistent with recent observations of bats at wind turbines. It is supported by the observation that mortality of bats at wind turbines is highly seasonal (August–September) and typically peaks during nights with weather conditions known to trigger large-scale migratory movements of insects (and songbirds). We also discuss other current hypotheses concerning the mortality of bats at wind turbines.

Keywords Aeroecology · Bat conservation · Insect behaviour · Moths · Wind energy

Introduction

Many bats are killed at wind turbines in Europe and North America (Kunz et al. 2007). This is a growing problem, because the wind industry is expected to increase and expand substantially in the near future (Kunz et al. 2007; EWEA 2008). Average annual mortality rates of 20–40 bats per turbine have been recorded at several places, although 1–3 dead bats per turbine is more typical (rates controlled for searching efficiency and scavenger removals; details in Arnett et al. 2008; Rydell et al. 2010). The highest mortality occurs at turbines located on bats' suspected migration routes inland (Traxler et al. 2004; Baerwald and Barclay 2009) or on the coast (Dulac 2008), but many bats are also killed at turbines on hill tops and ridges away from such flight routes (Kerns et al. 2005; Behr and Helversen 2006; Brinkmann et al. 2006; Arnett et al. 2008; Leuzinger et al. 2008). Population sizes of bats are poorly known, but since slow reproduction is typical (Barclay and Harder 2003), fear has been expressed that the populations may not withstand the increased mortality caused by wind turbines (Kunz et al. 2007).

Despite a decade of research and monitoring of bats at wind turbines on two continents, there is still no satisfactory explanation of why so many bats are killed. This note is based on a recent literature survey and a review of 20 monitoring studies of dead bats found at European wind farms (Rydell et al. 2010). The emerging picture is incompatible with some current hypotheses (reviewed by Kunz et al. 2007; Cryan and Barclay 2009).

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In Europe, bats found dead at wind turbines almost exclusively (98%; Rydell et al. 2010) belong to a suite of aerial-hawking species (*Nyctalus*, *Pipistrellus*, *Vespertilio* and *Eptesicus* spp.) that typically feed in the open air or at least several metres away from surfaces or vegetation (Baagøe 1987). These bats are more or less adapted (or perhaps pre-adapted) for high-altitude feeding on insects. They have relatively long and narrow wings, suitable for economic but comparatively unmanoeuvrable flight (Norberg 1990), and use a high-intensity narrow-band echolocation system (employing shallow frequency-modulated calls) suitable for long-range target detection in clutter-free airspace (Waters et al. 1995). The North American bats most often killed at wind turbines are morphologically and ecologically similar to those in Europe, but belong to other genera (*Lasiurus*, *Lasionycteris* and *Perimyotis* spp.; Barbour and Davis 1969; Kunz et al. 2007).

Examination of some current hypotheses

Bats are killed as they fly around the turbine towers and rotors, either through direct strikes of the moving rotor blades or following internal bleeding caused by rapid changes in air pressure near the blades (Behr and Helversen 2006; Baerwald et al. 2008). When flying around the towers and rotors of wind turbines, the bats actively feed on insects at least part of the time. Evidence for this comes from direct observations, using heat image cameras and spotlights, and from recordings of feeding buzzes, using ultrasound detectors (Ahlén 2002; Ahlén et al. 2007, 2009; Traxler et al. 2004; Brinkmann et al. 2006; Horn et al. 2008; Bach and Bach 2010). Furthermore, dissection of recently dead bats ($n=40$) picked up under wind turbines in Schwarzwald, Germany, strongly suggests that they had died whilst feeding or, possibly, shortly afterwards. The bats were in good physical condition and had food in their stomachs when killed (Brinkmann et al. 2006; Behr and Helversen 2006). The dissected specimens were common pipistrelles *Pipistrellus pipistrellus*, by far the most abundant bat in the Schwarzwald area, and some Leisler's bats *Nyctalus leisleri*.

Bats apparently fly around wind turbines irrespective of whether the rotors are moving or not (Ahlén 2002; Horn et al. 2008). Therefore, we can dismiss hypotheses that bats (and insects) are attracted to wind turbines by the heat, sound or magnetic fields generated by the nacelles or by the movement of the rotors (Kunz et al. 2007). Likewise, they seem not to be attracted (or repelled) by aviation warning lights mounted on top of turbines (Horn et al. 2008).

There is little direct evidence that bats approach and monopolise wind turbines, because they consider them suitable as pairing or mating stations (Cryan 2008) or

because they mistake them for trees or snags suitable for roosting (Kunz et al. 2007). For example, sperm, indicating recent mating activity, has not been reported from any of the bats found dead at wind turbines, including the dissected specimens referred to above (Behr and Helversen 2006; Brinkmann et al. 2006). However, whilst wind turbines in Europe apparently strike bats independently of sex and age (Endl et al. 2004; Seiche 2008), those in North America seem to kill mostly adult males (Arnett et al. 2008). This indicates that adult males of the American species may spend more time near the wind turbines than females and young. This observation is possibly (but not necessarily) consistent with Cryan's (2008) mating station hypothesis.

It also seems possible that the 'investigation' behaviour described by Horn et al. (2008, p. 129) can be responsible for some bat mortality at wind turbines in North America. They suggested that the bats were searching for roosting sites in the turbine nacelles. However, Ahlén et al. (2009), who observed a similar behaviour in Sweden, interpreted it as if the bats gleaned prey (moths) from the surfaces of the nacelles. Although the 'mating station' and 'tree roost' hypotheses cannot be rejected with the available data, there is little supporting evidence.

For the parti-coloured bat *Vespertilio murinus* of northern Europe, the annual peak mortality at wind turbines and the timing of its mating display, which probably occurs at the winter roosts, seem to be well separated in time (Fig. 1). This discrepancy provides a case against the mating station hypothesis for this particular species. Since the parti-coloured bat roosts in buildings or cliff crevices and almost never in trees (Baagøe 2001), we can also reject the tree roosting hypothesis in this case.

There is little or no evidence that collisions with turbine rotors occur randomly or coincidentally (Cryan and Barclay

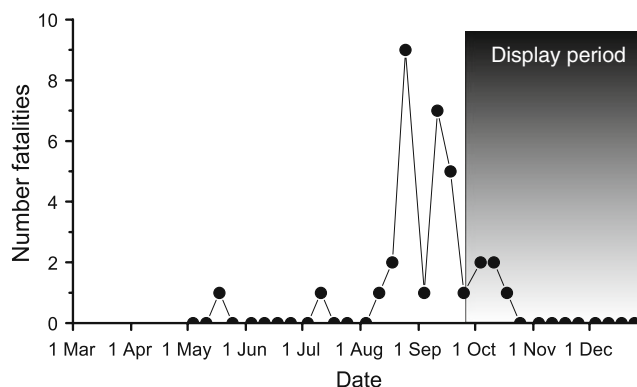


Fig. 1 Mortality of the parti-coloured bat *Vespertilio murinus* at wind turbines in northern Europe 2002–2009 (Dürr 2009) and the timing of its display period (Baagøe 2001). The mortality data are raw numbers (sums for quarter-month periods), obtained from Dürr's compilation of fatalities of bats at wind turbines in Europe, and are not controlled for differences in search effort over the season

2009). For example, it has been speculated that bats may collide with wind turbine rotors during high-altitude migratory flights, perhaps because the echolocation system is not in use or fails to detect the rotors in time (Kunz et al. 2007). However, observations suggest otherwise; common noctules *Nyctalus noctula* and other bat species migrating over the Baltic Sea always seem to echolocate normally (Ahlén et al. 2009).

Bat migration

In northern Europe, most of the mortality (90%) of bats at wind turbines occurs between late July and early October, and there is usually also a smaller (10%) mortality peak in May and June (reviewed by Rydell et al. 2010; Fig. 2). Typically, very few bats are killed in the intervening period. The pattern in North America is similar (reviewed by Arnett et al. 2008), although there is at least one important exception (Piorkowski 2006; see below). The mortality peaks coincide with the bats' migratory flights, and it has been implicitly assumed that there is a casual relationship between mortality and bat migration (e.g. Arnett et al. 2008; Cryan 2008; Horn et al. 2008). This correlation could

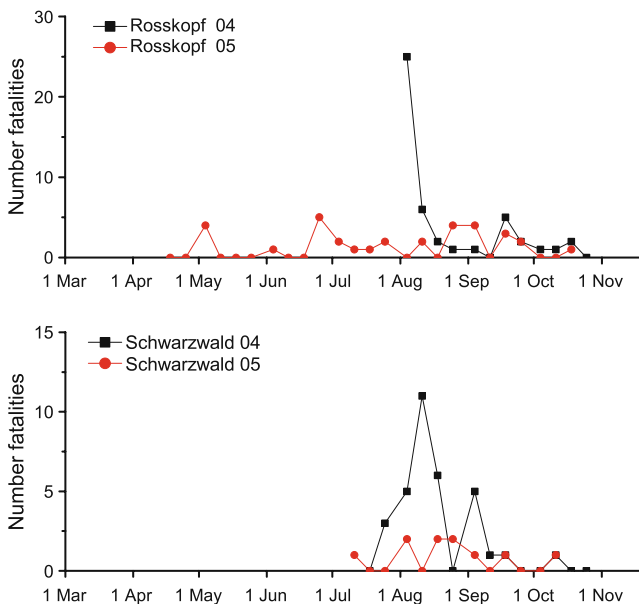


Fig. 2 Bat mortality (sums for quarter-month periods) at wind turbines in Schwarzwald, Germany, in 2004 and 2005. The *upper figure* refers to a single locality (Rosskopf, with four turbines, searched every 2–3 days; Behr and Helversen 2006) and the *lower figure* refers to the sums over seven other localities in the same general area (with 1–4 turbines per locality, total 16 turbines, searched every 5 days on average; Brinkmann et al. 2006). At these localities, mortality affected common pipistrelles *P. pipistrellus* and Leisler's bats *Nyctalus leisleri*. Mortality rates are raw numbers, not adjusted for variations in search efficiency and scavenger removals. In the periods without lines, there were no controls

be coincidental, however. Indeed, adaptations for high-altitude feeding, including long-range target detection and fast, economic flight, may independently have predisposed some species of bats for insect hunting at wind turbines as well as for long-distance migration.

A considerable part of the mortality at European wind farms affects bat populations that are considered to be non-migratory or that travel short distances only. This applies to the common pipistrelle, the species most frequently killed by wind turbines in Schwarzwald, Germany (Behr and Helversen 2006; Brinkmann et al. 2006) and on the Atlantic coast of France (Dulac 2008) and also to the northern bat *Eptesicus nilssonii*, the species most frequently killed by wind turbines in Sweden (Ahlén 2002). There are also American examples suggesting that high mortality at wind turbines occur independently of migratory movements. For example, females of the Mexican free-tailed bat *Tadarida brasiliensis* are subject to high mortality rates at wind farms in Oklahoma, USA, during their maternity period in June and early July, a time of the year when they are resident, but still make regular high-altitude flights in order to feed (Piorkowski 2006).

Insect migration

The Mexican free-tailed bat is a typical high-altitude bat (Barbour and Davis 1969), and its maternity period in southern USA coincides at least occasionally with nocturnal high-altitude migration of noctuid moths, such as the beet armyworm moths *Spodoptera exigua* (Westbrook 2008). The Mexican free-tailed bats also feed extensively on migrating moths during their own southward migration in late summer, when large numbers of corn earworm moths *Helicoverpa zea* and other pests are consumed (McCracken et al. 2008).

High-altitude feeding is thus linked to insect migration at least in the Mexican free-tailed bat. It seems quite possible that this pattern might be a more general phenomenon. High-altitude flying bats as well as migrating insects occur worldwide (Johnson 1969; Nowak 1994). Indeed, during two full seasons of radio-tracking of common noctules in Germany, Kronwitter (1988) noticed that the bats consistently changed their foraging behaviour in August and September and that the colour and texture of the faeces changed at the same time. They abandoned their normal feeding grounds to forage high over a forest area. Kronwitter (1988) suggested that the explanation for this change '...may be found in the migration of various insects which occurs sometimes at high altitudes'.

If there is a general link between insect migration and high-altitude feeding by bats, as suggested, insect migration may perhaps link back to the mortality of these bats at wind

turbines. The modern wind turbines are so tall (>150 m) that they reach into the lower part of the airspace used by insects during nocturnal migration (Taylor 1974; Chapman et al. 2008), and as suggested by the ‘clouds’ of insects sometimes observed at wind turbines (Ahlén 2002; Ahlén et al. 2007; Horn et al. 2008), they somehow interfere with the insects’ migratory movements. This may perhaps occur through something like a ‘hill-topping’ effect, where butterflies (or other insects) follow a hill (or a turbine tower) upwards and congregate at the top (Shields 1967). Bat mortality increases dramatically and possibly exponentially, as the height of the turbine towers exceeds about 60 m (Barclay et al. 2007; Rydell et al. 2010). An extended hill-topping effect may perhaps also explain why so many bats are killed at turbines located on hill tops and along ridges (Kerns et al. 2005; Brinkmann et al. 2006; Behr and Helversen 2006; Arnett et al. 2008; Leuzinger et al. 2008).

Observations from Europe and North America consistently show that most bats are killed on relatively warm nights with low wind speed. Detailed data were collected in a 2-year (2004–2005) study at two wind farms along the Appalachian ridges (in Pennsylvania and West Virginia, respectively), USA, where bat mortality and weather were monitored daily in both places (Kerns et al. 2005). Mortality changed dramatically from day to day, but simultaneously at the two sites (figures in Arnett et al. 2008). This suggests that the patterns of mortality were determined by the arrival of major weather systems and not by local phenomena. Indeed, most bats were killed on nights with weak northerly winds and high air pressure, following the passage of cold fronts. The variation in mortality was not closely correlated between the two years, presumably because cold fronts did not pass on the same day in subsequent years.

Although observations were less frequent and the precision therefore much lower, the pattern of mortality at wind turbines in Germany also suggests high correlation amongst sites within a season, but low correlation between years (Brinkmann et al. 2006; Behr and Helversen 2006). Indeed, the observations from Schwarzwald (Fig. 2) show that mortality peaks may not occur at all in summers with prevailing inclement weather, e.g. in 2005 (Brinkmann et al. 2006; Behr and Helversen 2006). Presumably, bats do not engage in high-altitude feeding at wind turbines or elsewhere, unless the weather has triggered migration of insects and therefore do not turn up dead under wind turbines.

During late summer and autumn nights with prevailing weak northerly winds and high air pressure, typically following the passage of cold fronts, insects, including billions of moths (e.g. silver Y moths *Autographa gamma*; Chapman et al. 2008), and, in addition, millions of song birds (Alerstam 1990) leave their breeding areas on their

southward migration. Much of this mass movement occurs 100–1,200 m above the ground on low jets that form within the atmospheric boundary layer at night (Taylor 1974; Reynolds et al. 2008; Wood et al. 2010). High-altitude bats in northern Europe, such as the common noctules mentioned above, regularly feed at such levels in late summer (‘...fly at an altitude of at least 250–500 m’; a rough and conservative estimate obtained by triangulation of radio-tagged bats; Kronwitter 1988, p. 45). Foraging noctules have also been observed, using a heat image camera, feeding at high altitude (up to 1,200 m) over the Falsterbo peninsula in southern Sweden in late summer (Ahlén et al. 2007, Zehnder et al. 2001).

Marine wind farms, located in the Baltic Sea up to 10 km off the Swedish coast, regularly attract bats in late summer just like wind turbines on land (Ahlén et al. 2009). As shown, using bat detectors, spotlights and an infrared video system from a ship, the bats actively fed on insects around the turbine towers. These insects were presumably on the move across the Baltic Sea, either actively or passively.

Conclusion

Mortality of bats at wind turbines is obviously a complex phenomenon, unlikely to be explained by a single hypothesis. Hence, we do not believe that the insect migration hypothesis, as presented in this review, can account for all fatalities recorded in the various bat species. Nevertheless, we believe that the hypothesis is potentially important, because we find it consistent with the observed patterns.

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