The Impacts of Small and Medium Wind Turbines on Bats

Volume 1 of 1

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Abstract

Global efforts to address climate change have recently introduced a new source of fatality risk to bats, from wind turbines. Bat fatalities have now been confirmed in varying magnitudes at wind energy facilities around the world. Research at large turbines and wind farms has started to produce a knowledge base regarding impacts upon bats, though many questions remain. Little, however, is known about risk levels at small and medium scale wind turbines. Equally, research regarding the impacts of turbines in the UK is limited.

This thesis examines the impacts of small and medium scale wind turbines upon bats. Planning records of wind turbines in Wales and south west (SW) England were reviewed. Approved planning applications for single and double turbine sites were found to greatly outnumber those for larger scale wind farms. The large majority of single and double turbine approvals were also for small turbines. The potential impacts of turbine presence and density on current bat roost populations and population changes were analysed, finding no impact. An estimate of bat fatality rates at small and medium turbines was calculated, using a trained search dog to locate carcasses. An average fatality rate between 0.81 and 15.15 turbine^{-1} year^{-1} was estimated. The higher rate accounted for uncertainty in the monitoring protocol. Only 3 bat carcasses were however observed across all monitored turbines, suggesting more stringent monitoring would likely confirm a lower maximum annual fatality rate. Bat activity levels were also compared between the turbine location and differing habitat types. A disturbance effect was consequently identified in proximity to turbines during high wind speeds. Finally moderating influences of environmental weather and habitat conditions upon bat activity were confirmed.

Social Network Analysis (SNA) methods were used to analyse bat movement networks within a small grid of bat detectors centred on each turbine. Associations were identified between bats' movement routes and habitat structures present at sites, highlighting vulnerabilities to disruption. Furthermore bats actively used the turbine area, potentially for foraging purposes. Finally by assessing bats' activity levels in response to a turbine noise playback experiment, small turbine noise was found to have no impact upon bat activity. Planning guidance regarding bats and small and medium turbines is highlighted as a priority for policy development.

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Abbreviations

Acronym	Definition
AIC	Akaike information criterion
ANOVA tests	Analysis of Variance
BCT	Bat Conservation Trust
CEH	Centre for Ecology and Hydrology
CPE	Columbia Plateau Ecoregion
CI	Confidence Intervals
DECC	Department for Energy and Climate Change
df	Degrees of freedom
EU	European Union
EWEA	European Wind Energy Association
EoA	Evidence of Absence
GLMM	Generalised Linear Mixed effect Model
GLMs	Generalised Linear Models
GIS	Geographical Information Systems
GPS	Geographical Positioning System
HSM	Habitat Suitability Model
ITE	Institute of Terrestrial Ecology
LCM	Land Cover Map 2007
LRT	Likelihood Ratio Test
MME	Multiple Mortality Event
MW	megawatt
MCS	Microgeneration Certification Scheme
NBMP	National Bat Monitoring Programme
SM2	One Wildlife Acoustics Song Meter 2
SE	Standard Error
SNA	Social Network Analysis
SW	South West
TIR	Thermal Infrared
UK	United Kingdom
BCT	UK Bat Conservation Trust
WWEA	World Wind Energy Association

1 Introduction and Literature Review

Bats account for one in every five mammal species and are the only truly flying mammals (Altringham, 2011). They have also evolved to feature a sophisticated echolocation system used to navigate, locate prey and explore surrounding environments (Russ, 2012). As a result bats comprise an important component of the planet's biodiversity. Bats have a slow reproductive rate; most bat species have only one litter per year and bear a single pup per litter (Kunz and Fenton, 2005). The slow life history of bats combined with loss of habitat, disturbance or destruction of roosts and the spread of diseases in recent decades have threatened the populations of bat species around the world (Hutson et al. 2001). Consequently many bats species have been classified as protected at both national and international scales (Collins, 2016; Mickleburgh et al. 2002).

Global efforts to address the negative impacts of climate change have recently introduced a new source of fatality risk to bats, from wind turbines. Bat fatalities have now been confirmed in varying magnitudes at wind energy facilities around the world (Arnett et al. 2008; Rydell et al. 2010a; Barros et al. 2015; Kumar et al. 2013; Doty and Martin, 2013). This topic has only truly become a focus of research in the last decade and is an important priority for bat conservation efforts, as global numbers of wind turbine installations increase (World Wind Energy Association (WWEA), 2016). In conjunction with the outbreak of White Nose Syndrome amongst bats in North America and ongoing habitat loss around the world, wind turbines pose a potential risk to bat populations (O'Shea et al. 2016).

In order to place the high-level estimated risk posed to bats from wind turbines in context, Table 1.1 presents an overview of global bat multiple mortality events (MME) from the primary risk sources, as recorded by O'Shea et al. (2016) (MME = "a case in which ≥ 10 dead bats were counted or estimated in a given locality within a maximum timespan of 1 year" (O'Shea et al., 2016)).

Table 1.1: "Summary of numbers of mass mortality events (MMEs) reported in bats, by category and region. The order of magnitude for maximum unadjusted numbers of observed carcasses (per year) documented for the largest MME within each category is given in rounded parentheses, following the number of reports for each region and category" (Text and table modified from O'Shea et al. (2016)). Data in squared parentheses manually added relative to original O'Shea et al. (2016) table, illustrating adjusted/extrapolated estimates of annual fatality potential (maximum estimate as above, to order of magnitude; '(C)' indicates calculation at a country or continental-scale), accounting for uncertainty in monitoring protocols and extents of hazard sources, relative to the observed carcass counts. Reference sources for the adjusted/extrapolated estimates are listed in the 'Extrapolation estimate reference source' column)

Category	**Africa**	**Asia**	**Australia**	**Europe**	**Islands**	**North America**	**South America**	**Events (n)**	**Species (n)**	**Extrapolation estimate reference source**
Intentional killing	11 (10^4)	20 (10^4)	13 (10^4)	21 (10^4)	50 (10^3)	58 (10^4)	32 (10^5) [10^6 (C)]	205 (10^5) [10^6 (C)]	69	O'Shea et al. (2016) (supp. mats.): note records from 1970's – no records of this magnitude since
Biotic	5 (10^1)	1 (10^1)	19 (10^3)	16 (10^2) [10^5 (C)]	16 (10^2)	40 (10^3)	10 (10^1)	107 (10^3) [10^5 (C)]	75	O'Shea et al. (2016) (supp.materials)
Abiotic	0	6 (10^3)	71 (10^3)	0	13 (10^3)	24 (10^5)	0	114 (10^5)	23	
Contaminants	0	0	1 (10^1)	27 (10^4)	1 (10^2)	14 (10^3) [10^5]	0	43 (10^4) [10^5]	16	Thies et al. (1996): note records from 1970's – no records of this magnitude since
Accidental (including collisions with motor vehicles on roads)	1 (10^1)	0	8 (10^1)	34 (10^2) [10^5 (C)]	1 (10^1)	22 (10^4)	0	66 (10^4) [10^5 (C)]	37	Altringham and Berthinussen (2014)
Wind turbines	1 (10^2)	0	2 (10^1)	59 (10^2) [10^5 (C)]	2 (10^1)	213 (10^2) [10^5 (C)]	4 (10^1)	281 (10^2) [10^5 (C)]	41	Voigt et al. (2015); Arnett and Baerwald (2013)
Viral or bacterial disease	1 (10^2)	1 (10^1)	2 (10^3)	2 (10^3)	6 (10^3)	13 (10^3)	0	25 (10^3)	14	
White-nose syndrome	0	0	0	0	0	266 (10^4) [10^6, (C)]	0	266 (10^4) [10^6, (C)]	6	Verant et al. (2012)
Unexplained	0	0	3 (10^2)	30 (10^3)	2 (10^3)	38 (10^5) [10^6]	0	73 (10^5) [10^6]	20	O'Shea et al. (2016) (supp. mats.): note records from 1960's – no records of this magnitude since
Totals	19 (10^4)	28 (10^4)	119 (10^4)	189 (10^4) [10^5 (C)]	91 (10^3)	688 (10^4) [10^6 (C)]	46 (10^5) [10^6 (C)]	1180	152 (unique species)	

The records also identify the maximum order of magnitude of estimated fatalities associated with events in each category.

The results show that wind turbines are one of the dominant global risks to bat populations. White Nose Syndrome may pose a greater risk in North America, however risk from the syndrome appears biologically focused in North America due to apparent immunity across other continents' bat populations (Zukal et al., 2016). Whilst 'intentional killing' was historically the dominant global risk factor, the proportion of events falling into this category has reduced since approximately the year 2000 (O'Shea et al., 2016) (similarly large estimated-magnitude fatality events in the 'unexplained' category were primarily historical). Greater protection of bats and associated regulation in recent decades and the future is likely to reduce mortality from intentional killing. Other risk categories such as biotic (e.g. bird and cat-caused deaths), abiotic (e.g. weather and climate) and accidental deaths (e.g. motor vehicle collisions on roads) are nonetheless significant in their contribution whilst additional indirect impacts (e.g. habitat loss and disturbance) will equally further exacerbate risk from many of the categories.

Research at large turbines and commercial wind farms has started to produce a reasonable knowledge base regarding impacts upon bats, though many questions remain unanswered. Little, however, is known about risk levels at small and medium scale wind turbines. Equally, published research regarding the impacts of turbines in the UK is extremely limited.

The primary mechanisms of bat-turbine interactions as theorised in the research literature to date are summarised in Table 1.2 below, with subjective scoring of their estimated relative likelihood and the approximate level of certainty provided by existing research. As is indicated by the scoring, the proximate causes of bat fatalities are largely known, however the ultimate behavioural causes of turbine impacts upon bats and the patterns of bat activity at turbines are less certain. The wider aim of this thesis will therefore be to improve knowledge in these latter areas, in addition to providing much-needed understanding of the impact of small-to-medium scale turbines upon bats.

Table 1.2: "Proposed hypotheses for explaining the proximate and ultimate causes of bat fatalities at wind turbines. Here we define proximate causes as those that address the mechanistic factors directly responsible for the deaths of individual bats. Ultimate causes are those that address why bats are in the vicinity of turbines before death. Hypotheses are not mutually exclusive and are intended to be applied at the species level. *Italicized* hypotheses of ultimate cause are those we consider 1st degree, the disproval of which would eliminate associated 2nd-degree hypotheses (i.e., those not italicized)" (reproduced from Cryan and Barclay et al. 2009). Three hypotheses are added from Strickland et al. (2011) and one from Baerwald and Barclay (2011) as referenced in the table. All text from Cryan and Barclay et al. (2009) unless otherwise referenced.

Category	Hypotheses	Predictions	Likelihood (Support = Y, Lack of support = N) and Certainty (0 = low, 5 = high)
Proximate causes			
	Collision with turbine towers	Numerous fatalities at nonmoving turbines. Numerous fatalities at other tall structures.	N / 4
	Collision with moving blades	Traumatic external injuries. No fatalities at nonmoving turbines.	Y / 4
	Barotrauma (decompression) near moving blades	Internal injuries.	Y / 2
Ultimate causes			
Random	*Fatalities proportional to bats present*	Fatalities reflect indices of activity or abundance. Demographics of fatalities reflective of the population present.	N / 2
Coincidental	*Susceptible while migrating*	Most fatalities involve migrants rather than residents. Non-migratory species or populations least affected. Fatalities peak during migration periods. Fatalities peak earlier at higher latitudes.	Y / 3 (North America)
	Migrants clump in time and space	Distribution of bats more clumped during migration. More migrating bats occur in windy areas. More fatalities with passage of storm fronts. Most fatalities during migration periods.	Y / 2
	Migrating bats fly higher than non-migrants	More migrants at higher altitudes. More fatalities at taller turbines.	Y / 3
	Migrants bats less likely to echolocate	No echolocation detected at nacelle height. More bats present than echolocation passes detected. Atypical echolocation calls (e.g., startle).	Y / 1
	Susceptible when not migrating	Most fatalities involve residents rather than migrants.	Y / 3 (Europe)
	Greater feeding activity results in greater mortality	Coincidental seasonal increases in feeding buzzes of affected bats.	Y / 4
	Greater mating activity results in greater mortality	Coincidental seasonal increases in captures of mating bats. Adult bias to fatalities.	N / 4

Category	Hypotheses	Predictions	Likelihood (Support = Y, Lack of support = N) and Certainty (0 = low, 5 = high)
	Lack of flight experience results in greater mortality	More young, inexperienced bats among fatalities.	N / 5
	“Thermal inversions force bats to the altitude of rotor swept areas” (Strickland et al., 2011)	Thermal inversion weather conditions should be apparent (e.g. dense fog in cool valleys). Insects may also display the same movement.	? / 0
	Electromagnetic-Field Distortion hypothesis: bats have receptors sensitive to “complex, electromagnetic fields in the vicinity of the nacelle” (Strickland et al. 2011)	“The flight behavior of bats may be altered by these fields” (Strickland et al. 2011).	? / 0
	Altered flight behaviour before or after the onset of storms (Baerwald and Barclay, 2011)	Larger number of bats (and therefore echolocation recordings and or/fatalities) before and/or after the passing of storm fronts	Y / 1
	Prey distribution influences fatality	Fatality rate correlated with regional or altitudinal prey abundance.	Y / 2
Attraction	*General attraction to turbines*	Bats more likely to fly toward than past turbines.	Y / 2
	Attracted to lights	More fatalities at turbines with aviation lights.	N / 5
	Attracted to sound of moving blades or generator	More activity at moving than at nonmoving blades. Playback of sound attracts bats. Bats respond more to sound on low-wind nights. Turbines emitting particular noises kill more bats.	N / 1
	Attracted to blade motion	More activity at moving than at nonmoving blades. Devices simulating blade movement will attract bats.	Y / 2
	Attracted to insect aggregations	Feeding buzzes more common around turbines. Insect abundance greater around turbines. Consistent patterns of insect activity around turbines. Dead bats have full stomachs. Consistent prey in bat stomachs. Dead bats have insects in mouth.	Y / 2
	Attracted to modified landscape features	More fatalities near newly created edge habitats, roads, or wetlands.	N / 1 (due to avoidance of creation of near-turbine edge habitat)

Category	Hypotheses	Predictions	Likelihood (Support = Y, Lack of support = N) and Certainty (0 = low, 5 = high)
	Attracted to turbines as roosts	Highly visible turbines kill more bats. More fatalities on moonlit nights. More activity at tallest, treelike structures. Low activity of species that do not roost in trees. Most fatalities occur as nightly activity ends. Equal activity at moving and nonmoving turbines.	N / 3
	Attracted to turbines as mating or gathering sites	Most activity at tallest trees or treelike structures in landscape. Mating activity at moving and nonmoving turbines. Male territorial behavior at moving and nonmoving turbines. Group formation at moving and nonmoving turbines. Sperm in males and females. Male bias to fatalities that disappears over time. Social calls detected at nacelle height. More social interaction at turbines in low winds. Equal activity at moving and nonmoving turbines.	N / 3
	Attracted to “reflection from white turbines under moonlit conditions” (Strickland et al. 2011)	Less fatalities during night with less moonlight / darker conditions. Possibly lower fatalities at turbines painted darker colours.	N / 2

This introductory chapter reviews the knowledge gained from research to date concerning the impacts of wind turbines upon bats and the ecological issues surrounding the topic. From this wider context, the refined resulting objectives of this thesis are presented at the end of this chapter.

Chapter aims

In order to contextualise the research topic and identify objectives, this chapter aims to review the following subjects:

- Recognition of the impact of wind turbines upon bats
- Estimates of the magnitudes of bat fatality

- Bat species affected
- Causes of bat fatalities at turbines
- Hypotheses for bats’ interactions with wind turbines
- Variability in bat activity, fatalities and behaviour results: Moderating factors
- Bats’ flight heights
- Turbine sound and electromagnetic emissions
- Visibility of turbines to bats, including turbine lighting
- Detection of turbines by bats and orientation of turbines vs. bat flight direction
- Non-fatal and behavioural impacts
- Population-level impacts
- Mitigation

1.1 Recognition of the impact of wind turbines upon bats

Recognition of wind turbines’ possible impacts upon bats largely originated from bird fatality studies at turbine sites during which dead bats were identified (Howell and DiDonato, 1991; Orloff and Flannery, 1992; Higgins et al. 1995). Dedicated investigations concerning impacts upon bats consequently ensued (e.g. Osborn et al. 1996). Research intensified after significant numbers of bat fatalities were recorded at key turbine sites in North America (Arnett et al. 2008). 1398-4031 bats fatalities were estimated at the Mountaineer Wind Energy Center in West Virginia, USA (Kerns and Kerlinger, 2004). Bat fatality rates have been found to vary between 0.1 and 69.6 fatalities/turbine/year (f/t/y) in the USA (Arnett et al. 2008) and 0 to 41.1 f/t/y in Europe (Rydell et al. 2010a).

Whilst a large volume of research has been undertaken in North America, a number of factors may limit our ability to directly apply the findings to European contexts. Some of the topographic and habitat settings in which the highest fatality rates have been observed are rarely found at UK wind turbine sites (e.g. forested mountain ridges (Arnett et al. 2008)), as may be the case in other European countries. Furthermore the composition of bat species is markedly different between the two continents. A number of North American species also display migratory flight behaviour in topographic settings suited to wind energy development, a trait that is less common across Europe (Rydell et al. 2010a).

1.1.1 Small turbines and/or sites with low numbers of turbines

No single wind turbine size classification scheme is universally recognised. References to wind turbine size categories in this thesis, unless otherwise stated, are based upon RenewableUK's classification of turbine size (RenewableUK, 2013). Turbine blade tip heights are classified as follows: micro: 10-15m; small: 15-30m; medium: 30-55m; large: above 55m; an additional category is also added for the purpose of this thesis – sub-micro: less than 10m.

Little research has been carried out at small wind turbine sites, though two field-based studies are available from the UK. The first found that operational turbines caused a decrease in bat activity within 0-5m from turbines during higher wind speeds, relative to lesser impacts at 20-25m from the turbine (Minderman et al. 2012). The second suggested that numbers of bat fatalities at small turbine sites are very low, estimating rates of between 0.008 and 0.169 f/t/y (Minderman et al. 2015).

1.2 Estimates of the magnitudes of bat fatality

Bat fatalities have been recorded at wind turbines across the globe, particularly in large numbers of studies from North America (Arnett et al. 2008; Piorkowski and O'Connell, 2010; Baerwald and Barclay, 2011; Jameson and Willis, 2012; Bicknell and Gillam, 2013; Smallwood, 2013) and Europe (Rydell et al. 2010a; Dubourg-Savage et al. 2011; Georgiakakis et al. 2012; Camina, 2012; Amorim et al. 2012; Lehnert et al. 2014; Minderman et al. 2015; Rodrigues et al. 2015). Initial studies have also recorded fatalities in Oceania (Hull and Cawthen, 2013), Africa (Doty and Martin, 2013), Asia (Kumar et al. 2013), South America (Escobar et al. 2015; Barros et al. 2015) and Mexico (Patraca, 2009).

The highest estimated magnitudes of bat fatalities have so far originated from sites in the USA. Table 1.3 provides an overview of fatality rates recorded by a review of North American sites, where fatality estimates ranged from 0.2-53.3

mean fatalities / megawatt $(MW)^{-1}$ $year^{-1}$ (Arnett et al. 2008). In Europe, however, relatively small numbers of fatalities at turbines sites have been reported (Rydell et al. 2010a), including in Sweden, Spain, France, England, Croatia, Greece and Slovenia (Dürr and Bach, 2004; Ahlén, 2002; Zagmajster et al. 2007; Jones et al. 2009a; Dubourg-Savage et al. 2011; Minderman et al. 2015). However a shortage of studies has restricted clear understanding of the risk of bat fatalities in Europe (Nicholls and Racey, 2007). Table A.1 (see *Appendices*) summarises the main fatality results collected across Europe to date.

There is a trend away from anecdotal reporting towards rigorous, structured field methodologies to investigate and report fatality numbers (Kunz et al. 2007a; Arnett et al. 2008; Dürr and Bach, 2004; Mathews et al. 2013). There is also recognition that some types of installations (e.g. small turbines, single turbines, old installations) are under-surveyed, and there is also under-representation of some geographic areas (e.g. Texas, USA (Arnett et al. 2008)).

Table 1.3: Reproduced from Arnett et al. (2008). Estimates of mean bat fatalities per turbine, per megawatt (MW) of energy produced per turbine, and per 2,000m^2 of rotor-swept area for 21 studies at 19 wind facilities in North America, 1996-2006

Study area location[a]	**Estimated mean fatality / turbine**	**Estimated mean fatality / MW**	**Estimated mean fatality / 2,000-m^2 rotor-swept area**
Canada			
CRAB	0.5	0.8	0.6
MLAB	0.5	0.7	0.5
SVAB	18.5	10.6	7.4
Eastern USA			
BMTN[b]	20.8	31.5	24.0
BMTN[b]	35.2	53.3	40.6
BMTN[c]	69.6	38.7	27.7
MRNY[d]	24.5	14.9	9.4
MYPA[d]	23.0	15.3	11.3
MTWV	48.0	32.0	23.6
MTWV2[d]	38.0	25.3	18.7
Rocky Mountains, USA			
FRWY	1.3	2.0	1.9
Pacific North West, USA			
HWCA	3.4	1.9	1.4
KLOR	1.2	0.8	0.6
SLOR	1.1	1.7	1.3
VAOR	0.7	1.1	0.8
NCWA	3.2	2.5	2.1
Midwestern USA			
BRMN1[e]	0.1	0.2	0.2
BRMN2[f]	2.0	2.7	2.4
BRMN3[g]	2.1	2.7	2.3
LIWI	4.3	6.5	5.0
TOIA	7.8	8.7	7.4
South-central USA			
WOOK[h]	1.2	0.8	0.7

[a] See Appendix A (Arnett et al. (2008) for study area abbreviations

[b] Estimated bats killed by 3 0.66-MW turbines

[c] Estimated bats killed by 15 1.8-MW turbines

[d] Estimated bats killed from daily searches conducted at these facilities

[e] Estimated bats killed by 73 0.33-MW turbines based on 4 yr of data

[f] Estimated bats killed by 143 0.75-MW turbines based on 4 yr of data

[g] Estimated bats killed by 138 0.75-MW turbines based on 4 yr of data

[h] Estimated mean over 8 surveys in 2 yr

1.2.1 Fatality recording approaches and survey techniques

A relatively standard set of survey techniques have developed from multiple studies to estimate raw observed fatality rates and adjusted fatality rates, the latter incorporating measures of survey effort, carcass removal and search efficiency (Kunz et al. 2007b). Fatality estimates are commonly based upon a fatality search either by human surveyors or dog-handler teams (Arnett, 2006, Paula et al. 2011) following a set of procedures as detailed in Kerns et al. (2005), Arnett (2006), Jones et al. (2009a) and Mathews et al. (2013).

Carcass removal trials are carried out using bat (or small mammal) carcasses prior to fatality searches to test the proportions removed by scavenging and time taken to scavenge. Scavenger trials should be repeated at multiple sites or locations to form average removal rates, as well as being repeated annually to determine annual variability (Kunz et al. 2007b; Kerns et al. (2005); Jones et al. (2009)). Availability of bat carcasses, length of survey site access and cost of survey effort may, however, restrict the ability to carry out multiple trials. Estimator formulas enable adjustment of fatality estimates for scavenger removal (Kerns et al. 2005; Jones et al. 2009a; Baerwald and Barclay, 2009; Huso 2011; Huso et al. 2015; Korner-Nievergelt et al. 2015).

Searcher efficiency trials consider the proportion of carcasses likely to be located, given inherent variability in searcher ability (Arnett 2006; Kunz et al. 2007b). The trials should account for vegetation cover and general habitat (Kunz et al. 2007b). The set up is similar to fatality searches with the exception that trial carcasses are placed at locations within the search area which are unknown to the searcher.

The proportion of the trial bats found is then used to adjust estimates from fatality searches. This may be stratified or further adjusted to account for conditions such as weather (Kerns et al. 2005), distance bands from the turbine and habitat variability (Arnett, 2006). Preparations may need to be made for the impact of scavenger removal on carcasses used in searcher efficiency trials (Kerns et al. 2005). Estimator formulas are available to adjust the fatality estimates for searcher efficiency (as listed for carcass removal above).

Fatality estimates may also be adjusted to account for any proportion of a survey site that is not accessible for searching, or variability in sizes of search plots (Jones et al. 2009a). Any ‘incidental’ carcasses found outside the search area should also be recorded (Jones et al. 2009a).

1.2.2 Small turbines and/or sites with low numbers of turbines

Arnett et al. (2008) highlight evidence from four field sites in the USA, indicating the potential impact of turbine height and rotor-swept area. Using records from a study at Buffalo Mountain, Tennessee, 65m tall towers with rotor-swept areas of 1,735m^2 were found to kill fewer bats per turbine, however more bats per MW, than larger 78m towers with almost three times the rotor-swept area (Arnett et al. 2008; Barclay et al. 2007; Fiedler et al. 2007). A second site in Minnesota however showed higher fatalities per turbine and MW at larger turbines, with site-records in Alberta strongly concurring (14 times fewer fatalities at smaller turbines) (Arnett et al. 2008; Barclay et al. 2007). Arnett et al. (2008) however note annual variation may have introduced bias due to different sampling years.

Variation in rotor-swept area was not found to be a significant causal factor of numbers of fatalities by Barclay et al. (2007), instead finding an exponential increase in fatalities with turbine height (the highest fatality rates were found at turbine towers of at least 65m). Even when results were standardised by power capacity (to fatality/MW), outliers were present (see Figure 1.1), indicating the effect of turbine size is not always consistent and that other factors may moderate fatality rates. No trend was observed between bat fatality rates and turbine size at the Altamont Pass Wind Resource Area (California, USA) (Smallwood, 2013). Monitoring in Canada has suggested that variations in fatality rates may be partly related to turbine height, but that other factors (including migratory bat activity) moderate this relationship (Baerwald and Barclay, 2009). The need to investigate the varying effects of turbine dimensions, spacing and numbers is also further emphasised by both Kunz et al. (2007a) and Morrison et al. (2010).

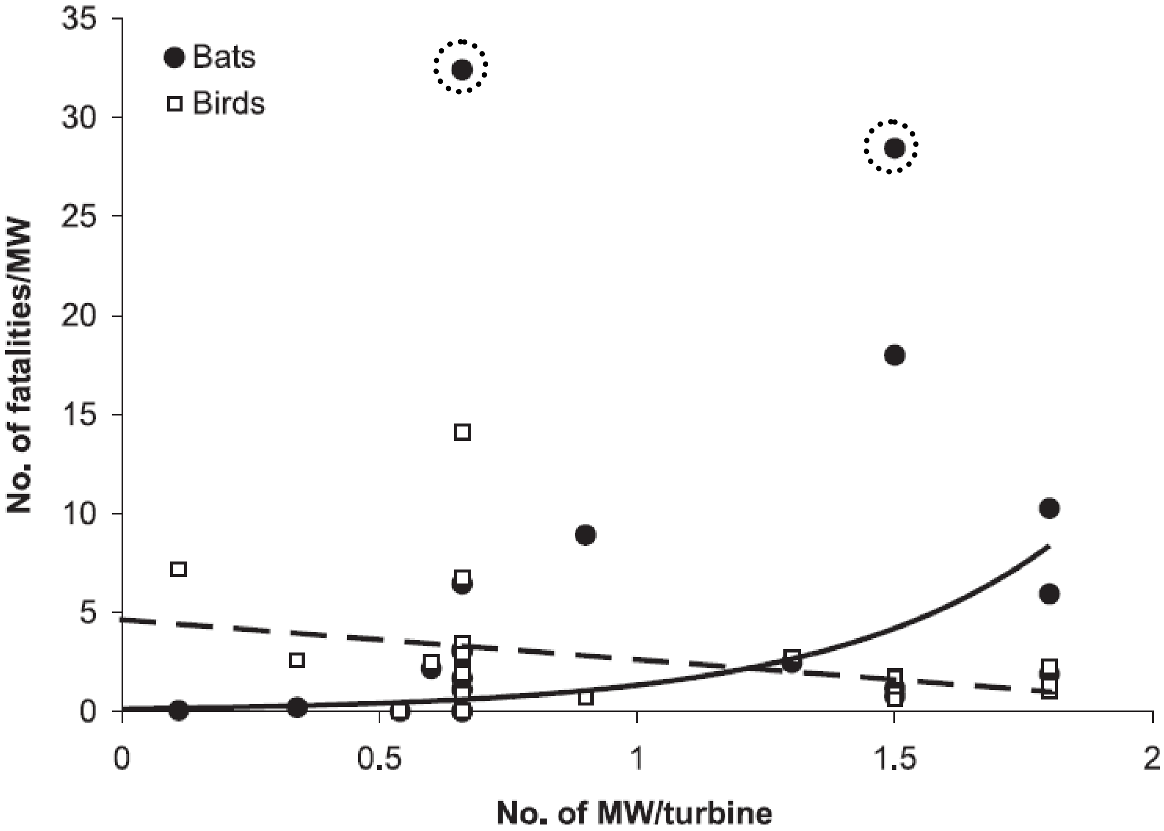

Figure 1.1: “Relationship between the corrected bat and bird fatalities per megawatt (MW) of installed capacity and the rated MW capacity per turbine at wind energy facilities in North America. The relationship for bats is significant ($F_{[1,19]} = 5.40$, $P = 0.031$; no. of bat fatalities /MW $= -1.90e^{2.22MW/turbine}$, $R^2 = 0.22$). Although the relationship for birds is not significant ($P = 0.9$), the best fit (broken) line is presented for ease of interpretation” (reproduced from Barclay et al. 2007). Apparent outliers are represented by dashed circles

Rydell et al. (2010a) reviewed published and unpublished reports from north-western Europe and found a positive correlation between bat fatalities and both turbine height and rotor diameter. It was however noted that the ground to lower-blade-tip measure did not have any influence, suggesting impacts near the top of the turbine may have been a large contributory factor.

A 2006 study in Germany found no correlation between turbine heights and fatalities. Fatalities were recorded at all sizes of turbines, with hub heights ranging from 69-98m (rotor diameters of 62-70m) (Brinkmann et al. 2006). Further unpublished data from Tobias Dürr analysed by Dubourg-Savage et al. (2009) shows bat fatality occurring at a wide range of turbine blade tip heights (20m to 80m), with peak rates occurring at different size turbines for 5 bat species (e.g. 31-50m for *Nyctalus noctula* ([common] noctule), 31-40m for

Nyctalus leisleri (Leisler's bat) and 20-50m for *Pipistrellus nathusii* (Nathusius' pipistrelle). The available studies appear to show bat fatality can occur at a wide range of turbine heights, with fatalities generally increasing with height; however this pattern is inconsistent.

Little knowledge is available regarding the influence of turbine height on bat fatalities in Britain (Jones et al. 2009a). Wind turbines at UK sites currently range up to approximately 150m to blade-tip (DECC, 2016). Only one peer-reviewed study has investigated bat fatalities at (small) turbine sites in the UK (Minderman et al. 2015). Zero fatalities were recorded during field data collection, whilst 3 anecdotal fatality records were collected from turbine owners. Corrected estimated rates of fatality were reported, though given the range of estimates provided (161-3363 fatalities year^{-1} from all UK small wind turbines), it is difficult to define the impact of small turbines. Without improved knowledge of UK bat populations, it is also difficult to contextualise turbines' population impacts.

The effect of turbine numbers per site on fatality rates is unclear. Rydell et al. (2010a) suggest that sizes of wind farms did not have a significant effect on fatalities in their study. It has been proposed that turbine numbers may be important in relation to hypotheses of bat attraction to turbines, as bats may be attracted to lower numbers of turbines, seeing them as prominent 'trees' in the landscape (Baerwald and Barclay, 2009). Field evidence from the latter study supported this, from monitoring at two sites with the same turbine model, where 2 and 39 turbines were installed, respectively. Fewer migratory-bat passes and a higher corrected fatality rate were recorded at the smaller site. It is possible however that differences in habitat and existing bat populations could have contributed to this pattern. Dubourg-Savage et al. (2011) recorded further examples of sites with low numbers of turbines that displayed relatively high adjusted fatality rates. No overall analyses were carried out during the latter study to investigate the influence or significance of this factor.

1.3 Bat species affected

1.3.1 Species patterns

Many studies have suggested particular species, or groups of species are especially vulnerable to turbine-related fatalities. Migratory, tree-roosting species are thought to be most vulnerable in the USA from existing records, in particular *Lasiurus cinereus* (hoary bat), *Lasiurus borealis* (eastern red bat), and *Lasionycteris noctivagans* (silver-haired bat) (Morrison et al. 2010; Fiedler et al. 2007). All these species fly at higher altitudes for longer distances than most other bats during migration, potentially leaving them vulnerable to turbines at height (Cryan and Barclay, 2009). Behavioural theories for bats' interactions with turbines are discussed in Section 1.5. Fatalities of *Pipistrelles subflavus* (eastern pipistrelle) and *Tadarida brasiliensis* (Brazilian free-tailed bat) are also reported in high numbers in regions where they have a high population presence (Arnett et al. 2008; Fiedler et al. 2007). Kunz et al. (2007a) list other species which are known to have been killed in the US, as follows: *Lasiurus blossivilli* (western red bat), *Lasiurus seminolus* (Seminole bat), *Myotis lucifugus* (little brown bat), *Myotis septentrionalis* (northern long-eared myotis), *Myotis evotis* (long-eared myotis) and *Eptesicus fuscus* (big brown bat). *Perimyotis subflavus* (tri-colored bat) is also listed by Arnett et al. (2011).

Dürr and Bach (2004) identify 10 species of bat known to have been killed by turbines in Germany, of which the Common noctule was the most affected (118 recorded fatalities). *Eptesicus nilssonii* (northern bat) was also noted as a common victim in Sweden. Rydell et al. (2010a) and Eurobats (Rodrigues et al 2015) have provided more recent summaries of European fatalities by species (see Appendix Table A.1 for detail). *Pipistrellus pipistrellus* (common pipistrelle) and Nathusius' pipistrelle feature prominently in fatality records. Fatalities have been recorded for *Plecotus austriacus* (grey long-eared bat) and *Barbastella barbastellus* (barbastelle bat), which are important to note as rare species in the UK. The *Myotis* and *Rhinolophus* genera only appear to be at minimal risk based on their low fatality totals.

Rydell et al. (2010a), Dürr and Bach (2004) and Dubourg-Savage et al. (2011) highlight the *Nyctalus*, *Pipistrellus*, *Vespertilio* and *Eptesicus* genera (which often forage in the open-air) as vulnerable in Europe. 98% of the bat fatalities recorded by Rydell et al. (2010a) were represented by these genera. The only bat species known to have been killed at wind turbines in the UK to date is the *Pipistrellus pygmaeus* (soprano pipistrelle) (5 fatalities, with a further 3 unidentified fatalities, judged likely to be soprano pipistrelles) (Jones et al. 2009a). However recent unpublished research may add to this range of species (University of Exeter, unpublished research). Natural England (2014) has published a summary of predicted risks of collisions and population-level threats to UK bat species, based on the limited existing evidence (Table 1.4).

1.3.2 Age and gender

In North America it has been found that turbines primarily cause more adult and male bat fatalities than juvenile and female (Arnett et al. 2008; Morrison et al. 2010), however this is known to vary by species and has varied by site (Morrison et al. 2010; Brinkmann et al. 2006). A study at two wind farms in Australia also found many more adult fatalities than juvenile (Hull and Cawthen, 2013). In contrast the gender and age balance in Europe is unclear based on current evidence (Rydell, et al. 2010a). A study at a wind farm in South America (Brazil) was also unable to find a significant difference in fatalities between male and female bats (Barros et al. 2015). It has been found that carcasses cannot always be sexed during surveys, leading to uncertainty in the recorded balance of male/female fatalities (e.g. Brinkmann et al. 2006; Bicknell and Gillam, 2013).

1.3.3 Echolocation frequency

Published guidance in the UK suggests larger, high flying bats with low frequency echolocation may be more at risk from turbines due to flight heights within the blade-swept area and potentially less frequent echolocation. See Table 1.5 for an overview of risk levels as defined by Natural England (2014). Table A.2 furthermore lists known flight heights of European bat species (Rodrigues et al. 2015). Other studies (e.g. Kerns et al. (2005) in the USA) have found ‘high’ frequency echo-locaters may be more vulnerable after recording higher numbers of fatalities of such bats. However in the context of UK species this likely equates to mid-frequency echolocation. The latter pattern was hypothesised to be a result of greater attenuation of higher frequencies with increasing distance, restricting the detection of blades until bats are in close proximity to them. However this contrasting view on frequency may be skewed by the US species with moderate/high frequency echolocation naturally flying higher than UK species with similar frequencies. In reference to this subject, Table 1.6 details the echolocation characteristics of European bats, including call intensity and detection distance.

Table 1.4: "The risk of collision fatalities affecting bat populations" (table and caption from Natural England, 2014)

Bat species	Relative population size and status**	Risk of collision^	Population Threat
Common pipistrelle	Common	Medium	Low
Soprano pipistrelle	Common	Medium	Low
Brown long eared bat	Common	Low	Low
Daubenton's bat	Common	Low	Low
Natterer's bat	Fairly common	Low	Low
Whiskered bat	Locally distributed	Low	Low
Brandt's bat	Common N.W, rare or absent E,S	Low	Low
Serotine	Widespread, restricted S	Medium	Medium*
Noctule	Uncommon	High	High
Leisler's bat	Scarce	High	High
Nathusius' pipistrelle	Rare	High	High
Lesser Horseshoe	Rare, endangered	Low	Low
Greater Horseshoe	V Rare, endangered	Low	Low
Barbastelle	Widespread, rare	Medium	Medium
Bechstein's bat	V rare	Low	Low
Grey long eared	V rare	Low	Low

^ Risk of collision is based on what we currently know about bat behaviour. *Within their distribution.
** Based on Battersby, J ((Ed)) & Tracking Mammals Partnership ((2005)).

Table 1.5: Assessing risk posed by turbines by taking account of various factors including habitat preference and flight behaviour (Natural England Technical Information Note TIN051 Bats and Onshore Windfarms 2014))

		Risk of turbine impact	
Factor	**Low Risk**	**Medium Risk**	**High Risk**
Habitat preference	Bats preferring cluttered habitat	Bats able to exploit background cluttered space	Bats preferring to use open habitat
Echolocation characteristics	Short range High frequency Low intensity Detection distance ~15m	Intermediate – more plastic in their echolocation	Long range Low frequency High intensity Detection distance ~80m
Weight	Lightest	Medium	Heaviest
Wing shape	Low wing loading Low aspect ratio Broadest wings	Intermediate	High wing loading High aspect ratio Narrow wings
Flight speed	Slow	Intermediate	Fast
Flight behaviour and use of landscape	Manoeuvre well will travel in cluttered habitat Keeps close to vegetation Gaps may be avoided	Some flexibility	Less able to manoeuvre May avoid cluttered habitat Can get away from unsuitable habitat quickly Commute across open landscape
Hunting techniques	Hunt close to vegetation Exploit richer food sources in cluttered habitat Gleaners	Hunt in edge and gap habitat Aerial hawkers	Less able to exploit insect abundance in cluttered habitat Aerial hawker Feed in open
Migration	Local or regional movements	Regional migrant in some parts of range	Long-range migrant in some parts of range
Conclusion	*Myotis* (most species) Long eared-bats Horseshoe bats	Common pipistrelle Soprano pipistrelle Serotine Barbastelle	Noctule Leisler’s bat Nathusius’ pipistrelle

Table 1.6: Detectability coefficients to compare activity indices. Annex 4 Rodrigues et al (2015) ((Guidelines for consideration of bats in wind farm projects – Revision 2014))

Open Space			
Intensity levels of calls	**Species**	**Distance of detection (m)**	**Detect-ability coefficient**
Low	*R. hipposideros*	5	5.00
	R. ferr./eur./meh.	10	2.50
	M. emarginatus	10	2.50
	M. alcathoe	10	2.50
	M. mystacinus	10	2.50
	M. brandtii	10	2.50
	M. daubentonii	15	1.70
	M. nattereri	15	1.70
	M. bechsteinii	15	1.70
	B. barbastellus	15	1.70
Medium	*M. blythii*	20	1.20
	M. myotis	20	1.20
	P. pygmaeus	25	1.00
	P. pipistrellus	30	0.83
	P. kuhlii	30	0.83
	P. nathusii	30	0.83
	M. schreibersii	30	0.83
High	*H. savii*	40	0.71
	E. serotinus	40	0.71
	*Plecotus spp.**	40*	0.71
Very high	*E. nilssonii*	50	0.50
	V. murinus	50	0.50

Clutter (underwood)			
Intensity levels of calls	**Species**	**Distance of detection (m)**	**Detect-ability coefficient**
Low	*R. hipposideros*	5	5.00
	Plecotus spp..	5	5.00
	M. emarginatus	8	3.10
	M. nattereri	10	3.10
	R. ferr./eur./meh	10	2.50
	M. alcathoe	10	2.50
	M. mystacinus	10	2.50
	M. brandtii	10	2.50
	M. daubentonii	10	2.50
	M. bechsteinii	10	2.50
	B. barbastellus	15	1.70
	M. blythii	15	1.70
	M. myotis	15	1.70
Medium	*P. pygmaeus*	20	1.20
	M. schreibersii	20	1.20
	P. pipistrellus	25	1.00
	P. kuhlii	25	1.00
	P. nathusii	25	1.00
High	*H. savii*	30	0.83
	E. serotinus	30	0.83
Very high	*E. nilssonii*	50	0.50
	V. murinus	50	0.50

N. leisleri	80	0.31
N. noctula	100	0.25
T. teniotis	150	0.17
N. lasiopterus	150	0.17

N. leisleri	80	0.31
N. noctula	100	0.25
T. teniotis	150	0.17
N. lasiopterus	150	0.17

*Note for *Plecotus* spp.: some high intensity calls are sometimes emitted during commuting flight in the open space (ref. Call DVD 3.93)

1.3.4 Small turbines and/or sites with low numbers of turbines

It seems likely that size of turbines will have an effect upon the selection and number of individual species killed, due to the different flight height preferences of bats during foraging, as well as commuting and migrating (Natural England, 2014). For example it is known that Common noctule bats are able to fly at great heights (up to 1.2km altitude) (Ahlén et al. 2009). Flight heights may be varied to account for obstacles, environment or reason for flight (i.e. foraging, migrating etc.) (Ahlén et al. 2009).

Hoary bats' and silver-haired bats' activity rates have been found to vary at different heights, with the opposite pattern of activity recorded between the species at ground level and 30m detection height (hoary bats were more active at 30m; silver-haired bats were more active at ground level) (Baerwald and Barclay, 2009).

The proportion of activity from species with low frequency echolocation calls has been observed to increase at turbine hub height relative to ground level. In contrast, the proportion of activity from species that use medium and high frequency calls reduces at hub height, though species using medium frequencies continue to comprise the highest proportion of activity (unpublished research, University of Exeter). As such, Noctule, Leisler and Serotine bats may be at higher proportional risk in the UK, though their population size and occurrence rate may produce lower total fatalities than more common species.

1.4 Causes of bat fatalities at turbines

Two primary mechanisms are thought to cause bat fatalities at wind turbine sites: collision with moving blades (Horn et al. 2008a) and internal injuries from barotrauma (see Definitions) (Cryan and Barclay, 2009; Grodsky et al. 2011). Collision with turbine towers has also been hypothesised, however this is considered of low likelihood (Horn et al. 2008a; Arnett et al. 2005).

1.4.1 Collision with moving blades

Multiple studies have provided evidence of the impact of moving turbine blades upon bats, with high bat fatalities frequently recorded at onshore wind farms, particularly in North America (Kerns and Kerlinger, 2004; Arnett et al. 2005; Arnett et al. 2008; Morrison et al. 2010), and Europe (Dürr and Bach, 2004; Bach and Rahmel, 2004; Ahlén, 2002, Rydell et al. 2010a; Dubourg-Savage et al. 2011; Camina, 2012). Horn et al. (2008a) recorded thermal infrared (TIR) video and still images of bats being struck by moving turbine blades 5 times during their study, equating to 0.5% of the bat passes recorded. Across the monitored 42-turbine facility, this could lead to a strike rate of 21 bats night^{-1}. Recent TIR monitoring in North America provided further observations of bat flight in proximity to turbine blades, with a small number of possible blade strikes also observed (Cryan et al. 2014). The available evidence suggests that collision with moving turbine blades is likely to be the major contributory source of fatalities at turbine sites.

1.4.2 Barotrauma

Barotrauma, or tissue damage due to excessive air pressure changes, may also contribute to fatalities at wind turbines (Baerwald et al. 2008; Grodsky et al. 2011; Dürr and Bach, 2004). Of the 188 bats found killed the previous night by Baerwald et al. (2008) at a wind farm in Canada (this timing was visually judged by level of decomposition, rigor mortis and degree of insect scavenging), 87 were reported to have no fatal external injuries based upon gross internal necropsy. Of the 75 ‘fresh’ carcasses found, 90-92% suffered internal haemorrhaging consistent with barotrauma.

Evidence of barotrauma has also been recorded by industrial fatality reports in Europe (Rydell et al. 2010a), whilst Escobar et al. (2015) also recorded internal injuries to bats consistent with barotrauma during a study in Chile. However Grodsky et al. (2011) later found a third of all bats judged to have no broken bones from field-based examinations did indeed have broken bones, following radiological imaging. Results found from a second forensic investigation of bat carcasses from wind farms support the latter result, identifying concurrent traumatic injuries in 69% of those bats with ruptured tympana (a marker of barotrauma). Only 6% of the carcasses showed symptoms exclusively suggesting the possibility of barotraumas, leading the study to conclude that barotrauma is at best a minor etiology in bat fatalities at wind turbines (Rollins et al. 2012). The study furthermore suggested that lung tissues should not be used to assess the occurrence of barotrauma, due to the physical effects of post-mortem time, environmental temperature and freezing of carcasses that can mimic diagnostic symptoms of barotrauma.

Brinkmann et al. (2006) also found injuries to bats that could not be confidently attributed to either direct collision or barotrauma. Furthermore 82% of the 17 bat carcasses examined during a study at a wind farm in Oklahoma, USA featured broken bones; the remaining 3 carcasses showed no obvious signs of barotrauma (Piorowski and O’Connel, 2010). Given the difficulties of assigning cause of death even after extensive veterinary diagnostic procedures (including gross necropsy, histopathology, and radiology examinations (Grodsky et al.2011)), and the requirement for very fresh carcasses in order to diagnose barotraumas, it may be prudent to treat all bat deaths collectively. Houck (2012) (op. cit National Renewable Energy Laboratory, 2013) later used computational fluid dynamic modelling to consider the pressures that would theoretically exist around wind turbine blades, concluding with a hypothesis that the pressure changes would be insufficient for fatal barotrauma to occur.

1.4.3 Delayed impacts

Impacts and mortality may be delayed after suffering a partial blow from a blade or receiving internal injuries from barotrauma that are not immediately fatal. Additionally, bats may become weaker and more vulnerable to predation.

Barros et al. (2015) found grounded live bats with no external injuries during carcass searches at a wind farm in Brazil, though barotrauma was not confirmed as the cause of injury. Both Baerwald et al. (2008) and Grodsky et al. (2011) suggest haemorrhaging may occur in the middle and/or inner ear as a result of barotrauma. This would severely affect bats' echolocation ability and therefore increase the likelihood of a delayed fatal impact from turbines. The latter study recorded these injuries in 12 of the 23 dead bats' whose ears were examined and suggested that delayed fatalities may cause underestimation of fatality estimates at wind farms.

1.4.4 Collisions with turbine towers

Bat fatality rates from collisions with stationary structures are generally assumed to be minor, with low numbers of bats killed where incidences have been recorded (Crawford and Baker, 1981; Timm, 1989; Cryan and Barclay, 2009). However recent investigation into free-flying bats' use of multiple sensory systems for navigation has suggested they may rely more upon vision than previously understood. This may affect their ability to avoid obstacles, e.g. Orbach and Fenton (2010) provided findings of frequent collisions with obstacles in an experimental setting (in this case not fatal). Possible seasonal changes were also noted during this study, where bat collision rates changed during August from being susceptible to collision with non-reflective materials and in lighter conditions, to colliding equally with all material types and more so in dark conditions. As these patterns apparently coincided with swarming and mating cycles occurring during August, this warranted further investigation of behavioural changes in navigational methods. From current evidence it seems that collision with static wind turbine towers or blades is unlikely to be a major contributor to bat fatalities (Arnett et al. 2005; Horn et al. 2008a), however systematic categorisation of observed fatalities (e.g. through use of TIR imaging (Horn et al. 2008a; Arnett et al. 2005)) would provide more robust clarification.

1.4.5 Small turbines and/or sites with low numbers of turbines

Variation in the cause of bat fatalities between different turbine sizes is largely unexplored. Taller turbines may present a greater risk of direct collisions at the flight heights of migrating bats, if some species of migratory bats flying at higher altitudes do not echolocate as frequently as when foraging at lower height (as suggested by Crawford and Baker (1981)). Larger blade-tip vortices and air turbulence are also created by the longer blades of large turbines (Morrison et al. 2010). Furthermore the associated low pressure pockets of air will be created in a wider area and at higher altitudes, therefore the risk of barotrauma may also increase. Smaller turbines often have blades closer to ground level and may therefore impinge on habitats used by bats for foraging. Smaller turbines' blade rotation speeds are able to increase at a faster rate with rising wind speeds than large turbines. The time to complete a blade rotation is also much shorter; therefore direct collision may be a more likely cause of fatality at small turbines than barotrauma. Research into the effect of turbine numbers upon causes of bat fatalities is also unexplored.

1.5 Hypotheses for bats interaction with wind turbines

Most studies agree that the behavioural causes of bat fatalities at wind turbines are unclear (Cryan and Barclay, 2009; Strickland et al. 2011; Kunz et al. 2007a; Rydell et al. 2010b; Fiedler et al. 2007; Schuster et al. 2015), however many hypotheses have been presented for investigation (e.g. Kunz et al. 2007a; Rydell et al. 2010b; Dürr and Bach, 2004; Cryan and Barclay, 2009).

The presence of bats at turbines has been variously attributed to investigation of turbines (Horn et al. 2008a; Ahlén et al. 2009; Cryan et al. 2014), foraging behaviour (Horn et al. 2008a; Ahlén et al. 2009; Gorresen et al. 2015; Rydell et al. 2010b), roost searching (Horn et al. 2008a; Ahlén et al. 2009; Cryan et al. 2014), migration flights (Baerwald and Barclay, 2011) and possibly mating behaviours (Cryan, 2008; Cryan et al. 2012). Bats may also alter course towards turbines during flight in response to turbine-caused changes in air currents and using vision, often approaching on their downwind side (Cryan et al. 2014; Gorresen et al. 2015). Rydell et al. (2010a) collated limited evidence from a small number of studies using TIR observation, concluding that bats actively fly around turbine blades, most likely to feed on insects accumulating there. Interestingly, monitoring of offshore turbines in Scandinavia found bats roosting in the turbine nacelles (Ahlén et al. 2009) and emissions of territorial and mating calls during bats' flight around the turbines. Insect presence on the surface of turbines has now been confirmed, alongside observations of insect matter in the stomachs of bats found dead at wind turbines, lending weight to foraging hypotheses (Rydell et al. 2016).

Activity observed by Horn et al. (2008a) included foraging around turbines and movement towards blades, interpreted as chasing or involuntary movement caused by blade-tip vortices. Ahlen et al. (2009) similarly recorded bats foraging around turbine blades and masts, whilst foraging in the airspace near turbines was recorded by Gorresen et al. (2015). After confirming bats were being struck by turbine blades, Horn et al. (2008a) emphasise the higher likelihood of bat fatalities from foraging behaviour than commuting behaviour, recording a lack of straight-line flights near turbines. Attraction of bats to turbine blades could furthermore be due to visual cues, sensing of the blades' location by echolocation or air movement (Cryan et al. 2014; Gorresen et al. 2015) or hearing sounds from blade movement (such as the blades cutting through the air) (some bats are known to be attracted to distant sounds (e.g. Buchler and Childs, 1981)).

Cryan and Barclay (2009) provide a summary of current hypotheses for bat fatalities at wind turbines. The summary is shown in Table 1.2 together with four additional hypotheses from Strickland et al. (2011) and Baerwald and Barclay (2011), with subjective scoring of their estimated relative likelihood and the approximate level of certainty provided by existing research.

1.5.1 Small turbines and/or sites with low numbers of turbines

The height and number of turbines may impact likelihood of particular hypotheses being supported. In relation to the 'attracted to modified landscape features' hypothesis, smaller turbine sites are likely to be sited in smaller clearings with more cluttered habitat surroundings, relative to larger turbine sites. At smaller sites, bats may therefore be more likely to fly close to turbines when foraging around the edge of the sites. With regard to the 'Attracted to turbines as mating or gathering sites' hypothesis, the tallest tree-like features in a landscape may represent the most desirable mating territory, therefore activity levels may vary according to turbine height if this hypothesis is accurate.

1.6 Variability in bat activity, fatalities and behaviour results: Moderating factors

Due to large variations in bat activity and fatality recordings at similar turbine sites, authors have measured and suggested potential influencing factors (Baerwald and Barclay, 2009; Szewczak and Arnett, 2006; Arnett et al. 2005; Rydell et al. 2010a), which are discussed below.

1.6.1 Seasonal variation

Many authors have noted the dominant seasonal patterns of bat fatalities, which have largely been related to hibernation, mating, feeding and migration behaviours. Peak fatality rates have commonly been recorded during July-September. Fatalities have also been observed outside that period and throughout the active bat season (approximately March to November), but in lower numbers (exact timings may vary according to weather, bat species and geography) (Arnett et al. 2008; Dürr and Bach, 2004; Fiedler et al. 2007; Rydell et al. 2010a; Morrison et al. 2010; Brinkmann et al. 2006; Kunz et al. 2007a; Baerwald and Barclay, 2011; Camina, 2012; Arnett et al. 2016). This timing relates both to bats leaving their summer colonies and autumn migration (Behr, 2007 op. cit Schuster et al. 2015). The late summer/autumn seasonal peak was also observed during two studies in the Southern Hemisphere, the first in Australia finding most fatalities during March and April (Hull and Cawthen, 2013) and the second in South Africa identifying a peak during December-March (Doty and Martin, 2013).

A study by Arnett et al. (2008) provided supporting evidence, recording highly correlated temporal patterns of fatalities at two sites in different states which were surveyed simultaneously. Some variations in the timing of fatality peaks have been observed. Dubourg-Savage et al. (2011) noted southern European fatalities are more equally bimodal in their temporal distribution (peaks centred around May and August); whereas northern European fatalities are more likely to occur primarily around the August peak (a less significant peak was centred upon May). Rydell et al. (2010a) also noted results from France showing a smaller peak in fatalities during spring/early summer. Abnormal weather conditions have been suggested to modify the timing of or remove peaks in fatalities (Rydell et al. 2010a). Fatalities have even been found to extend to December in Spain (Camina, 2012). Similarly to some of the European observations, the silver-haired bat was found to also have an additional peak fatality period in the spring (between April and June) in the USA (Arnett et al. 2008).

Despite these overall patterns, peak mortality appears to vary in frequency and timing across years (Rydell et al. 2010a; Arnett et al. 2008).

1.6.2 Distribution of fatalities and activity across the night

Reported temporal patterns of bat activity through the night at wind energy sites have been relatively consistent, however timing of fatalities is not well known due to a lack of studies and the difficulty in directly observing fatalities. A North American study by Arnett et al. (2005) showed peak fatality rates during the first two hours after sunset. The primary peak in bat activity in another North American study (Gorresen et al. 2015) was found to be 2-3 hours after sunset, followed by a smaller peak at approximately 4 hours before sunrise. Baerwald and Barclay (2011) found migratory bat passes in Alberta, Canada were distributed throughout the night, with two peaks at 3 and 6 hours after sunset. The study also noted that numbers of fatalities varied considerably between consecutive nights.

Results from Europe concerning temporal patterns are focused upon bat activity. Peak activity around turbines was again noted during the first 2-3 hours after sunset by Brinkmann et al. (2006). Two peaks were also reported by Limpens et al. (2013), for the 0.1-0.2 and 0.7-0.8 fractions of the night (whereby they treated 0 as the start of the night and 1 as the end, in order to standardise for night lengths).

1.6.3 Weather-related variability

1.6.3.1 Wind speed

Higher bat fatalities are generally recorded during lower wind speeds (Arnett et al. 2008; Brinkmann et al. 2006; Kerns et al. 2005; Kunz et al. 2007a; Rydell et al. 2010a; Amorim et al. 2012). Figure 1.2 shows the relationship analysed from the Mountaineer and Meyersdale sites in the USA (Kerns et al. 2005). Exceptions to the pattern have also been recorded (Fiedler et al. 2007; Fiedler, 2004). Whilst studying wind farms in the Mediterranean, Amorim et al. (2012) identified that 81% of fatalities occurred during nights with mean wind speeds of <4 m/s, with no fatalities above 5 m/s.

Brinkmann et al. (2006) recorded bat activity at all wind speeds up to 10.9 ms-^{1}, however this reduced above 7.5ms-^{1}. Higher bat activity levels during lower wind speeds were also recorded at wind farms by Baerwald and Barclay (2011), Bach et al. (2011), Weller and Baldwin (2012), Cryan et al. (2014) and Gorresen et al. (2015), as well as in the review article by Rydell et al. (2010a). The same pattern has also been recorded in other environments (e.g. Blake et al. 1994; Cryan and Brown, 2007). Rydell et al. (2010a) and Bach et al. (2011) also found that resistance to higher wind speeds was variable amongst bat species. *Pipistrellus nathusii* was observed as more wind-tolerant than *Nyctalus noctula* during the latter study, whilst *Nyctalus noctula* was more wind-tolerant than smaller *Pipistrellus* species in the former study. This has implications for the mitigation of bat fatalities at different wind speeds.

1.6.3.2 Rainfall

Rain levels appear to have a negative relationship with fatality numbers (Kerns et al. 2005); however ‘inclement’ weather does not always have a significant effect (Baerwald et al. 2009). Bat activity has been found to be negatively associated with rainfall occurrence at turbine (Limpens et al. 2013; Gorresen et al. 2015) and non-turbine sites (Erickson and West, 2002). However this is not a consistent association (e.g. Scanlon and Petit, 2008).

1.6.3.3 Barometric pressure

Limited evidence notes a peak in fatalities when barometric pressure increases following the passing of storm fronts (Kerns et al. 2005). However, the opposite pattern has also been observed (Baerwald and Barclay, 2011). Increases in bat activity during low and increasing pressure periods were also observed by Horn et al. (2008b) and Gorresen et al. (2015). It has been suggested that bats' physiological ability to recognise pressure changes may enable 'anticipation' of poor weather by bats (Baerwald and Barclay, 2011). This may lead to higher fatalities when bats fly faster with less echolocation to flee a storm or forage rapidly before a storm. Earlier evidence of higher migratory bat activity during low pressure periods, from Cryan and Brown (2007), support Baerwald and Barclay's (2011) assertions.

1.6.3.4 Temperature

Multiple studies have identified a positive correlation between temperature and bat fatality (Arnett et al. 2011; Ahlen et al. 2007; Amorim et al. 2012; Georgiakakis et al 2013). Amorim et al. (2012) reported that 88% of fatalities occurred during nights with mean temperatures >15^{o}C and no fatalities at <13^{o}C. The same association was observed in southern Europe (Georgiakakis et al. 2013). A weak positive correlation was also recorded at one of two sites studied by Kerns et al (2005). No correlation however was recorded by Fiedler et al. (2007).

A positive association between bat activity and temperature has also been recorded at wind energy facilities (Baerwald and Barclay, 2011; Alcalde, 2003; Weller and Baldwin, 2012; Gorresen et al. 2015) and in other environments (Anthony et al. 1981; Erickson and West, 2002; Scanlon and Petit, 2008). Results from North America suggest activity rates may peak at approximately 20^{o}C (Arnett et al. 2007a), though the likelihood of nightly temperatures reaching this threshold in northwestern Europe is low.

Bats' responses to temperature may vary between species. Arnett et al. (2007a) found species using high frequency echolocation were more responsive to temperature change than low frequency echolocators. This may be explained by the typically lower body mass of high frequency echolocators; heightening vulnerability to temperature fluctuations.

1.6.3.5 Modelling bat activity

Multivariate regression models can predict large proportions of bat activity levels. For example Horn et al. (2008a) suggested wind speed, temperature and turbine rotations per minute (RPM) variables can predict/explain 95% of the variability in numbers of passes recorded at their monitoring site. Similarly generalised linear mixed effect models (GLMM) have been used to identify the moderating influence of turbine operation, weather and habitat conditions upon bat activity at small turbine sites (Minderman et al. 2012).

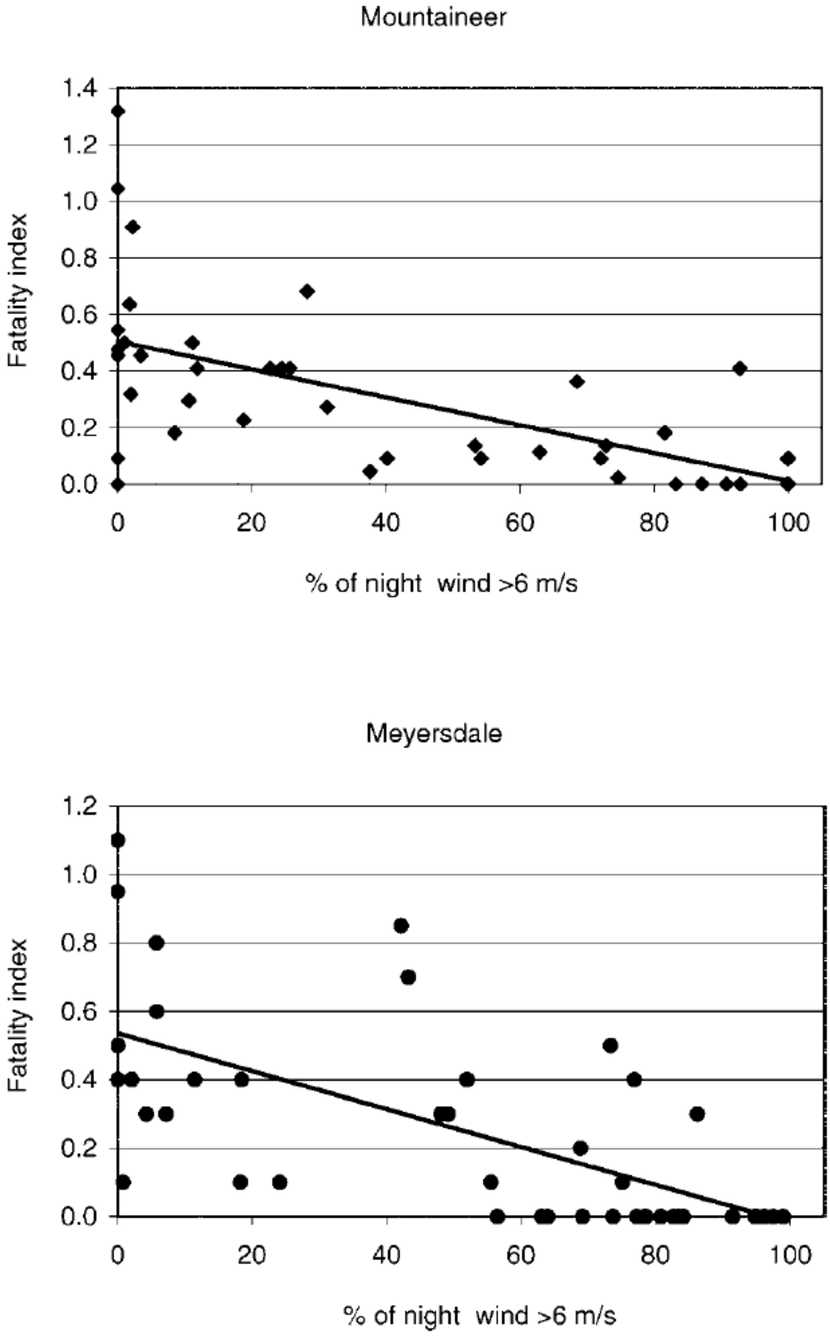

Figure 1.2: "Relationship between daily fatalities (no. of fresh bat fatalities/no. of turbines searched) and average percentage of the night where wind speed at turbines was >6 m/sec at the Mountaineer Wind Energy Center in West Virginia, USA (31 Jul–11 Sep 2004) and the Meyersdale Wind Energy Center in Pennsylvania, USA (2 Aug–13 Sep 2004; Kerns et al. 2005). Fatality index is the total number of fresh bats found on a given day divided by the number of turbines searched that day." (reproduced from Arnett et al.2008)

1.6.4 Geographical and environmental variability

It is widely recognised that the presence and behaviour of bats is influenced by habitat and landscape structures (e.g. Fuentes-Montemayor et al. (2011); Klingbeil and Willig (2009); Perry et al. (2008); Sandel et al. (2001); Jenkins et al (1998); Vaughan et al. (1997); Walsh and Harris (1996a)). This may also influence the abundance and behaviour of bats in proximity to turbines and may partially explain variations in fatality rates between sites with similar turbine models. Limited research has also considered the influence of the spatial layout of turbines at wind farms which could feasibly influence a bats' perception of a site's landscape (Kerns et al. 2005; Baerwald and Barclay, 2011).

Kerns et al. (2005) propose a range of variables that could modify levels of bat fatalities, as follows:

- "configuration of the turbines (e.g., linear, nonlinear, single row, double row)
- orientation of a ridge where turbines might be located (e.g., N-S, E-W, NE-SW, etc)
- dominant ecotype (e.g., open prairie, deciduous forest, cropland)
- abundance of bats in the area
- landscape configuration
- proximity to key features such as maternity roosts or hibernacula
- model of turbine used
- proximity of a turbine to habitat features (e.g., open water, forest edge)
- large scale / regional habitat"

Bats commonly display a preference for prominent linear vegetation (e.g. hedges) and landscape features for navigation (Walsh and Harris, 1996b; Entwistle et al. 1996; Limpens et al. 1989; Verboom and Huitema, 1997). Other observed functional habitat associations include: the presence of trees for roosting (Spada et al. 2008; Lookingbill et al. 2010: supplementary material; Russo et al. 2005; Ruczyński and Bogdanowicz, 2005; Perry et al. 2008), navigation (Entwistle et al. 1996; Verboom and Huitema, 1997; Verboom and Spoelstra 1999; Downs and Racey, 2006) and prey sources (Entwistle et al. 1996; Verboom and Huitema, 1997; Lumsden and Bennett, 2005). Waterways have also been associated with navigation (Serra-Cobo et al. 2000; Greif and Siemers, 2010; Downs and Racey, 2006) and foraging behaviours (Brooks, 2009; Kusch and Idelberger 2005; Siemers et al. 2001), particularly in areas of high insect abundance (Vaughan et al. 1997; Warren et al. 2000; Holloway and Barclay, 2000).

1.6.4.1 European Results

In a review of studies considering north-western Europe, Rydell et al. (2010a) found that fatality rates showed a strong association with features including topography and vegetation. The highest fatalities recorded in Rydell et al. (2010a) were at sites on the top of forested hills and at a marsh area. In particular fatalities were found to be higher within 100m of woodland areas. Variable mortality rates were observed in flatter, more open farmland areas, in various countries. The topography and habitat structure of field sites was found to have an impact upon the species most likely to be killed at different sites, in Germany (Rydell et al. 2010a).

A small amount of evidence from surveys in southern Sweden and north-western Germany illustrated higher proportions of fatalities found at turbines within 500m of/near a coastline (respectively), than those further inland. This may suggest coastline features are used for navigation or foraging (due to high insect presence) by bats (Rydell et al. 2010a). Bach et al. (2011) also found that higher activity rates of bats were retained during higher wind speeds in coastal areas, where they were not further inland. Some species of bat may be likely to occur near coastlines due to their use of these areas during migration (Rydell et al. 2010a). These latter pieces of evidence suggest coastal features should be considered in analysing influences upon fatalities at turbine sites, whilst they suggest potentially significant impacts upon bats when considering offshore turbines.

A review of European studies by Dubourg-Savage et al. (2011) discovered inconsistent relationships between fatalities and surrounding habitat. Fatalities at sites in Portugal were found to have little correlation with habitat variables, with the exception of a somewhat surprising negative correlation with tree cover. No clear pattern was highlighted for sites in either France or Greece.

77% of fatalities recorded in Germany up to 2004 were found to have occurred at turbines less than 50m from the nearest wooded features or hedgerows (Dürr and Bach, 2004). When considering particular species or groups of species, the pattern also became clearer. *Pipistrellus* fatalities were largely found close to wooded areas/hedgerows, whilst Noctule and Serotine fatalities showed a weaker relationship with these features. It should be noted that low sample sizes in this study limit the confidence levels in the results.

During a later study in Freiburg, southern Germany, 50 carcasses were found, all recorded in forested, clear fell and forest border areas, whilst none were found in open land areas (bat activity was however recorded in open areas – particularly at greater heights) (Brinkmann et al. 2006). This appears to suggest a strong influence of habitat upon fatalities.

1.6.4.2 North American Results

When considering habitats proximal to wind farms in Canada, Baerwald and Barclay (2009) found that Hoary bat and Silver-haired bat presence was more likely close to the foothills of the Rocky Mountains (with trees, ridgelines and river networks), than to prairie grasslands. Arnett et al. (2008) reviewed studies at turbines sites across North America, finding that three studies considering geographical and environmental input showed little or conflicting evidence of the influence of these factors.

Further North American studies have observed fatalities in agricultural landscapes and mixed-grass prairie (Kunz et al. 2007a). Piorowski and O’Connell ((2010) and Johnson et al. (2004) recorded a lack of association between fatalities or activity and most landcover and topography types., Nonetheless two habitat variables indicated a relationship: (1) the heads of eroded ravines (which related to fatalities in the former study) and (2) distance to woodland (activity was observed to reduce with increasing distance in the latter study). The overall lack of, or weakness of habitat associations within the North American results may be considered somewhat surprising, given the evidence for bats’ habitat preferences discussed above. This poses an interesting need for further research in the area (as also suggested by Kunz et al. (2007a) and Morrison et al. (2010)).

Migratory bats may utilise landscapes in a different manner to those engaged in commuting and foraging. There is a lack of research into these differences with regard to activity around turbines. Baerwald and Barclay (2009) however investigated the movements of migratory bats, noting varied activity among sites and concentration of flight routes along selected trajectories rather than wide dispersal. This may offer a beneficial method to identify ‘risk’ areas for turbine placement in relation to migratory bats. Through the use of stable carbon and nitrogen isotope ratios, recent research has been able to identify associations of Nathusius’ pipistrelle bats with aquatic habitats during autumn migration and similarly of noctule bats with terrestrial habitats during this time (Voigt et al. 2016). Identification of wind farms near movement corridors dominated by these habitat types may aid mitigation of fatality impacts during migration periods.

1.6.5 Bat prey-related factors

The presence and abundance of insect prey species in proximity to turbines may be a significant factor attracting foraging bats and thereby increasing fatality risk (Rydell et al. 2010b). The number of bat studies at wind turbine installations that have measured insect activity is low, though the issue has been recognised in the literature (Kunz et al. 2007; Rydell et al. 2010b; Long et al. 2011). Insects have been observed flying in the vicinity of turbines (Horn et al. 2008a; Cryan et al. 2014), whilst bats have also been observed hunting insects next to the nacelle and blades (Ahlén, 2003). It has been hypothesised that the warmer air produced around these areas (as observed using TIR imaging) attracts insects which subsequently may attract bats (Ahlén, 2003).

TIR-based studies of wind turbines have identified positive correlations between bat and insect activity (Horn et al. 2008a; Gorresen et al. 2015). Insect levels were found to peak post-sunset, potentially impacting upon timings of bat fatalities (Horn et al. 2008a). Valdez and Cryan (2013) carried out analyses of the digestive tracts of bats found killed beneath wind turbines. Large amounts of insects were found in the bats’ stomachs (also found in 25% of necropsied bats from Grodsky et al. (2011) and one of six analysed in Hull and Cawthen (2013)), however no insects were found in their mouths or throats. This may otherwise have indicated the occurrence of death whilst feeding. The study recommended further research including improved characterisation of insect types at turbines and recording of bats’ feeding buzzes in order to establish causality (concurring with Reimer et al. 2010). Additionally, TIR monitoring could aid determination of whether blade strikes of bats occurred alongside periods of feeding buzzes.

Rydell et al. (2016) later confirmed insect presence on the surface of turbines and insects in the stomachs of dead bats found at turbines. This study additionally theorised that bats are likely to be able to detect insects on the surfaces of turbines and target them during foraging.

1.6.5.1 Influence of habitat structure and weather

Habitat structure contributes to both bat and insect activity levels (Muller et al. 2012); therefore habitat and prey influences on bat fatality levels may be interlinked. Insect ‘treetopping’ behaviour (Alcock and Dodson, 2008; Shields, 1967) may also overlap with similar activity hypothesised for some bats (e.g. Barbastelle (Russo et al. 2004)). This blurs analysis of the effects of prey abundance and bat behaviour on fatalities at turbines. The same complication may apply to the effects of prey levels and weather (Kerns et al. 2005; Corten and Veldkamp, 2001).

1.6.5.2 Feasibility of data collection

Whilst data is required on this subject, insect monitoring at turbines’ blade or nacelle height will continue to be restricted by research logistics. Standard insect traps are often designed to monitor close to ground level. Furthermore techniques such as using balloons to sample with insect monitoring equipment at height are labour intensive and have the potential to cause conflict with wind turbine operators. Furthermore, recording insects at nacelle height is often not possible whilst monitoring with TIR cameras due to the small size of the target (Horn et al. 2008a).

1.6.6 Turbine layout configuration

Little research is available regarding the effect of turbine layout configuration upon levels of impacts to bats or bat activity. A small amount of field evidence was produced by Kerns et al. (2005), studying 2 wind farms in North America. Fatalities were found to be spread across turbines, though peaks in fatality numbers were identified near the extremes or centres of turbine strings. This pattern was not repeated however during a Canadian study. Nonetheless fatality rates were found to be higher at the northern end of the wind farm than the southern end (no difference was found comparing the eastern and western ends) (Baerwald and Barclay, 2011). The observations at this site were hypothesised to be the consequence of the flight direction of migratory bats, as a result of which they would be likely to reach this side of the wind farm first. This seems a potential area for further investigation to understand the impact of site design upon fatality rates.

1.7 Bats' flight heights

Limpens et al. (2013) recorded activity at ground height that was on average 15-20 times higher than at hub height during monitoring at five wind farms in the Netherlands. They also observed a correlation between activity rates at ground and hub height. During monitoring at a wind farm in Eastern Tennessee, significantly higher levels of activity were recorded at ground height than at hub height (70m), however no significant difference was found between activity levels at ground and 15m heights (Fielder, 2004). This indicates that whilst prediction of hub height activity from ground level results may be restricted at large turbines, such prediction may be viable for small turbines.

Patterns of activity between flight heights may vary between species. Baerwald and Barclay (2009) found that *L. cinereus* and *L. noctivagans* exhibited contrasting levels of activity at different heights at operating wind farms. The former was more commonly detected at a height of 30m, whilst the latter showed a preference for flight near ground level. In a similar study using the same heights for recording, Collins and Jones (2009) identified that *Pipistrellus* species were significantly more likely to fly near to ground level, whilst *Nyctalus/Eptesicus* species were recorded more often at 30m height (though the latter finding was not statistically significant).

During a North American study, calls from bats with low echolocation frequencies (<35 kHz) (i.e. those of a similar morphology and ecological niche to *Nyctalus/Eptesicus*; physically large, associated with flight in open areas and at greater heights) comprised an increasing proportion of recorded calls with increases in detector height (49.2%, 83.6% and 98.5% of calls at 2m, 22m and 52m heights, respectively) (Weller and Baldwin, 2012). Different flight heights were also observed for species with echolocation frequencies greater or lesser than 35 kHz at another North American wind farm (Arnett et al. 2007a). The evidence shows that recording exclusively at ground level is likely to produce misleading results at large turbines, both in relation to volume of calls and species composition, as has been previously recognised during ground level monitoring (e.g. Jain et al. 2011). The same conclusion was reached during monitoring at wind farms in the UK (University of Exeter, unpublished research).

Baerwald and Barclay (2009) suggest future research in this area should encompass larger sample sizes, a variety of habitat types and species compositions. Furthermore they recommend that bat activity is monitored at consistent heights (>=30 m for large turbines) to enable comparison between studies. Where migratory bat species are concerned, differences in flight heights between migratory seasons should also be considered, as observed by (Furmankiewicz and Kucharska, 2009).

1.8 Turbine sound and electromagnetic emissions

The emission of ultrasound and other noise by turbines has given rise to suggestions of bats being attracted to these environmental conditions. Research on turbine noise emissions regarding bats – and indeed birds – is limited. Szewczak and Arnett (2006) measured ultrasonic turbine emissions at ground level (34m below rotors) and found that only minor noise was emitted above ambient levels, with emissions decreasing as sound frequency increased. A different result may nevertheless have been obtained if ultrasound was sampled at nacelle height. Furthermore, data from this study was only collected at one model of turbine. Our perception of large and small ultrasound levels are also taken from a human perspective, which could vary from the amplitude discrepancies of importance to bats.

1.8.1 Ultrasound emissions from anemometers

During a small-scale experiment measuring the effect of ultrasound emissions from anemometers installed on wind turbines (at approximately 38 kHz – within the frequency range utilised by the bat species using the sites), Kerns et al. (2005) recorded marginally lower fatalities at turbines with anemometers disabled, however this difference was not found to be significant. Some high frequency noise can also be created at blade tips (Twidell, 2003) and from blade defects (Dooling, 2002), the latter of which may help birds avoid turbine blades (Dooling, 2002).

1.8.2 Ultrasound deterrents

Mixed results have been observed from the use of acoustic ultrasound bat deterrents in a laboratory setting, at turbines and at a pond field test site (Spanjer, 2006; Szewczak and Arnett, 2008; Johnson et al. 2012; Arnett et al. 2013a). Some success was achieved in reducing bat activity over small distances suggesting ultrasound may deter rather than attract bats. Attenuation of the ultrasound over larger distances and during humid conditions limited the effect of the deterrent. The nature of any ultrasound emissions (e.g. higher vs. lower frequencies or constant vs. modulated frequencies) could contribute to the effect of the noise.

1.8.3 Ultrasound frequencies

Bats have been found to adjust echolocation characteristics when the frequency band of interfering ultrasound is the same or similar to their own echolocation (Gillam and McCracken, 2007; Gillam et al. 2007; Bates et al. 2008). Therefore investigations into ultrasound emissions impacts at turbine sites should consider frequency variations. Additionally, bats' ability to successfully navigate blades could be impeded by turbine noise emissions, taking into account evidence that they struggle to process multiple streams of acoustic input (Barber et al. 2003).

1.8.4 Electromagnetic fields

It has been hypothesised that the production of electromagnetic fields around turbine nacelles may disrupt bats' navigational abilities (Kunz et al. 2007a), however this has received little research attention. Some indication may be given by previous bat activity monitoring around active radar installations and from the use of radar technology as a bat deterrent at turbines, where activity was reduced in both situations (Nicholls and Racey, 2007; Nicholls and Racey, 2009). However the level of similarity between electromagnetic fields created by radar technology and turbine nacelles is not known, therefore this is a subject requiring further research.

1.9 Visibility of turbines to bats, including turbine lighting

1.9.1 Moon illumination

Higher fraction of moon illumination was identified as a significant variable correlating with high fatalities by Baerwald and Barclay (2011), supporting the hypothesis of bat attraction to turbines due to increased visibility. Moon illumination was also found to be important for predicting bat activity (Weller and Baldwin, 2012). Bats were also more frequently observed at turbines during moonlit nights by Cryan et al. (2014). However evidence from Cryan and Brown’s (2007) study causes uncertainty, finding higher migratory bat activity during dark phases of the moon and higher levels of cloud cover. Moonlight has also been found to have a negative impact (Ciechanowski et al. 2007) or lack of any effect (Scanlon and Petit, 2008) upon bat activity levels in other, non-turbine environments and minimal effect at a wind farm site (Gorresen et al. 2015). Cryan and Brown’s (2007) study was however focused upon migratory activity and was not undertaken at a wind energy site, therefore if bats are attracted to turbines to forage, these different behavioural activities may relate to varying environmental conditions.

Individual bat species are known to display differing responses to lighting, including attraction to, avoidance of and indifference to lighting (Rydell, 2006; Scanlon and Petit, 2008; Polak et al. 2011; Stone et al. 2012).The effect of moon illumination may therefore vary by species. Different nocturnal insect groups have furthermore similarly been found to display contrasting positive and negative associations with moonlight (Bidlingmayer, 1964, Anthony et al. 1981) which could influence bat activity and fatality levels.

1.9.2 Aviation safety lighting

The attraction of bats to aviation safety lighting on turbine nacelles has been investigated. Kerns et al. (2005) found no difference in bat fatality levels between lit and unlit turbines during monitoring at two wind farms in the USA, despite insect levels being higher at lit turbines. Investigations at a range of other sites (including Johnson et al. (2003a), Johnson et al. (2004), Kerlinger et al. (2006), Fiedler et al. (2007) and Horn et al. (2008a) (all in the USA) and Baerwald and Barclay (2011) (in Canada)) have shown the same lack of impact from lighting at wind farm sites. Horn et al. (2008a) found a non-significant difference in bat foraging flight activity between lit and unlit turbines (slightly higher at lit turbines). Complementary research considering the effect of varying lighting types (e.g. blinking white beacons and non-blinking red beacons) has also indicated little effect on fatality or activity levels (Jain et al. 2011). These studies show a general lack of effect from lighting upon bat impacts at wind turbines.

Whilst a later study in Texas found a significant difference in fatality numbers between lit and unlit turbines, fatality numbers were lower at the lit turbine; supporting the continued use of aviation lighting (Bennett and Hale, 2014). Furthermore the difference was statistically driven by a single species (eastern red bats - *Lasiurus borealis*) and no effect was identified for the five other species present, suggesting a more generalisable pattern of no effect.

1.10 Detection of turbines by bats and orientation of turbines vs. bat flight direction

The form of echolocation reflections from turbines and the relative orientation of turbine blades vs. bat flight direction may affect bats’ ability to detect blades. The process of reflection has been experimentally modelled in a laboratory environment by Long et al. (2009), who found that ultrasonic pulses reflected from a mini-turbine (blade-diameter 0.91m) featured a high level of scattering. Only a small percentage of the input pulse energy was returned over a short distance, following reflection. Returned echoes were particularly low when facing the turbine blade edge from a lateral direction (i.e. in line with the blades, rather than viewing the face of the blades). Frequency shifts have also been identified in reflected pulses at different angles to the blades, which along with low simulated numbers of echoes may lead to poor or late blade detection (Long et al. 2010). Some echo features were also found to have the potential to attract bats. Such results may suggest bats could struggle to locate and avoid turbine blades. Long et al. (2009) do however highlight that it is possible that bats may naturally receive low proportions of energy from original echolocation pulses (and are therefore potentially adapted to such circumstances) and that the results may not translate to larger turbines.

Evidence is available from monitoring at wind energy sites to assess detection of turbines and direction of approach. Bats have been witnessed investigating both moving and non-moving turbine blades as well as turbine masts, during TIR monitoring (Horn et al. 2008a). The behaviour included bats carrying out multiple ‘check’ passes on the same part of a turbine, as known to occur during a bat’s approach to a roost (linking to the roost-finding hypothesis discussed above), suggesting they are able to detect the structures. Active avoidance of moving blades during flight in proximity to blades has also been observed (Brinkmann et al. 2006; Horn et al. 2008a), supporting this hypothesis. On the basis of field acoustic and radar monitoring, Millikin (2009) (*op. cit* Jones et al. 2009a) proposes that bats do use echolocation around turbine blades, however that they use last minute avoidance behaviour close to blades, suggesting short detection distances.

A study using thermal imaging suggested bats can detect or investigate the presence of turbines through recognition of changes in airflow when flying downwind of a turbine (Cryan et al. 2014). The proportion of bats approaching the monitored turbines on their downwind side increased with wind speed when blades were put on brake (i.e. not turning) but decreased when blades were turning. This variation in activity was suggested to be a result of avoidance of complex turbulent air conditions created downwind of moving blades (Cryan et al. 2014). Bach and Rahmel (2004) provide further evidence that bats can detect turbine blades, identifying straight flight at consistent heights when flying parallel to turbine blade orientations, but flights dipping below the height of the nearest blade edge when flying at right angles to blade orientation (see Figure 1.3).

1.10.1 Small turbines and/or sites with low numbers of turbines

Though research at small turbines is very limited, bat activity has been observed to reduce by a greater amount in close proximity to turbines during increases in wind speed relative to locations further from turbines (Minderman et al. 2012). The reduction is also therefore associated with increases in blade rotation speed; bird density has similarly been found to be negatively associated with blade rotation speed (Leddy et al. 1999). It is possible that the faster blade rotation speed of small turbines may effectively create a perception of a semi-solid circular surface to bats, which could increase detection rates in contrast to the less frequent blade rotation cycles of medium and large turbines.

1.11 Non-fatal and behavioural impacts

Bats have been found to investigate wind turbines (Brinkmann et al. 2006; Horn et al. 2008a; Ahlén et al. 2009) as well as to use them for foraging sites (Ahlén, 2002; Ahlén et al. 2009; Behr and Helversen, 2005 (referenced in Brinkmann et al. (2006)); Horn et al. (2008a); Rydell et al. 2010a) and roosts (Ahlén et al. 2009; Hensen, 2004). Such activity shows that the installation of wind turbines has the potential to cause deviation from bats' historical use of the habitat.

Few studies have directly investigated non-fatal disturbance to bats and habitat loss from turbine development. Turbine placement within forested openings and the production of cut edges may alter bat habitat and introduce spatial conflict (Kerns et al. 2005). Bat abundance in proximity to forested areas can increase following the creation of 'cutblocks' due to reductions in habitat clutter (Grindal and Brigham, 1998), however this must be weighed against risk to bats.

Woodland-dwelling species such as *Myotis myotis* (greater mouse-eared bat), *Myotis bechsteinii* (Bechstein's bat) and *Myotis nattereri* (Natterer's bat) could potentially be affected by woodland clearance for turbines (Bach and Rahmel, 2004). This approach is often used to reduce both wind turbulence in proximity to turbines and habitat suitability for bats, to avoid conflict.

The previously described drop in bat activity in close proximity to turbines during increases in wind speed/blade rotation speed (Minderman et al. 2012) suggests disturbance may occur at small wind turbine sites.

The construction of a wind farm in Germany appeared to cause displacement, reducing numbers of *Eptesicus serotinus* (Serotine bat) present over a 5 year period (Bach and Rahmel, 2004). In contrast, *Pipistrellus pipistrellus* (common pipistrelle) numbers increased, perhaps attracted by the turbines. However their spatial distribution was altered, appearing to become more excluded from the wind farm’s interior and concentrating along its edge (Figures A.1 and A.2 - see *Appendices*). Foraging activity of Serotine bats along hedge lines within 50m of the turbines dropped over 3 years (whilst increasing at control, non-turbine hedges). Meanwhile common pipistrelle activity increased; flight heights of the latter along hedges furthermore changed with varying proximity to turbine blade tips (Figure 1.3). Avoidance behaviour by *Nyctalus noctula* (Noctule) and Serotine bats was also observed near a different, 9-turbine wind farm (Bach and Rahmel, 2004). Jain et al. (2011), meanwhile, found no difference in activity between turbine sites and non-turbine control sites, suggesting a lack of disturbance.

Whilst little research concerning non-fatal impacts of turbines upon bats has been completed, studies of this nature regarding birds exist. Results from bird-focused studies may provide transferable disturbance hypotheses and suggest likely impacts. Strickland et al. (2011) provide a review of research into wind energy impacts upon birds, from which the key material and categories in Table A.3 (see *Appendices)* are quoted, along with other reference material. Transferable outcomes for bats are interpreted in the final table column.

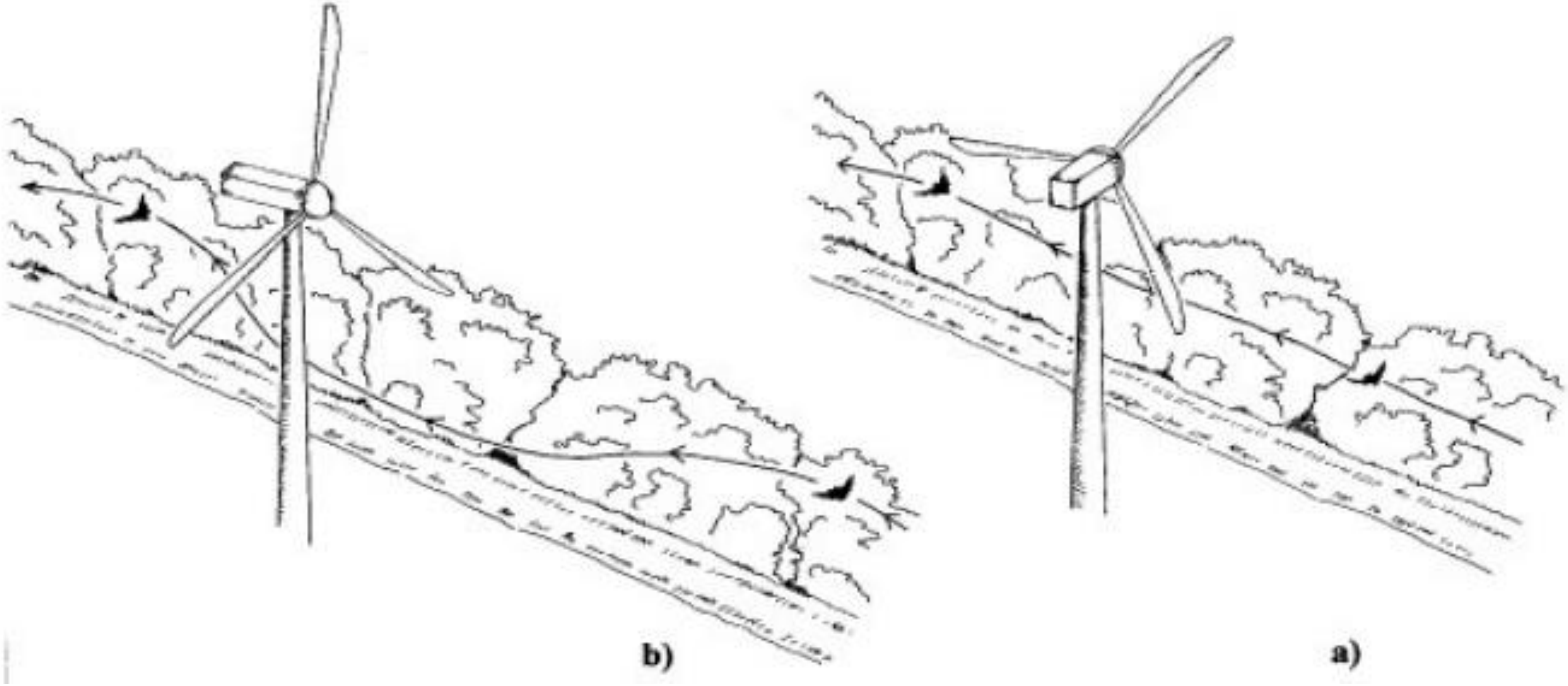

Figure 1.3: “Changes in behaviour of *Pipistrellus pipistrellus* in direct vicinity of rotating blades: a) blades rotate parallel to bat flight path, b) blades rotate across the flight path” (from Bach and Rahmel, 2004)

1.12 Population-level impacts

Threats to bat populations include climate change, disease, habitat fragmentation (including from anthropogenic development), intensive agriculture and intentional killing for food or pest reasons (Harris et al. 1995; Haysom et al. 2013; O’Shea et al. 2016). Climate change and habitat loss are highlighted as the factors most likely to proportionally increase in contribution to multiple mortality event (MME) levels in the near future (O’Shea et al. 2016). However, the largest sources of MME’s since the year 2000 were wind energy installations and the white nose syndrome (WNS) disease (O’Shea et al. 2016).

There is a general consensus that impacts upon bats from wind turbines have the potential for effects at a population level (Kunz et al. 2007a; Kunz et al. 2007b; Arnett et al. 2008; Erickson et al. 2002; O’Shea et al. 2016; Arnett et al. 2016). Bats are vulnerable to disruptions to populations as a result of low reproductive rates (Kunz et al. 2007a; Jones et al. 2009b; Barclay and Harder, 2003; Barclay et al. 2004). Therefore if turbine mortality rates are high, populations may be likely to decline and could take a long time to recover from losses (Erickson et al. 2002; Humphrey and Cope 1976; Jones et al. 2009b). Bats are also sensitive to disturbance in their habitats and roosting sites (Jones et al. 2009b) therefore impacts are not just limited to direct mortality. Population size patterns do not just rely on existing population sizes; rates of mortality, reproduction, immigration and emigration will all contribute to fluctuations in population (Strickland et al. 2011).

Some studies have indicated that rates of survival of adult bats are more important for population endurance than rates of juvenile survival (Schorcht et al. 2009; O’Shea et al. 2011) therefore any bias in mortality rates between ages of bats may have disproportionate levels of population impact. Small populations may not have the genetic diversity to survive losses (Strickland et al. 2011; Pylant et al. 2016).

1.12.1 Species vulnerability

Risk to populations of individual species is considered to vary due to factors such as population size and genetic diversity as well as choice of preferred habitat, life history and behavioural characteristics (Kunz et al. 2007b; Natural England 2014; Pylant et al. 2016). For example red bat populations in the USA are considered more likely to be resilient to impacts from turbines than hoary bats (Pylant et al. 2016).There are some fears that individual species may not be able to survive projected turbine-related fatalities (Kunz et al. 2007a). Table 1.4 shows the population risk levels estimated for bat species present in the UK (recreated from Natural England (2014)).

Populations of migratory and tree-roosting bats may be at particular risk (Kunz et al. 2007a; Arnett et al. 2008; Strickland et al. 2011; Cryan 2008; Baerwald and Barclay, 2009) and individual wind farm or turbine sites in this context have the potential to impart population impacts over a wide geographical area if placed along key migration routes (Baerwald et al. 2014; Lehnert et al. 2014). It has been suggested that animals that migrate often have a higher vulnerability to extinction than non-migratory species (Pimm et al. 1988); this concern is exacerbated if pregnant migrating bats are killed (Voigt et al. 2015).

1.12.2 Indirect effects

Potential risks to populations are not just from direct turbine fatalities, but include indirect effects of wind turbine (and other) developments such as habitat disruption or removal, alteration of prey levels, roost damage or removal, presence of humans and behavioural impacts (Kunz et al. 2007a; Kunz et al. 2007b). It has been suggested that the consequences of wildlife displacement upon breeding success and survival are critical for deciding outcome population effects (Drewitt and Langston, 2006).

1.12.3 Cumulative impacts

Cumulative impacts upon populations will increasingly become a concern in areas featuring rapid expansion of wind energy installations (Strickland et al. 2011). The assessment of cumulative impact is often over-simplified (Arnett et al. 2013b; Roscioni et al. 2013; Valenca and Bernard, 2015). This topic is further complicated by variable definitions of what comprises cumulative impact. For example Strickland et al. (2011) noted that US federal law and regulations and academic/reference sources provide differing definitions. Equally there is no guarantee that similar definitions are used in other countries. Other outstanding areas for clarification include the time period and geographical area over which cumulative impacts should be measured.

Cumulative impact may even occur within a single wind farm over time as it expands from future extensions or repowering (Strickland et al. 2011). As turbine sizes increase over time at wind farm developments, it may also not be appropriate to generalise population effects from older installations to newly proposed sites (Strickland et al. 2011). The spatial pattern of wind farm sites should also be considered – multiple turbine sites placed along bat migration routes may have disproportionately large cumulative impacts (Baerwald et al. 2014).

A number of estimations of cumulative mortality totals from turbines have been calculated. Two different models were applied by Kunz et al. (2007a) to estimate annual mortality by the year 2020 for the Mid-Atlantic Highlands region of the USA, projecting fatalities will total 33,000-111,000 bats. Projected annual fatalities (at 2020) of migratory tree roosting bat species were estimated at 9,500-32,000 hoary bats, 11,500-38,000 eastern red bats and 1,500-6,000 silver-haired bats. A later study by Arnett and Baerwald (2013) calculated cumulative fatalities in the USA for the 2000-2012 period of between 0.8 and 1.7 million bats, with considerable variability between regions. Wind turbine numbers were found to increase substantially over this period and therefore future impacts are likely to increase further.

Fewer information sources are available in Europe, however a review of data from EUROBATS reporting (Rodrigues et al. 2014) estimated 5,626 fatalities across 18 countries, a figure considered likely to represent only a small portion of actual fatalities across that region (O’Shea et al. 2016). The majority of fatality reporting is from Germany, Spain, France and Portugal (Rodrigues et al. 2014).

In Germany, 10-12 bat fatalities turbine^{-1} year^{-1} are estimated at turbines with a lack of mitigation measures (Brinkmann et al. 2011). When extrapolated to all turbines in Germany at the time of publishing (assuming no mitigation), this represented 200,000 fatalities a year (or 6-8 bats per MW of production capacity) (Voigt et al. 2015). The only study currently available that considers cumulative fatalities at small wind turbines produced an estimate of 161-3,363 bat fatalities per year in the UK (Minderman et al. 2015). The input fatality data was however sourced from a small sample and was based on human searches for bats (an approach known to feature very low chances of observing carcasses (Arnett 2006; Mathews et al. 2013)) and turbine owner questionnaires.

Previous research regarding birds has largely found a lack of population impacts, even when taking into account collision mortality and non-fatal disturbance and displacement (Hunt, 2002; Drewitt and Langston, 2006; American Wind Wildlife Institute, 2015; Schuster et al. 2015).

1.12.4 Global population impacts

It is important to consider species' population distributions without imposing the restrictions of human-defined political boundaries (Arnett et al. 2013b). Whilst fluctuations of 'rare' bat populations within the UK may be of concern from a national perspective, such fluctuations may comprise insignificant changes to a larger main population at a sub-continental scale (Harris et al 1995). Conversely, assessing population impacts just within one country, state or local authority area may be hazardous if cumulative impact across a number of these areas critically affects a wider population status (Arnett et al. 2013b; Arnett et al. 2016). Centralised governmental regulation and/or policy may therefore be required in order to avoid variable local practice (Arnett et al. 2016).

1.12.5 Population data

No conclusive studies have been completed to confirm whether bats are being impacted by wind turbines at a population level (Voigt et al. 2015) and our ability to identify such impacts is very limited using existing data (Erickson et al. 2002; Strickland et al. 2011; Aronson et al. 2013; Arnett et al. 2016); this limitation is true of the UK (Jones et al. 2009a; Natural England, 2014). It is very difficult to carry out a risk assessment of effects on a species without a baseline population estimate (Kunz et al. 2007a; Kunz et al. 2007b; Strickland et al. 2011; Arnett et al. 2013b; Baerwald et al. 2014; Arnett et al. 2016) and ideally measures of genetic diversity and population structure (Kunz et al. 2007b). Furthermore long term monitoring of populations under pressure from external factors such as wind turbines is needed to understand species' ability to recover from population perturbations (Kunz et al. 2007b; Strickland et al. 2011). Some encouragement can be taken from recent reviews of research regarding wind energy impacts on wildlife, finding many bird species' populations are unlikely to decline from current fatality rate estimations (American Wind Wildlife Institute, 2015; Schuster et al. 2015).

1.12.6 Observed UK bat population trends

The UK NBMP has identified a statistically significant increase in populations of five bat species between 1997 and 2013, in addition to recording stable population trends for a further five species (Bat Conservation Trust, 2014; Barlow et al. 2015). The population trend estimates produced by the NBMP as at 2013 are shown in Table A.4 (see *Appendices*). The temporal period over which we consider population changes is important, as the positive trends highlighted are considered to be in contrast to a previous longer term decline in populations (Bat Conservation Trust, 2014).

1.12.7 Observed European-level bat population trends

Monitoring at the European level (through collation of national results) to create a continental-scale population indicator measure, has shown an overall increase in bat numbers of 43% between 1993 and 2011 and relative stability since 2003. At a species level, positive population trends have been observed for nine species. One species (*Plecotus austriacus*) has experienced a significant decline and no trends were available for 2 species (Haysom et al. 2013; Van der Meij et al. 2015).

1.12.8 External influences on observed population trends

Wider local or regional impacts on populations, for example from changes in agriculture, may explain fluctuations in populations observed at wind energy sites. A similar pattern has been observed with regard to birds in Kansas, where vegetation burning and heavy cattle stocking accounted for bird population changes at a wind energy site and in separate nearby areas (Strickland et al. 2011).

1.12.9 Lag times for population impacts

A lag time may exist in observable population impacts, as has been suggested from monitoring studies of the impacts of oil and gas facilities on birds. These studies found lag times of 2-10 years before such population impacts became apparent (Strickland et al. 2011). Furthermore we currently have no knowledge of bats' ability to habituate or acclimatise to the presence of wind energy sites (mixed responses by bird species are discussed by Strickland et al. (2011)). Consequentially there is a possibility that fatality rates may peak before falling if they are able to acclimatise.

In order to identify time-lagged impacts or acclimatisation to turbines by wildlife, long-term monitoring programmes are required at wind energy sites. This produces large expenditure demand which may not be feasible within the constraints of a single wind farm development (Strickland et al. 2011; Jones et al. 2009a). Modelling of likely cumulative impacts upon populations, followed by field validation of predicted model outcomes, may reduce monitoring demand and costs (Strickland et al. 2011).

1.13 Mitigation

1.13.1 Turbine curtailment

Mitigation of wind turbines' impacts upon bats may be possible by curtailing operational turbines using increased cut-in speeds and shut downs during high risk periods (Arnett et al. 2013a). A range of studies in North America have observed large reductions in bat fatalities during curtailed periods at operational wind farms, using both increased cut-in speeds and feathering of turbine blades during low wind speed conditions (Baerwald et al. 2009; Arnett et al. 2011; Arnett et al. 2013a; Hein et al. 2013; Hein et al. 2014). Increases of cut-in speeds by 1.5m/s have been found to reduce fatalities by 50% at a number of sites (Arnett et al. 2013a). Mortality has even been observed to reduce by up to 93% using increased cut-in speeds (Arnett et al. 2011). Operational curtailment could also be improved using advanced turbine-control algorithms that only apply planned curtailment periods during weather conditions representing a high risk of bat presence.

1.13.2 Fatality trigger thresholds

Some statutory authorities have proposed the use of bat fatality trigger thresholds before turbine curtailment is required (Arnett et al. 2013b). The definition of fatality trigger thresholds is however often based upon inadequate monitoring data or flawed assumptions regarding bat population sizes (Strickland et al. 2011; Arnett et al. 2013b). Additionally the use of trigger thresholds does not align well with conservation legislation, which prohibits the killing of individual bats (Voigt et al. 2015). With increasing numbers of turbines being planned, per-turbine fatality allowances may become unsustainable, particularly concerning small populations (Voigt et al. 2015, Arnett et al. 2013b). Set trigger thresholds also assume stable bat population sizes. This assumption seems questionable in the context of the fluctuating population trend estimates that have been recorded for some species (Haysom et al. 2013; Van der Meij et al. 2015). The thresholds also do not account for unknown future trends in other population threats such as white nose syndrome and wider habitat loss (Arnett et al. 2013b). The latter publication emphasizes an example of a location with high bat mortalities (Pennsylvania, USA), where trigger thresholds may never be reached if bat populations are already declining and therefore rates of mortality remain small but continual until populations are expended.

1.13.3 Turbine placement

Improvement of turbine placement is a simple pre-construction mitigation measure. A study of the suitability of landscape-scale habitats for bats and placement of wind farms within a region of Italy found that the 41% of the landscape that was theoretically suitable for bats featured over 50% of recorded wind farms (Roscioni et al. 2013). A follow on study identified that the wind farm locations were likely to intersect probable movement corridors within the habitat areas (Roscioni et al. 2014). These studies provide an indication of the potential for cumulative impacts and suggest there may be opportunities for minor re-location of proposed sites to mitigate this. Guidance concerning bat conservation in England and Europe already recommends placement of turbines away from habitat of value to bats (Natural England, 2014; Rodrigues et al. 2015).

1.13.4 Bat deterrents

Acoustic bat deterrents have been applied at a number of wind farms to test their effectiveness in reducing bat activity near turbine blades and therefore fatality levels. Initial laboratory-based experiments indicated bats' showed an aversion to the emission of ultrasonic noise (Spanjer, 2006). Later field tests of acoustic, ultrasound emitting deterrents at wind energy sites in the USA, however, illustrated limitations in the spatial noise envelope created. Coverage of the turbine blade swept area was not achieved, limiting the deterrent of bats (Horn et al. 2008b; Arnett et al. 2013a). The effective range of one such device was estimated to be 12-15m; however reductions in activity within this range to 2.5-10.4% of that observed during control periods indicated the potential of such devices (Szewczak and Arnett, 2008). Lower effect levels were however recorded in a later test study at pond sites, achieving only a 17.1% reduction in activity (Johnson et al. 2012). As ultrasound is known to attenuate quickly across air volumes particularly at high frequencies (Griffin, 1971; Lawrence and Simmons, 1982), projecting ultrasonic emissions from a device across large areas may present a technical challenge, particularly in high wind conditions at wind farms' hub heights. Humidity levels have also been found to moderate signal propagation (Arnett et al. 2013a).

Radar signals have furthermore been found to reduce bat activity, in particular those with electromagnetic field strengths of >2 volts/meter; the process causing bats to be repelled may be thermal induction and resulting hyperthermia (Nicholls and Racey, 2007; Nicholls and Racey, 2009). The narrow directional beams used to produce suitably high field strengths however limit the spatial envelope of the deterrent effect (Nicholls and Racey, 2009).

1.13.5 Habitat management

A mitigation topic that has received little research attention is habitat management. A single field-based study has investigated the use of compensation measures at wind farm sites in agricultural landscapes, including fallows, hedgerows, bushes and grass strips. Variable, season-dependant responses to the compensation measures were observed from different bat species groups. The study suggested further research was required to define appropriate habitat management approaches (Millon et al. 2015). A range of theoretical habitat management strategies has furthermore been proposed to mitigate impacts upon bats from wind farms. These include management of autochthonous forests, diversification of forest and agriculture monocultures, preservation of existing roosts, provision of new roosts and creation of ponds (Peste et al. 2015).

1.13.6 Conservation policy

Policy-based conservation efforts at a national and continental scale are also important. The positive provisional bat population trends recorded in Europe are suggested to have been the product of conservation legislation, designations to protect species and sites and improved awareness of bats. These factors have resulted from conservation agreements such as the EUROBATS programme (Haysom et al. 2013). It has been suggested that targets for further improvement should include the expansion of monitoring programmes to countries where results are scarce (Haysom et al. 2013). European Union (EU) member states under current legislation are required to make efforts to restore or maintain bat populations at a favourable conservation status (Arnett et al. 2016). The application of this legislation at the level of a single wind energy site, however, appears to be poorly understood. Additionally, the question of whether active regulation should focus upon individual fatalities or wider population impacts also remains unanswered (Voigt et al. 2015; Arnett et al. 2016).

A limited knowledge of bat population sizes and mortality rates from wind turbines has restricted UK efforts to assess the risk of turbine impacts on bats (Natural England 2014; Arnett et al. 2016). Improved monitoring and reporting together with clear planning practice for wind turbines is therefore crucial in mitigating impacts upon bats at a local site level (Park et al. 2013).

1.14 Thesis Objectives

Following this chapter's review of the existing research and literature context regarding the impacts of wind turbines upon bats, the objectives of this thesis have been identified. They are to:

1. Identify the locations of planned wind turbines within Wales and south-west England, including all wind turbine sizes and historical records. Using the collated wind turbine data, identify whether wind turbines have any impact (both individually and cumulatively) upon local bat roost populations

2. Quantify the rate of bat fatalities at small and medium wind turbines and identify whether the wind turbines cause disturbance of bat activity in their immediate proximity. Furthermore investigate whether any environmental factors moderate bat activity levels at small and medium wind turbine sites

3. Investigate bats' spatial movements in proximity to small and medium wind turbines and identify bats' use of habitat structures at the turbine sites

4. Evaluate an outstanding hypothesis proposing that bats’ are attracted to wind turbines’ noise emissions. Furthermore identify whether wind turbine noise has any negative impact upon bat activity levels

At a wider level, this thesis aims to provide research evidence to support the production of updated small and medium wind turbine planning guidance in relation to bats.

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1.16 General methods

The chosen study area was Wales and the south west (SW) region of England – areas with relatively large, species-diverse populations of bats (Bat Conservation Trust, no date). Potential study sites were identified from wind turbine planning applications. Sites with no more than three installed turbines were selected, with a total height to blade tip <100m. Each turbine was required to be mounted on a standalone mast (not building-mounted) and to have a horizontal axis (see Chapter 3, Figure 3.1). Differing numbers of blades were acceptable. If multiple turbines were installed at a site, only one was monitored; selection was random unless constrained by access. The distribution of the sites across the regions' planning authorities is shown in Figure 1.4.

RenewableUK's height to blade tip criteria (RenewableUK, 2013) classifies wind turbines into the following size categories: micro: 10-15m; small: 15-30m; medium: 30-55m; large: ≥55m. An additional category was added for this thesis to account for very small turbines: sub-micro: ≤10m.

The monitored turbines fell into the following size categories: sub-micro (3); micro (7); small (13); medium (5); and large (3). It was felt beneficial to include the three large individual wind turbines within the sample as an associated wind farms partner project included only sites with at least five turbines. Furthermore whilst technically classified as large, none of the three turbines' blade tips exceeded 100m and therefore by modern wind farms' standards were relatively moderate in size.

The monitored turbines featured a mean blade tip height of 26m (std. dev. = 18m), a mean height to hub of 19m (std. dev. = 12m), a mean blade diameter of 14m (std. dev. = 12m) and a mean power rating of 77kw (median = 11kw; std. dev. = 154kw). 24 of the turbines had 3 blades, 6 had 2 and one had more than 3. A mean of 4 years (std. dev. = 3 years) had passed between the turbines gaining planning permission and the onset of monitoring (i.e. a relative measure of turbine installation length).

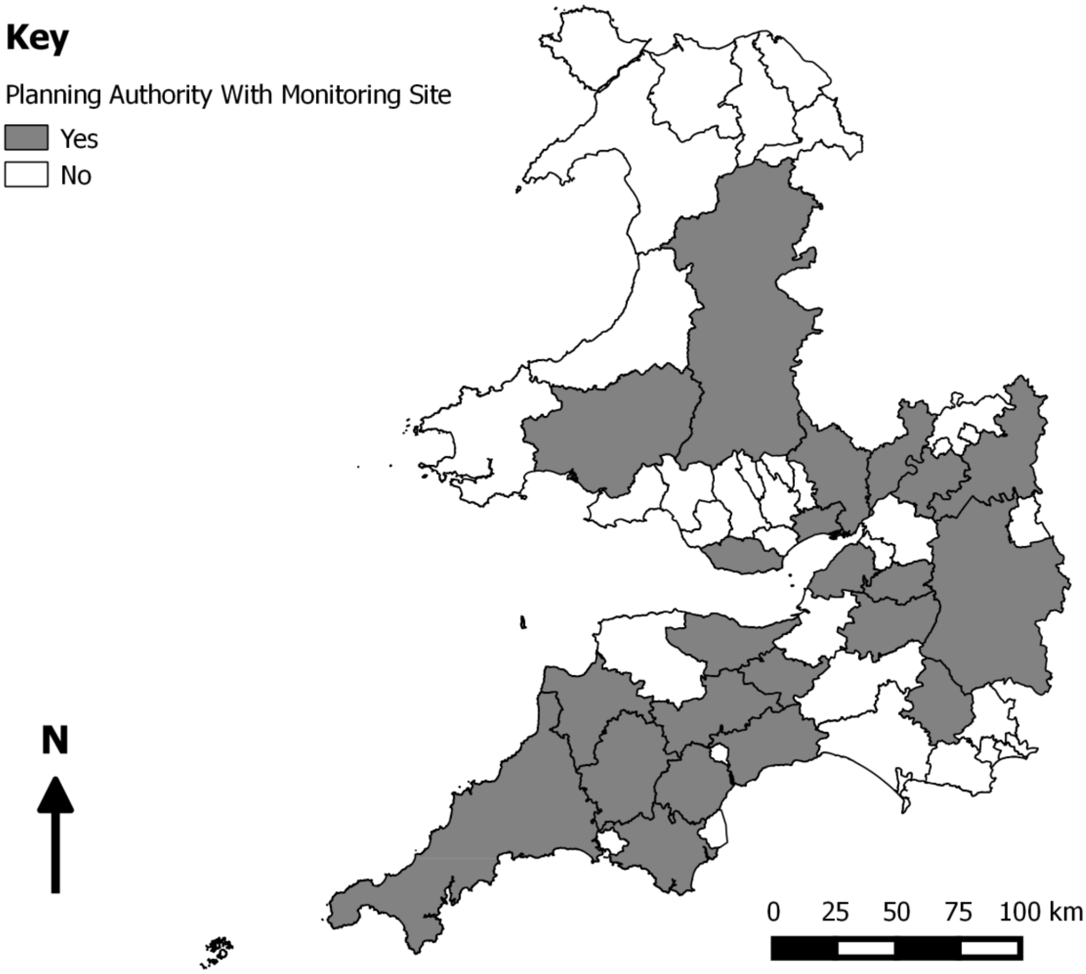

Figure1.4: The distribution of the 31 monitored wind turbines sites across Wales and SW England

The site types within which the turbines were installed were as follows: domestic garden (5); domestic agricultural small-holding (7); arable farmland (4); pasture farmland (11); mixed use farmland (4). Field monitoring was carried out during May-October in 2012 (13 sites) and 2013 (14 sites) and June-July in 2014 (4 sites), with monitoring taking place concurrently at groups of 2-4 sites at a time. Monitoring was planned for 4 weeks at each site with 5 visits per site.

Bat carcass searches were conducted at approximately equal intervals (5 at each site during 2012 and 2014, 3 during 2013) using a professionally-trained sniffer search dog (trained specifically for bat carcass searches) and handler (Figure 1.5). The handler worked the dog along parallel 100m transects spaced approximately 5-10m apart (depending upon habitat density), traversing a 100x100m square centred upon the turbine. The dog was allowed to deviate from these transects in order to follow scents and then was subsequently returned to the last point reached along the transect, before continuing.

Figure 1.5: Search dog and handler carrying out a carcass search

A search efficiency trial with methods following Mathews et al. (2013) was conducted at most sites (25/31) to assess the dog and handler’s search performance. In addition, rates of carcass removal by predators were estimated by monitoring, at each visit, whether 3-5 bat carcasses remained where they had been placed on the first monitoring day, within a 100x100m area.

Nine tripod-mounted Batbox Baton frequency division bat detectors linked to Zoom H2n audio-recorders and external batteries were planned to be installed at each site, in a 3x3 grid centred on the turbine, with each detector being

33.3m apart (see Figure 1.6) and installed on a 1.5m tripod. One Wildlife Acoustics Song Meter 2 (SM2) full spectrum bat detector (also powered by an external battery) was installed with its microphone attached to a 2.5m tripod at the base of the turbine. Finally a weather station was installed on a 1.5m tripod, located in open space to reduce wind shading or turbulence due to vegetation and buildings. Detectors' external battery levels, use of recording storage capacities and any damage to equipment were recorded during each site visit.

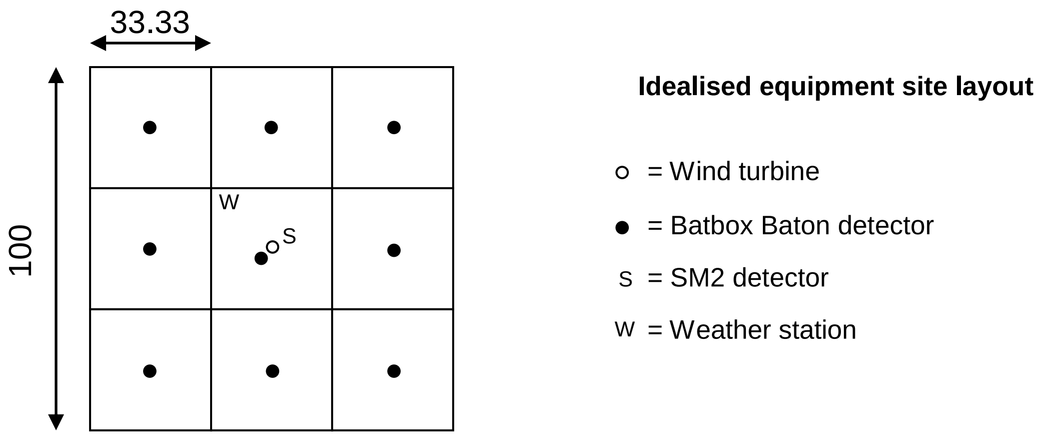

Figure 1.6: An idealised diagram of equipment layout at monitored wind turbine sites

1.17 References

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2 Wind energy and bat conservation on a regional scale

2.1 Abstract

Large scale increases in renewable energy generation are required in the UK and Europe to reach climate change and sustainable energy policy targets. The technologies used to generate renewable energy however also have the potential to cause other environmental impacts. This includes the fatality risk to bats from wind turbines. Thousands of fatalities have been documented across Europe and North America and initial reports show similar risk to bats across the globe. No study has considered the geographical spread of wind turbines across the UK and their potential for conflict with bats at a regional scale.

This study investigated the planning of wind turbines and wind farms in Wales and south west (SW) England and the potential resulting conflicts with bats. All sizes of turbines were considered, including micro rooftop turbines, farm and domestic scale single turbines and wind farms. A comprehensive database was developed identifying virtually all proposed wind turbine sites in Wales and SW England up to and including 2013. This represented a large improvement on current wind turbine databases for these regions. Wind turbine planning trends were analysed, producing an overview of turbines' spatial distributions, planning approval/refusal rates and sampled patterns of turbine size categories. The potential impacts of turbine presence and density on bat roost populations were explored using Generalised Linear Models (GLM), both for current roost population sizes and changes in roost populations over time. Consistently high numbers of planned turbines were observed in recent years, with a high proportion of sites comprising single turbines. No impacts of wind turbines upon bat roost populations were found. These initial exploratory analyses provide some reassurance that the impact of wind turbines on bat populations at regional scales may be limited. Further research is required to confirm this early indication. It is recommended that future research focuses upon long-term monitoring at roosts in close proximity to turbines, including direct observation of activity between the two features. Planning guidance regarding bats and small and medium turbines is highlighted as a priority for policy development.

2.2 Introduction

Wind energy production is increasing rapidly across the globe. Whilst contributing to reducing carbon emissions, wind turbines have the potential to impact upon components of the ecosystem, notably bats (Arnett et al. 2008; American Wind Wildlife Institute, 2014; Rydell et al. 2010). Bats are legally protected species across Europe, with those in EU states classified under the Habitats Directive. Planning guidance concerning bats has therefore been produced for onshore turbines in response to this risk in the UK and Europe (Natural England, 2014; Natural England et al. 2009; Rodrigues et al. 2015). A single UK study has considered planning policy for bats and small wind turbines (Park et al. 2013). This highlighted variations in the approaches taken by planning authorities whilst assessing turbine applications, partially due to a lack of a robust evidence base on their impacts. Information regarding the impact of turbines upon bats at a population level is also very limited (Arnett et al. 2016). Furthermore existing databases recording wind turbines do not provide adequate coverage of small and medium wind turbines. Without this information, our understanding of regional-scale impacts of turbines upon bats is limited.

This study aimed to reduce the knowledge gap in this area, by providing an investigation of the current state of wind turbine planning in two regions of the UK and identifying the impact of wind turbines in these regions upon local bat roost populations.

Attention is currently focused on understanding the scale of fatalities at wind turbine sites and identifying factors linked with local variations in risk (Arnett et al. 2008; Rydell et al. 2010; Baerwald and Barclay, 2011; Minderman et al. 2015). Furthermore initial investigations into bat behaviour at turbine sites and methods of impact mitigation have been undertaken (Horn et al. 2008; Ahlen et al. 2009; Minderman et al. 2012; Gorresen et al. 2015; Szewczak and Arnett, 2008; Johnson et al. 2012; Arnett et al. 2013). However, there has been no regional-scale assessment of the geographical spread of wind turbines and their potential conflict with bats. This is important due to the possibility of unmitigated cumulative impacts upon bats over large regions (Voigt et al. 2012). As local planning authorities are responsible only for development within their respective boundaries, cross-border impacts and wide-scale effects may go unnoticed (Arnett et al. 2013). Little information is currently available to planners to judge risk from cumulative impacts.

2.2.1 Study aims

By compiling wind turbine planning data from local authorities, this study provides an understanding of the current state and trends of turbine planning within selected regions of the UK featuring large and diverse bat populations. In doing so, an accurate estimate of total planned turbines is produced, including otherwise under-recorded small and medium turbines. The collected records are then used to investigate whether spatial distributions and numbers of turbines have any impact upon bat roost populations across wide areas. Furthermore the hypothesis that turbines may be preferentially proposed in environments which are coincidentally also of importance for bat roosting is tested. Variations in planning patterns and outcomes are considered for different sizes of turbine and the quality of current wind turbine databases is assessed against the compiled data from this investigation.

This study aimed to increase our ability to understand and plan for the distribution of wind turbines across regional scales and their potential for cumulative impacts upon bats.

2.3 Materials & methods

2.3.1 Study area and wind turbine planning applications

Wales and south west (SW) England (regions with large, species-diverse bat populations) were used as the study area. Wind turbine planning application records submitted up to the end of 2013 were collected from each planning authority in Wales and SW England, to identify the number of turbines of all sizes planned. These ranged from micro rooftop to large wind farm turbines. Both horizontal axis and vertical axis wind turbines were included and all planning outcomes were recorded i.e. approved, refused, withdrawn and pending. Records came from 64 Local Authorities, i.e. district and unitary council authorities (including 5 National Park planning authorities), represented by 67 planning search websites.

13 keywords were used to search planning proposal descriptions on the planning authorities’ websites for turbine applications. The use of a further 6 terms was explored, however these were not applied for all planning authorities after trials for subsets yielded negligible improvements in results (only 0.6% of records found). Table 2.1 presents the full keyword list and the proportion of authorities searched using the supplementary keywords.

48 of the 67 websites were able to be searched via database downloads, programming scripts or manual use of their planning search portals. For the remaining websites, turbine planning searches were requested from the planning authorities, with requests stipulating the use of the same keywords. Whilst some of these authorities did not rigorously apply the exact requested method, all provided the output from a turbine search. All records were manually checked and filtered to exclude irrelevant records found by keywords, e.g. those relating to ‘hydropower turbine’ proposals. The time-span covered by the digital archives varied between planning authorities and start years ranged from 1948-2010. 55 authorities (86%) had data available for a minimum of 10 consecutive years up to the end of 2013 and 61 (95%) provided at least 8 years of data. Those with the least years of data tended to represent small coastal authorities in areas with tourism-focused economies that would not be likely to feature many turbines, due to their often negatively-perceived visual impact (Tatchley et al. 2016).

To validate the coverage of the dataset and add any potentially missing records, as well as to consider any improvement achieved by the dataset relative to existing databases, the data was compared against 6 other turbine databases (see Table S2.1 in Supplementary Materials).

In order to carry out spatial analyses of turbine distributions and their proximity to bat roosts, individual-turbine installed or proposed coordinates were gathered for those sites with 3 or more turbines. Approximately half of the sites with 2 turbines were also processed (due to time constraints). Where data was readily available, exact coordinates were entered on an ad-hoc basis for single turbine sites. Overall, this provided British National Grid coordinates for 54.2% of all individual turbines planned (as opposed to a single coordinate per site for example at a wind farm). Postcode centroid coordinates were extracted from the remaining turbines' site addresses.

Table 2.1 Planning application search keywords used to find wind turbine records. 88% of the total records were found using search keywords, 12% were identified from existing wind turbine lists received direct from a planning authority, or records from other wind turbine databases. Search terms that could exist as 1 or 2 words (e.g. 'windfarm' or 'wind farm') were applied using both formats

Planning Applications Search Keyword	Percentage of records obtained using this keyword	Percentage of planning websites searched using keyword
turbine	95.2	100
generator	3.23	100
wind energy	0.08	100
wind farm	0.36	100
wind mast	0	100
electricity generation	0.04	100
renewable	0.04	100
wind power	0.08	100
energy generation	0	100
sustainable energy	0	100
mast	0.08	100
tower	0.16	100
rotor	0.12	100
wind charger	0.16	92.5
wind park	0.04	88.1
microgeneration	0.08	88.1
wind machine	0	85.1
windmill	0.32	70.1
windturbine	0.04	70.1

To gain an understanding of the sizes of turbines being planned, for a subset of 12 planning authorities, the database was extended to include data on turbine height dimensions (for the most recent versions of proposals). Planning patterns were analysed by height category, based upon RenewableUK's classification of blade-tip heights (RenewableUK, 2013) (micro: 10-15m, small: 15-30m, medium: 30-55m, large: above 55m; an additional category was also added – sub-micro: less than 10m). Selection of the authorities aimed to achieve a sample representing a wide spread of geographical locations, authority sizes, inland and coastal positioning, urban and rural areas, prevalence rates of turbine planning and types of wind energy sites typically planned (e.g. single turbines or wind farms).

2.3.2 Bat roost records

The locations of surveyed bat roosts (of all species) up to 2012 that were included in the National Bat Monitoring Programme (NBMP) were supplied by the UK's Bat Conservation Trust (BCT). This is the most robust, validated roost monitoring dataset available in the UK and provides in depth data regarding roost population sizes (with annual totals) and accurate roost locations. However it does not represent an exhaustive record of all roost locations, as not all roosts are monitored by the NBMP and some roost locations are unknown. Most roost locations in the dataset were recorded at spatial resolutions of 10m or 100m, with a minor proportion (1.8%) recorded at 1km and 10km resolutions. Those with 10km resolutions were excluded from any analyses. A descriptive summary of the roost characteristics within this dataset is provided in Table 2.2.

Table 2.2: Descriptive summary of the BCT bat roost data used in this Chapter's analyses, categorised by species and genus

Species / Genus	Number of roosts	As a percentage of all roost species	Mean of 3-year mean counts (2010-12)	Min. 3-year mean count (exc. zero counts)	Max. 3-year mean count	Std. dev. of 3-year mean counts
Common pipistrelle	101	15%	56.4	1	352	67.1
Soprano pipistrelle	86	12.7%	228.6	1	688	204.4
Pipistrelle sp.	106	15.7%	99.4	1	596	170.5
Brown long-eared bat	37	5.5%	28	2	76	22.3
Brandt's bat	1	0.1%	3	3	3	N/A
Daubenton's bat	1	0.1%	62	62	62	N/A
Natterer's bat	15	2.2%	63.6	17	180	52.8
Whiskered / Brandt's / Alcathoe bat	2	0.3%	45	45	45	N/A
Whiskered bat	2	0.3%	24.5	20	29	6.4

Leisler's bat	1	0.1%	92	92	92	N/A
Noctule	2	0.3%	36.5	20	53	23.3
Serotine	35	5.2%	24.9	1	141	39.6
Greater horseshoe bat	24	3.6%	270.6	1	1565	347.7
Lesser horseshoe bat	260	38.5%	129.2	1	895	125.4
Unknown bat sp.	2	0.3%	32.5	65	65	46.0
Pipistrellus	293	43.4%	133.5	1	688	171.5
Plecotus	37	5.5%	28	2	76	22.3
Myotis	21	3.1%	53	3	180	46.7
Nyctalus/Eptesicus	38	5.6%	30.6	1	141	39.7
Rhinolophus	284	42.1%	142.6	1	1565	164.3
Unknown genus	2	0.3%	32.5	65	65	46.0
Grand Total	675	100%	125.3	1	1565	159.5

Mean roost counts were calculated for the 2010-12 period, thereby smoothing some of the temporal variability in roost sizes. The number and density of individual wind turbines approved in planning up to and including 2007, within a range of set distances from BCT-recorded roost locations were calculated using ArcMap software (version 10, ESRI) for each roost. This allowed for typical turbine procurement, financing, installation and commissioning times following approval. A maximum radius of 5km was applied, based on an estimate of the maximum likely night foraging flight distance from roosts (see Table A.2 - see *Appendices*) by the primary species listed in the BCT roost dataset. These calculations were made for the following radii (‘sustenance zone’ sizes) from each roost: 5km, 4km, 3km, 2km, 1km and 500m.

To enable analyses of changes in roost counts over time, 3-year mean and 5-year mean roost counts were calculated for periods from 10 to 5 years prior to the ‘current’ 2010-2012 mean roost size. The historic roost count survey record extended backward by varying numbers of years for different roosts, therefore earlier years' data were not always available. Total approved turbines as at 3 years prior to each historical roost count period were calculated within each sustenance zone size (to allow for procurement and commissioning time). Final analyses were carried out using the 5 year gap period (starting data: mean of 2005-07 counts, 2002 turbine approvals), within 5km and 4km sustenance zones, as this represented the optimum choice for sample size and associated turbine records.

2.3.3 Land class categories

The Institute of Terrestrial Ecology (ITE) spatial Land Classification dataset was used in a GIS format to identify the range and dominant classes of broad landscape-types within which both roosts and planned turbines were typically found. This aimed to consider the level of likelihood that conflict may occur due to use of the same coarse landscapes. The Centre for Ecology and Hydrology's (CEH) Land Cover Map 2007 (LCM) dataset was also applied in models of turbine impact to account for the modifying effect of local-scale habitat characteristics.

2.3.4 Statistical analyses

2.3.4.1 Impact of turbine presence and density within roost sustenance zones

Generalised Linear Models (GLMs) with a negative binomial error structure were built to assess the link between roost counts and the presence or absence of a turbine, using the 'R' software (R Core Team, 2015).

Mean 2010-12 roosts counts (rounded to integers) were set as the outcome variable, with turbine presence/absence included as a fixed factor. To consider the modifying effects from landcover type, percentage coverage of 'urban areas' (incorporating a suburban class) and 'broadleaved woodland' (representing deciduous woodland, recent broadleaved tree growth (<10 years), mixed woodland and scrub), as recorded by the LCM dataset within roost buffer zones, were included as fixed covariates.

Moran's I test was also used prior to analysis to confirm that no spatial autocorrelation existed in roost sizes. Correlation values between each pair of predictor variables were assessed to confirm no inter-variable correlation. Model fit was assessed and model assumptions verified (homogeneity and normality of residuals, independence of variables and no overly-influential observations) using model residuals plots (residuals vs. fitted, Normal QQ plot, histogram of residuals and Cook’s distance plot), the residual deviance vs. residual degrees of freedom ratio (for models with a negative binomial error structure) and plots of model-predicted outcome variable values vs. observed values for each predictor variable.

These analyses were carried out for the 5km, 4km, 3km and 2km sustenance zone sizes (those with adequate sample sizes) and then repeated for those genera with a large enough roost sample size (*Pipistrellus* and *Rhinolophus*). The same analysis was then repeated with turbine density used as a fixed covariate in place of the presence/absence measure.

2.3.4.2 Planning of turbines near roosts

The hypothesis that turbines may be preferentially planned in areas which are coincidentally also of importance for bat roosting (i.e. areas close to large bat roosts) was also tested. This hypothesised pattern could occur due to shared requirements for landscape structure, or the location of turbines at rural properties which are inherently closer to diverse habitats of preference to bats. This analysis used the same model variables and approach as above, however turbine presence was set as the outcome variable (a binomial error distribution was used for the model) and mean 2010-12 roost counts as a fixed covariate.

2.3.4.3 Impact of turbine presence on roost size changes

GLMs were used to test the effect size of turbine presence and density on roost size changes over a number of years (5km and 4km zone size models – those with adequate sample sizes). Models were built for 5 year time periods, using a Gaussian error distribution. Percentage landcover of broadleaved woodland and urban areas were included in all models. Models were validated in the same manner as described above. Sample sizes were not sufficient to analyse individual genera.

2.4 Results

2.4.1 *Land class categories*

The total number of individual approved turbines and BCT-recorded roosts in each broad landclass is shown in Figure 2.1. Turbines and roosts are found across a range of landclass types.

The dominant turbine landclasses in SW England are shallow and complex valley systems, floodplains and table lands. Similarly, the dominant roost landclasses are shallow and complex valley systems and floodplains and table lands, in addition to variable lowlands and shallow slopes.

The dominant turbine landclasses in Wales are rounded mountains and upper valleys, low mountains/hills, complex valley systems and table lands. In contrast, shallow slopes, and flat river valleys/lower hill slopes are the dominant land classes for roosts in Wales.

The level of crossover in landscape types in which turbines and roosts are found is therefore variable and there are few landclasses in which only turbines are found (a situation that would otherwise offer low potential for conflict).

2.4.2 *Presence of turbines within roost sustenance zones*

No significant effects of turbine presence upon roost populations were identified from the GLMs for the *Pipistrellus* genus (the genus with the largest sample size; see Table 2.3 for the results), or from those for the *Rhinolophus* genus and ‘all roost species’ analyses (see Supplementary Materials Tables S2.2-S2.5), for any of the sustenance zone sizes. Only urban landcover was found to have a significant (negative) effect within the *Pipistrellus* model. Broadleaved woodland was additionally found to have a significant positive effect within the *Rhinolophus* and ‘all species’ models.

2.4.3 *Density of turbines within roost sustenance zones*

Turbine density was not found to have any significant effect upon roost counts for any species group or within the ‘all species model’ (Table 2.4 and Tables

S2.6-S2.9). See Figures 2.2 and 2.3 illustrating the lack of effect from turbine density within the *Pipistrellus* genus model, at 2km and 3km roost radii. The only significant covariates were again found to be urban and wooded landcover (the latter finding restricted to the *Rhinolophus* and ‘all species’ models).

2.4.4 Roost size changes and presence of wind turbines

No significant effect was identified from turbine presence upon roost size changes over 5 years (Table 2.5). A positive effect was identified from broadleaved woodland cover at both 5km and 4km scales. The same results were observed from the turbine density models (Table S2.10).

2.4.5 Planning of turbines near roosts

Roost size was not found to be a significant predictor of turbine presence at any sustenance zone size (Table S2.11 and Table S2.12). Urban and suburban landcover was significantly positively associated with turbine presence at 5km and 4km scales only, whilst broadleaved woodland landcover was also a significant predictor at the 5km scale.

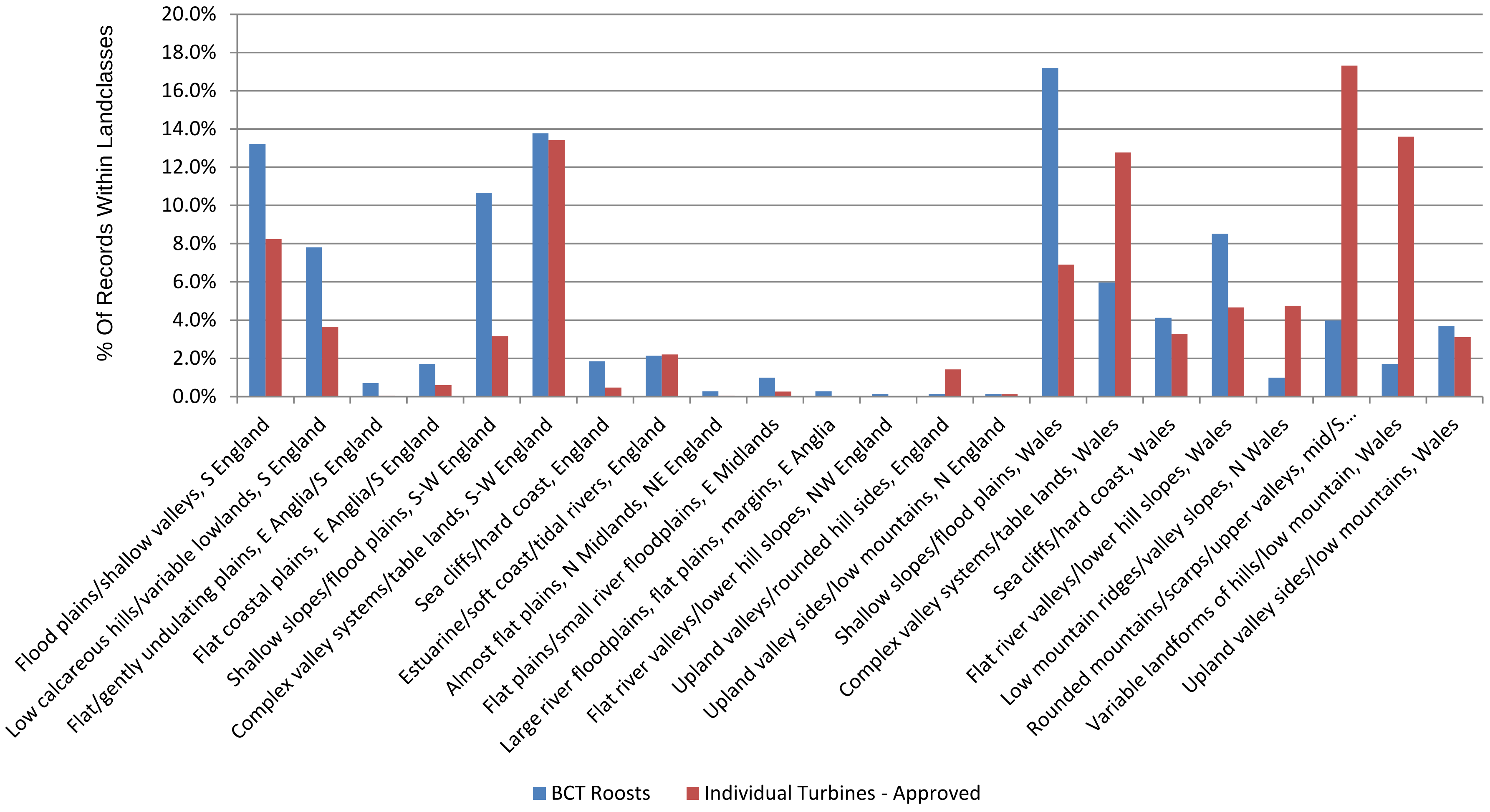

Figure 2.1: The distribution of approved individual wind turbines and BCT-recorded bat roosts by ITE landclass. Landclasses with no turbine or roost records were excluded

Table 2.3: GLM output from the model assessing the impact of turbine presence upon *Pipistrellus* genus bat roost populations, applying sustenance zone radii of 5km, 4km, 3km and 2km, 2010-12 mean roost population counts and a negative binomial error distribution. The values for Deviance, AIC, the Likelihood Ratio Test (LRT), degrees of freedom (df) and significance (p) relate to the removal of each variable individually from the full model and testing the difference between the resulting and full models

Fixed Effects	**Estimate**	**Standard Error**	**Deviance**	**AIC**	**Likelihood Ratio Test**	**df**	**p**
Sustenance zone size: 5km (n = 113)							
Intercept	5.23	0.32					
Turbine presence	-0.07	0.28	139.70	1287.2	0.05	1	0.815
Broadleaved woodland % land cover	-0.01	0.03	139.78	1287.3	0.13	1	0.721
Urban and suburban % land cover	-0.03	0.02	143.59	1291.1	3.94	1	0.047
Sustenance zone size: 4km (n = 115)							
Intercept	5.21	0.29					
Turbine presence	-0.16	0.28	142.44	1304.8	0.33	1	0.565
Broadleaved woodland % land cover	-0.01	0.03	142.22	1304.6	0.11	1	0.743
Urban and suburban % land cover	-0.03	0.01	146.32	1308.7	4.21	1	0.040
Sustenance zone size: 3km (n = 116)							
Intercept	5.06	0.27					
Turbine presence	-0.05	0.29	143.30	1317.3	0.03	1	0.860
Broadleaved woodland % land cover	0.002	0.02	143.27	1317.3	0.01	1	0.939
Urban and suburban % land cover	-0.03	0.01	148.44	1322.5	5.17	1	0.023
Sustenance zone size: 2km (n = 117)							
Intercept	5.02	0.25					
Turbine presence	-0.04	0.34	144.35	1326.8	0.01	1	0.903
Broadleaved woodland % land cover	0.01	0.02	144.44	1326.9	0.10	1	0.749
Urban and suburban % land cover	-0.03	0.01	150.85	1333.3	6.51	1	0.011

Table 2.4: GLM output from the model assessing the impact of turbine density upon *Pipistrellus* genus bat roost populations, applying sustenance zone radii of 5km, 4km, 3km and 2km, 2010-12 mean roost population counts and a negative binomial error distribution. The values for Deviance, AIC, the Likelihood Ratio Test (LRT), degrees of freedom (df) and significance (p) relate to the removal of each variable individually from the full model and testing the difference between the resulting and full models

Fixed Effects	**Estimate**	**Standard Error**	**Deviance**	**AIC**	**Likelihood Ratio Test**	**df**	**p**
Sustenance zone size: 5km (n = 113)							
Intercept	5.25	0.30					
Turbine density	-1.17	2.04	139.79	1287.2	0.15	1	0.699
Broadleaved woodland % land cover	-0.01	0.03	139.83	1287.2	0.19	1	0.666
Urban and suburban % land cover	-0.03	0.02	143.81	1291.2	4.17	1	0.421
Sustenance zone size: 4km (n = 115)							
Intercept	5.12	0.29					
Turbine density	1.07	3.79	142.23	1304.8	0.10	1	0.747
Broadleaved woodland % land cover	-0.01	0.03	142.22	1304.8	0.09	1	0.770
Urban and suburban % land cover	-0.03	0.01	146.77	1309.4	4.64	1	0.031
Sustenance zone size: 3km (n = 116)							
Intercept	5.02	0.27					
Turbine density	2.25	3.93	143.79	1317.3	0.57	1	0.449
Broadleaved woodland % land cover	-0.0001	0.02	143.22	1316.7	0	1	0.995
Urban and suburban % land cover	-0.03	0.01	148.41	1321.9	5.20	1	0.023
Sustenance zone size: 2km (n = 117)							
Intercept	5.00	0.25					
Turbine density	1.00	3.25	144.44	1326.8	0.11	1	0.738
Broadleaved woodland % land cover	0.01	0.02	144.41	1326.8	0.09	1	0.763
Urban and suburban % land cover	-0.03	0.01	151.08	1333.5	6.75	1	0.009

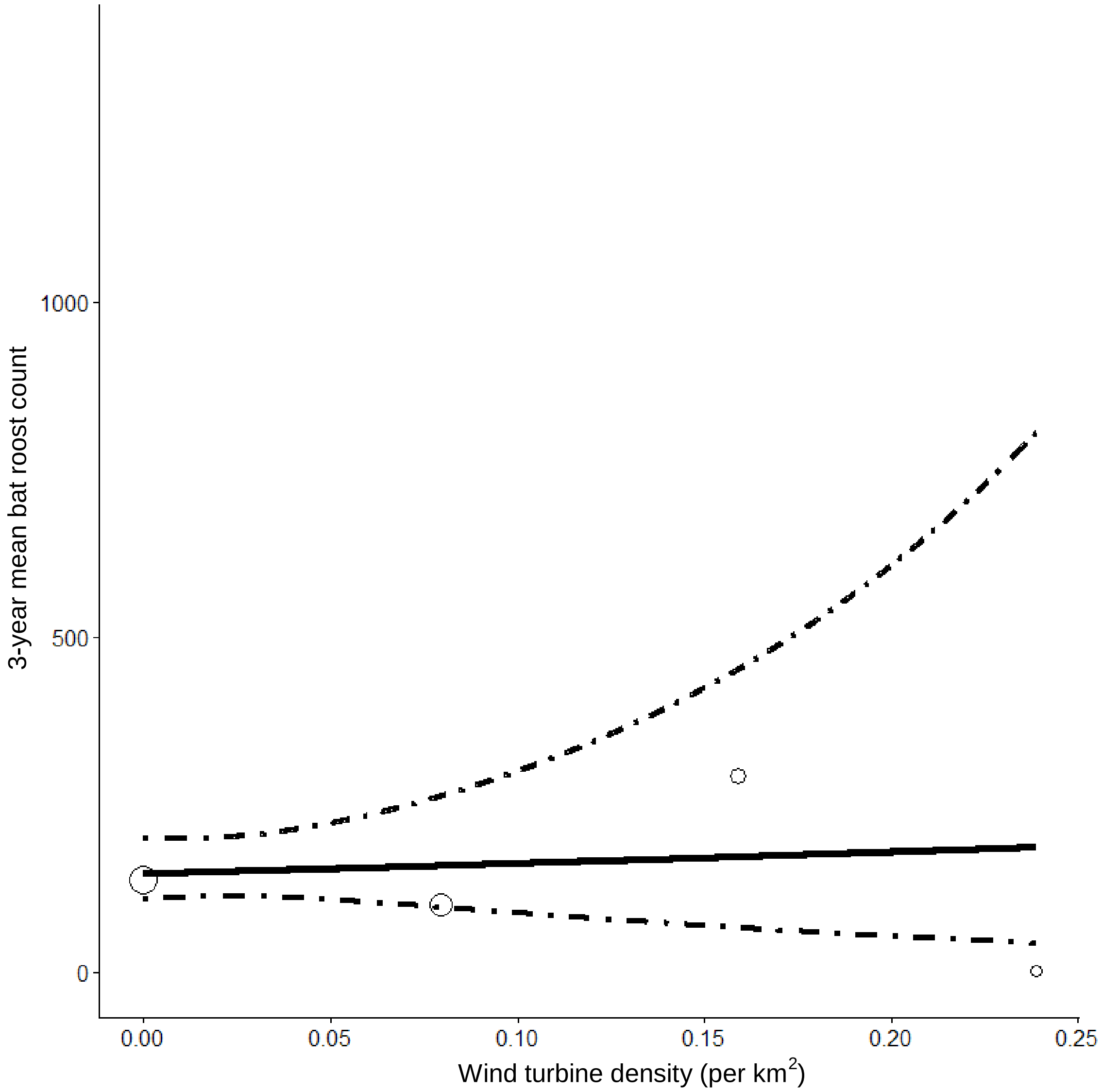

Figure 2.2: Prediction plot from the *Pipistrellus* genus turbine density GLM analysing the effect of wind turbine density (per km^2) within a 2km radius (of roosts) upon bat roost counts. Dashed lines indicate 95% confidence intervals; circles = mean observed 3-year average roost count; relative sizes of circles represent relative contributing levels of data (larger = more data)

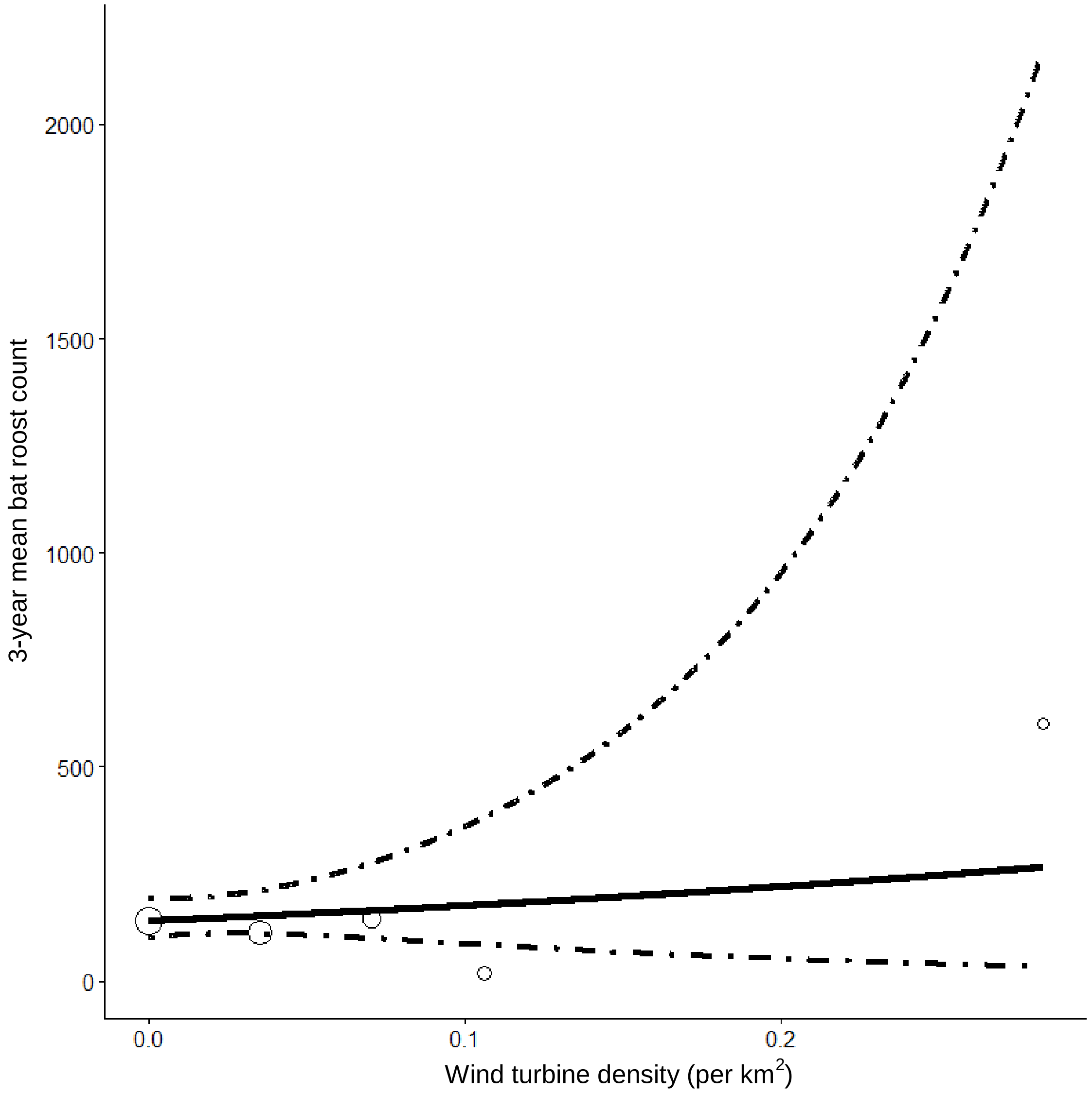

Figure 2.3: Prediction plot from the *Pipistrellus* genus turbine density GLM analysing the effect of wind turbine density (per km^2) within a 3km radius (of roosts) upon bat roost counts. Dashed lines indicate 95% confidence intervals; circles = mean observed 3-year average roost count; relative sizes of circles represent relative contributing levels of data (larger = more data)

Table 2.5: GLM output from the turbine presence vs. roost size change over 5 years model, applying sustenance zone radii of 5km and 4km, changes in mean roost population counts (of all species) over the 2005-07 to 2010-12 period and a Gaussian error distribution. The values for Deviance, AIC, the Likelihood Ratio Test (LRT), degrees of freedom (df) and significance (p) relate to the removal of each variable individually from the full model and testing the difference between the resulting and full models

Fixed Effects	**Estimate**	**Standard Error**	**AIC**	**Likelihood Ratio Test**	**df**	**p**
Sustenance zone size: 5km (n = 243)						
Intercept	-16.11	16.62				
Turbine presence (approved 2002)	4.93	20.64	2965.10	0.06	1	0.811
Broadleaved woodland % land cover	2.90	1.55	2968.60	3.52	1	0.06
Urban and suburban % land cover	-1.33	1.07	2966.60	1.55	1	0.214
Sustenance zone size: 4km (n = 250)						
Intercept	-20.39	16.15				
Turbine presence (approved 2002)	-8.54	24.66	3064.20	0.12	1	0.729
Broadleaved woodland % land cover	2.85	1.38	3068.40	4.27	1	0.040
Urban and suburban % land cover	-0.83	0.97	3064.80	0.73	1	0.393

2.4.6 Overview of wind turbine planning trends

Planning records were refined from 63 of the 64 local authorities in Wales and SW England: Cornwall was excluded from this investigation as the number of turbine applications greatly exceeded those from any other region of England or Wales, and it was therefore considered to be atypical. Across the authorities, 3874 initial planning records were collated. Following the removal of irrelevant records, pre-application enquiries, screening/scoping opinions and duplicate applications for the same sites (e.g. amendments, condition discharges and repeat applications following refusals or withdrawals), 2353 unique proposed wind turbine or wind farm sites were identified. Of these, 1476 sites (2446 individual turbines) (63%) were granted permission including 84 via appeal; 621 (26%) were refused, withdrawn or returned as invalid including 100 via appeal; 251 (11%) were pending a planning decision; and 5 were of unknown decision status.

2.4.6.1 Planning approvals

Wind turbine planning showed considerable spatial variability (see Figure 2.4; for details by planning authority see Supplementary Materials Table S2.13). An overview of annual turbine approval trends is given in Figure 2.5, highlighting the increased rate of turbine planning since the early 2000s. Whilst numbers of turbine approvals in the study area peaked during the last years observed (2011-13), approval totals across the UK are known to have decreased by a large amount during the 2014-16 period. This was due to large-scale changes in UK government renewable energy policy, subsidies and planning guidance (DECC, 2016a; DECC, 2015; RenewableUK, 2015a; UK Department for Communities and Local Government (DCLG), 2015; UK Parliament, 2016). For example the mean annual number of individual turbine approvals of 1MW+ capacity in the UK during 2012 and 2013 was 761, which fell to 580 during 2014-April 2016 (2016 data treated as 0.3 years; DECC (2016a)). These changes have largely been focused in England and Wales.

Peaks in this study's observations are visible from the construction of large wind farms, and a clear dip in 2010 corresponds to the UK economic recession. Single turbine sites were by far the most frequent size of development (see

Figures 2.6-2.7), followed by 2-turbine sites. Wind clusters of 3-4 turbines were the next most common scale, followed by small wind farms with 8-11 turbines.

2.4.6.2 Turbine size

The turbine size search covered 495 applications incorporating 1340 turbines. The sampled applications represented 21% of the total database and 29.7% of approved individual turbines. Data recording height to blade tip was available for 348/495 applications (70.3%). Planning success rates were found to drop with increasing turbine size (Table 2.6).

2.4.6.3 Wind turbine planning databases

After comparing against 6 other turbine databases (Table S2.1), a mean of 88% of the external databases' records were already found in this study's collated data, 5% were not found (these 62 records were added to this study's database) and the site-specific identity of 7% of the external turbine records could not be confirmed (restricting matching against the collated data).The created database achieved a very large improvement in coverage relative to existing databases. The largest coverage achieved by an external dataset (RegenSW database) represented only 15.1% of the collated data. As that particular external database only covered SW England, this comparison was also only compared on the basis of coverage of SW England and not Wales.

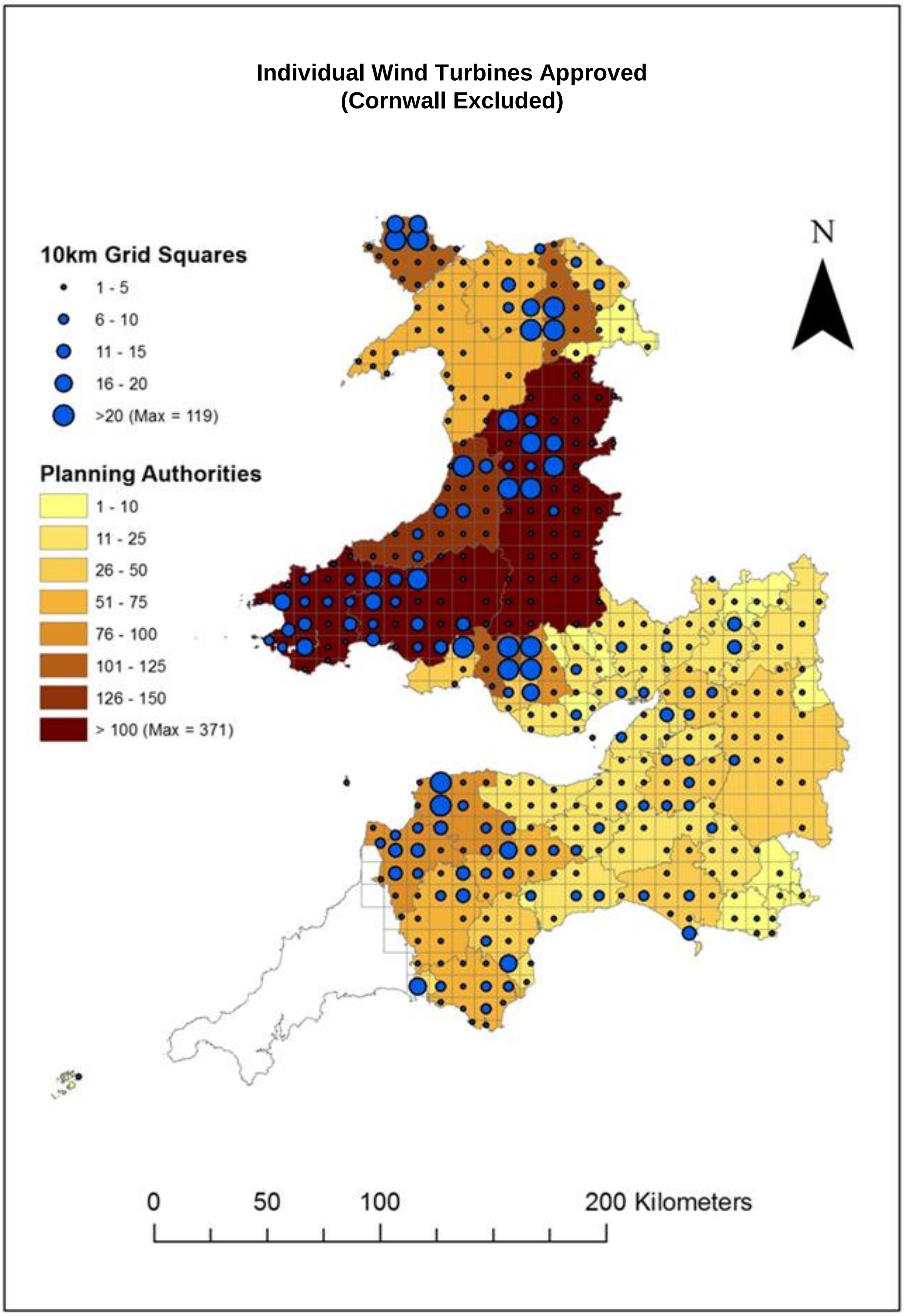

Figure 2.4: Map of approved turbine totals by planning authority and 10km National Grid square boundaries

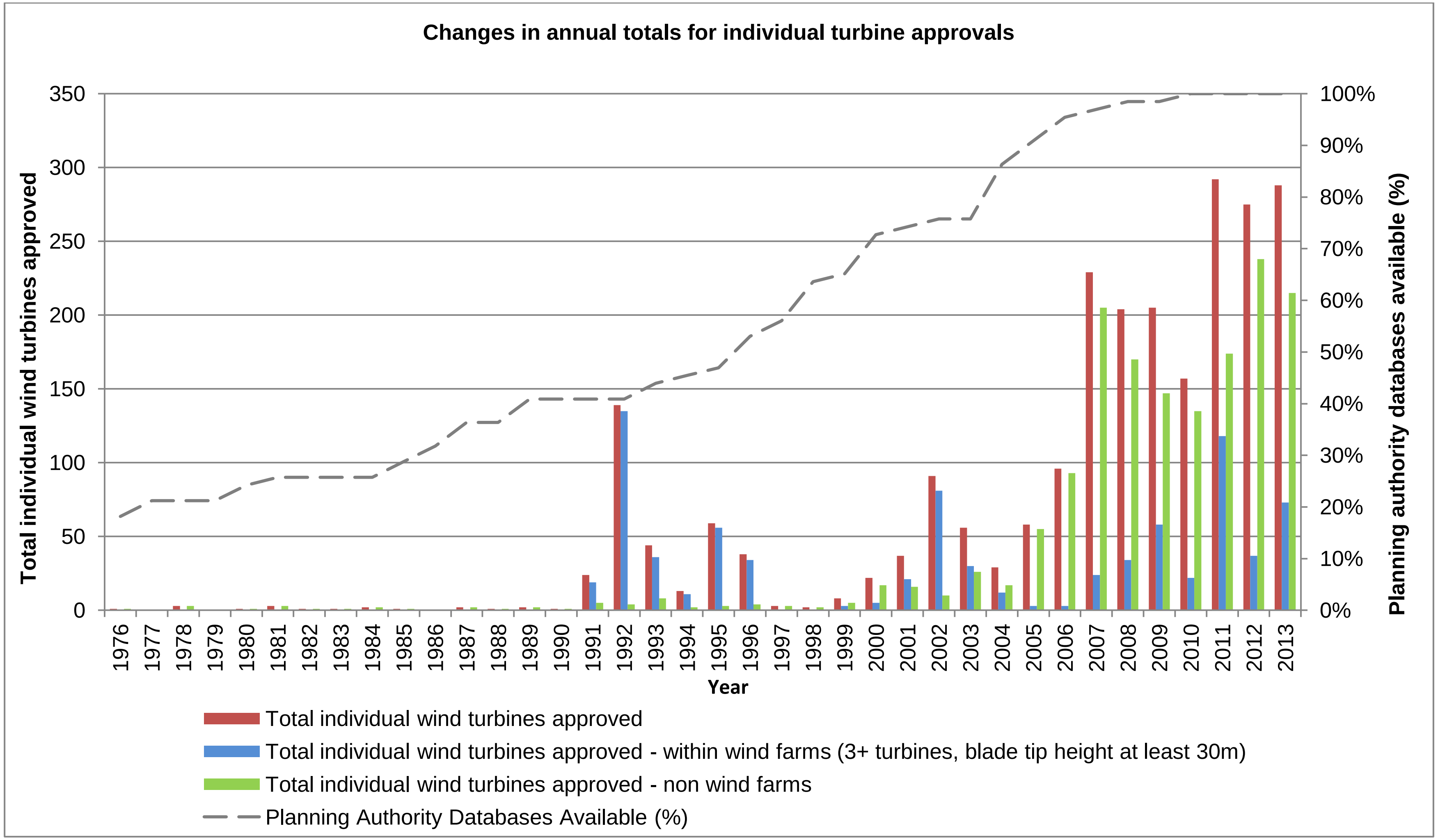

Figure 2.5: Annual trends of wind turbine approval across Wales and SW England (excluding Cornwall)

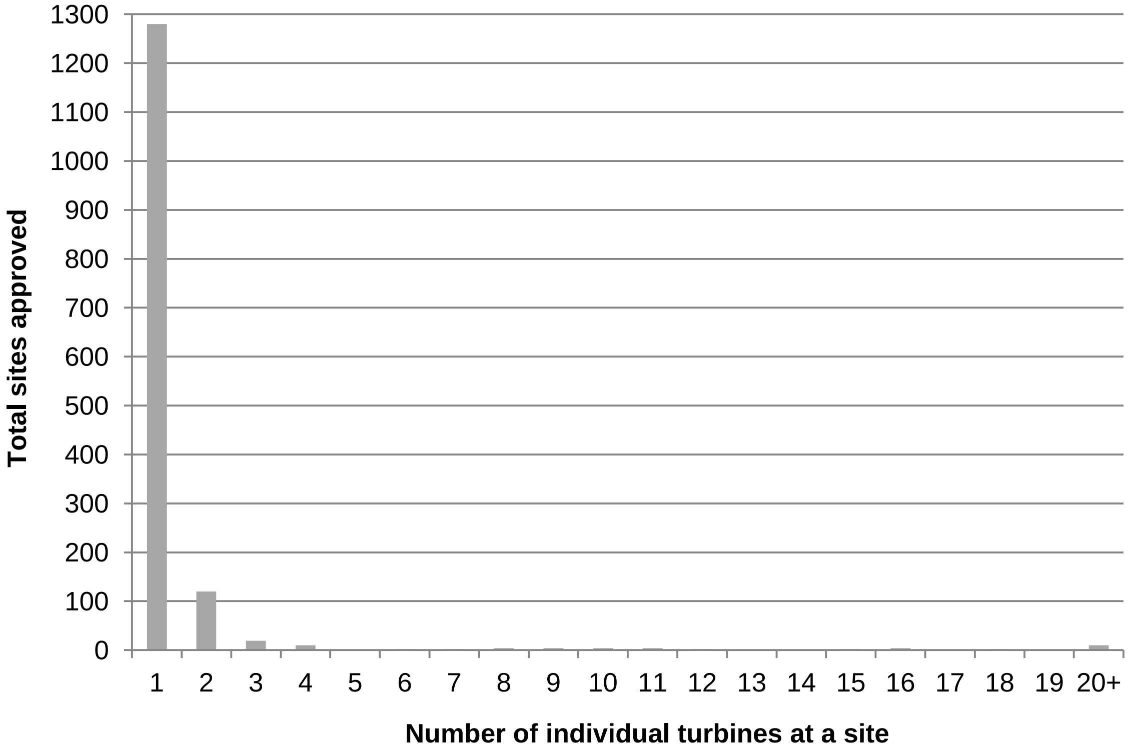

Figure 2.6: Total sites approved by number of individual turbines proposed

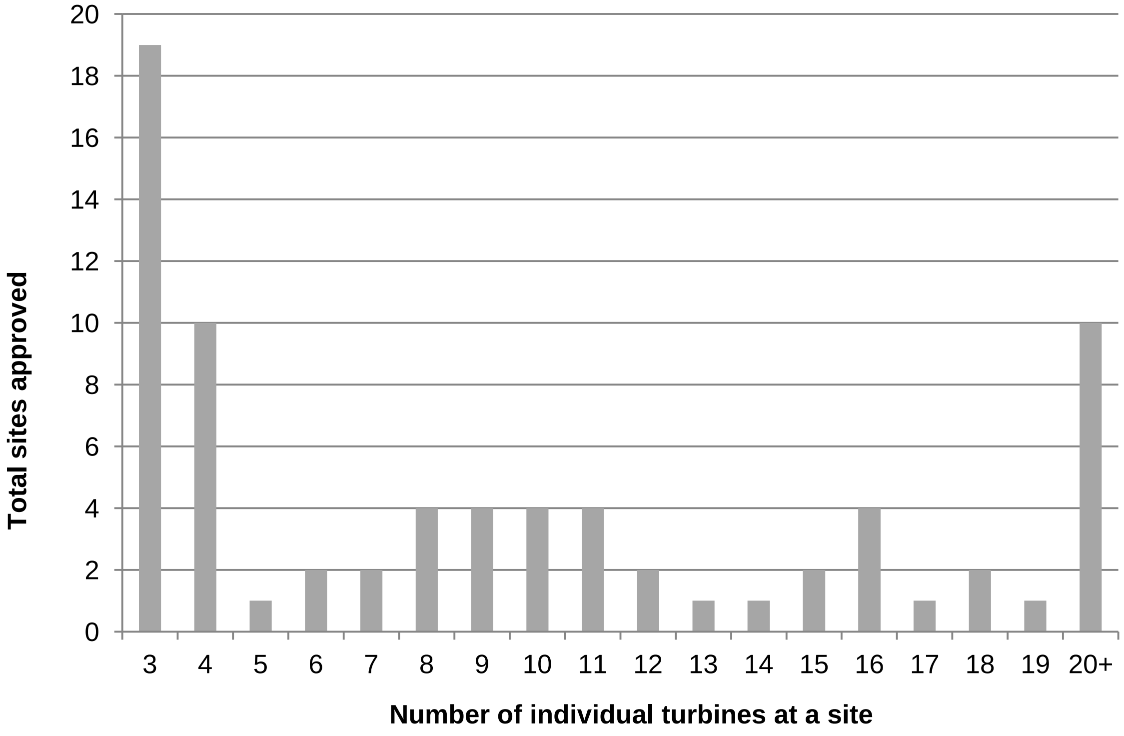

Figure 2.7: Total sites approved by number of individual turbines proposed: Sites with 3+ turbines

Table 2.6: Distribution of planned turbines across height categories, based on a sample of 12 planning authorities (figures in brackets represent percentages of totals within a height category). Note 1 application's permission status was not known. Planning authorities included in the sample were as follows: Teignbridge District Council, North Dorset District Council, Stroud District Council, South Gloucestershire Council, South Somerset District Council, Wiltshire Council, Caerphilly County Borough Council, Monmouthshire County Council, Powys County Council, Rhondda Cynon Taf County Borough Council, City and County of Swansea and Snowdonia National Park Authority.

Turbine height category (heights to blade tip)	Total unique turbine site applications	Total individual turbines	Mean number of turbines per application	Applications / turbines approved	Applications / turbines refused or withdrawn	Applications / turbines pending decision
Sub-Micro (<10m)	26	31	1.19	22 (85) / 24 (77)	4 (15) / 7 (23)	0 (0) / 0 (0)
Micro (10 - <15m)	56	62	1.11	45 (80) / 49 (79)	9 (16)/ 11 (18)	2 (4) / 2 (3)
Small (15 - <30m)	134	158	1.18	103 (77) / 114 (72)	22 (16) / 30 (19)	9 (7) / 14 (9)
Medium (30 - <55m)	57	238	4.18	34 (60) / 212 (89)	17 (30) / 19 (8)	6 (11) / 7 (3)
Large (55m+)	75	602	8.03	23 (31) / 216 (36)	22 (29) / 107 (18)	30 (40) / 279 (46)
Unknown height category	147	249	1.69	102 (69) / 111 (45)	43 (29) / 125 (50)	1 (1) / 12 (5)
TOTAL	495	1340	2.71	329 (66) / 726 (54)	117 (24) / 299 (22)	48 (10) / 314 (23)

2.5 Discussion

This study aimed to address the current lack of understanding of the impacts of planned wind turbine installations upon bat roost populations at a regional scale. No current impacts of turbines upon roosts were identified. However, the analysis indicated consistently large volumes of wind turbine applications entering the planning system. This suggests that ongoing monitoring of the situation should be considered to avoid conflict. Furthermore, the study has identified spatial concentrations of planned turbine installations within Wales and SW England; potentially introducing conflict within these focused areas.

2.5.1 Turbines and roosts conflict analyses

Whilst landclass in itself was not shown to be a clear indicator of potential for turbine or roost presence, more detailed classifications of surrounding matrices of landcover types and measures of local anthropogenic development (e.g. urban areas and agricultural land use) may provide further insight into the influence of landscape structure.

2.5.1.1 Turbine presence and density

No effects from turbine presence or density upon nearby roosts were found. This suggests a general lack of impact from turbines at a regional scale. However this does not prohibit further research into cumulative impacts from multiple turbine sites in very close proximity to high risk roosts. While the BCT dataset is an excellent resource, it is subject to survey sampling bias and is by no means an exhaustive record of bat roosts present; therefore roosts may be present closer to turbines. A negative effect of urban landcover upon roost sizes was frequently observed, as was a positive effect of broadleaved woodland landcover. This indicates that wider scale habitat removal or conservation can detrimentally affect or support roost populations, respectively. Similar impacts from habitat structure and modification upon bat distributions and roosts have been indicated by previous research (Jones et al. (2009); Frey-Ehrenbold et al. (2013); Roscioni et al. (2014); Peste et al. (2015)). Recent studies have furthermore highlighted the multi-scale spatial effects of habitat upon bats during habitat suitability modelling (HSM). They have illustrated differing influence across multiple spatial scales for individual, varied species (Bellamy et al. 2013; Ducci et al. 2015) and shown potential for conservation efforts (Razgour et al. 2011; Wordley et al. 2015) – including from the use of common record centre data (Bellamy and Altringham, 2015). These observations of multi-scale effects are consistent with the findings presented here, which suggest habitat influences are present across varying spatial scales and multiple species.

2.5.1.2 Turbine placement

The lack of association of roost size in predicting turbine presence is encouraging, suggesting placement of turbines is not biased towards landscape types likely to support large bat populations. The positive association of turbine presence with urban landcover at 4km and 5km scales matches expectation of turbine presence close to urban fringes.

2.5.1.3 Impacts on roost changes over time

No significant effect of turbine presence or density on change in roost size over 5 years was found. However, the possible analyses were limited to sustenance zones of 4km and 5km scales. Further long-term monitoring of roosts at closer distances to turbines may therefore be required to confirm this result. Broadleaved woodland landcover was however shown to have a positive association with roost size change over 5 years, suggesting conservation of this habitat type for bats may support long-term viability of roost populations.

2.5.1.4 Further discussion

Any roost population losses identified during monitoring programmes are unlikely to be purely from wind turbines. The assumption that a direct causal link exists between the two ignores the potential for an association between turbine installations and other anthropogenic developments. Where turbines are installed, it is probable that roads will be within a close proximity; furthermore buildings and urban infrastructure may be constructed and land altered for farming. Such developments may introduce further sources of fatality and habitat loss for bats (Berthinussen and Altringham (2012); Lesiński et al. (2011);

Abbott et al. (2012); Wickramasinghe et al. (2003); Waring et al. (2013)), thereby introducing ambiguity in identifying causal factors of roost impacts.

Turbine sizes were not accounted for during the roost analyses. As rigorous research regarding effect of turbine sizes is yet to be undertaken (Minderman et al. 2015; American Wind Wildlife Institute, 2014; Rydell et al. 2010) this approach was considered acceptable. Future studies may incorporate this factor.

The use of postcode co-ordinates for 45.8% of the planned turbine locations will have introduced a small amount of error to the distance-to-roost analyses, as would the small number of roosts locations that were defined at a 1km resolution (for the latter, their number was however considered negligible). Some turbines analysed may no longer be installed, having either reached their engineering lifespan or been removed for other reasons. A common turbine planning condition observed, limits retention to 25 years (UK planning guidance recommends use of decommissioning conditions (UK Government, 2014)). Having applied an additional 2 years, representing lag-time between permission and installation, only 0.5% of this study’s turbine records exceeded this age. Therefore it was chosen to retain all turbines.

Future similar studies could improve the presentation of null results such as those found here by adding a power analysis carried out prior to the study. The power of a study determines the probability of being able to detect a given effect size – assuming it exists – and reject the null hypothesis, when using a set sample size (University of California (Los Angeles) Institute for Digital Research and Education (UCLA IDRE), 2017), thereby avoiding Type II errors (not identifying an effect where one existed). A power analysis would therefore ensure a study design provides a reasonable level of probability of identifying a positive result should one exist, through adequate sample size and study design structure, increasing confidence in study outcomes including null results. If studies are concerned about their sample size, they may still be able to at least confirm adequate power to rule out a large effect size. These approaches would in turn avoid unproductive research effort and help inform future studies of required sample sizes within a particular discipline (including for the detection of effects to varying degrees of accuracy (UCLA IDRE, 2017)).

Radio or GPS tracking of bats from roosts in proximity to multiple turbines may provide an indication of the likelihood that their foraging habitat suffers from complex cumulative impacts in a landscape. This is particularly key in the context of wind farm sites, where large numbers of (relatively) closely spaced turbines may create a ‘barrier’ effect, restricting bat movement through the turbine group. This has been observed regarding birds at wind farms (Drewitt and Langston, 2006; Plonczkier and Simms, 2012; Villegas-Patraca et al. 2014; Everaert, 2014). Barrier impacts upon bats have also been observed from major roads (Kerth and Melber (2009); Berthinussen and Altringham (2012)).

2.5.2 Turbine planning overview analysis

2.5.2.1 Geographical variation

Spatial concentrations of planning-approved turbines appear to exist. As would be expected, large commercial wind farms contribute heavily to the distribution patterns of individual numbers of turbines. Table 2.7 outlines prominent patterns of planned turbine distributions. All planning authorities had approved at least 1 turbine, with 48 (76%) having approved at least 10. 46 authorities (73%) had received 10 applications for turbine *sites* regardless of number of turbines at the site or planning outcome. However there are areas notable for their relative lack of, or abundance of, approved turbines (Table 2.7). Cornwall has received a very large number of wind turbine applications.

2.5.2.2 Planning approval

On a turbine *site* basis, approximately 63% of planning applications have been approved, with 26% refused or withdrawn; 11% are pending a decision. These permission patterns vary when considering different size categories of turbine. Based upon the sample used in this study, the percentage of approved applications (excluding pending applications) drops from 82-85% for ‘sub-micro’ to ‘small’ sized turbine sites, to 67% for ‘medium’ turbines and then to 51% for ‘large’ turbines. Numbers of individual turbines approved per year have grown dramatically over the last 15 years, at a slowly increasing rate over time; in 1999 8 turbines were approved, whilst 288 were approved during 2013.

Table 2.7: Dominant qualitative spatial patterns of wind turbines approved in planning in Wales and SW England

Planned Turbine Category	Areas with Relatively High Numbers of Approved Turbines	Areas with Relatively Low Numbers of Approved Turbines
Wind Farms	• Northern area of Powys / northern area of Ceredigion • Isle of Anglesey / Denbighshire / Conwy • Pembrokeshire / western area of Carmarthenshire • Northern area of Swansea / Neath Port Talbot / Bridgend / Blaenau Gwent • North Devon / Torridge • Mid Devon [Note two 10km cells with high numbers of turbines can be seen in south Devon though these are not wind farms, instead representing a cumulative clustering of individual turbines in the Plymouth area and a long string of micro turbines planned along a seafront esplanade in Paignton]	N/A due to restricted areas available for wind farms
Individual Wind Turbines	• North Powys / Ceredigion • South-east and south-west Wales • The Isle of Anglesey and parts of north-east Wales • Devon • The northern half of Somerset • The West of England area / west Gloucestershire • [Cornwall]	• South Powys • Gwynedd (this planning authority however features a large area of the mountainous Snowdonia National Park) • North and east areas of Gloucestershire • Most of Wiltshire (particularly the southern and eastern areas) • Eastern areas of Dorset / areas of southern Somerset

2.5.2.3 Further discussion

The data collected is a best estimate of total wind turbines planned. With limited availability of historic planning data, a complete historical record would be extremely difficult to achieve. Other limiting factors include obscure proposal descriptions that elude searches, lack of explicit reference to turbines within larger developments, and deviations from search processes where the planning authority provided search data. Additionally, sub-micro wind turbines generally have permitted development status and thus are not well documented. Small wind turbines installed prior to the UK government’s Microgeneration Certification Scheme (MCS) may also be less well recorded.

The 10 year (2004-13) timespan for which planning data was obtained from most local authorities represented the majority of the proliferation period of wind turbine installations in the UK (Figure 2.5). Prior to this, the main peaks resulted from construction of small numbers of large wind farms. It is estimated that 81% of the individual turbines approved in planning during 1991-2003 (see Figure 2.5) were part of wind farm developments (in this case treated as sites with at least 3 freestanding turbines). It was therefore ensured that all constructed wind farms in the study region were included in the search results (records for large wind farms are widely available).

Relative to the six external databases assessed, far larger numbers of turbine installations are recorded by reporting from both RenewableUK (RenewableUK, 2015b) and the UK Department for Energy and Climate Change (DECC) (DECC, 2016b and 2016c). Both however only report total installation numbers, not applications or turbine locations (other than regional totals); furthermore the DECC dataset features data from 2010-onwards only.

With high planning approval ratios (at least up to 2013) and national and EU-level renewable energy/climate change targets, it is reasonable to suggest that wind turbines are and will increasingly be important features to consider in the landscape. The effects of the recent UK EU referendum, however, are not yet known. 94.9% of approved wind turbine sites featured only a single turbine or two turbines (Figure 2.6). Based upon the sample of applications with turbine heights recorded (Table 2.6), most single and twin turbine applications (69%)

can be categorised as ‘sub-micro’, ‘micro’ or ‘small’ turbines. This indicates that the current windfarm-focused planning guidance for bats and turbines may be completely unsuitable for the large majority of turbine planning applications. Consequently further monitoring and research regarding small and individual wind turbines is urgently required to form appropriate guidance (as highlighted by Minderman et al. (2012, 2015) and Park (2013)).

Peaks and troughs within larger trends of turbine approvals will be created by a number of factors, including large wind farm approvals, turbine development costs, subsidy rate changes, renewable energy production targets and national economic wellbeing. Recent changes to UK planning and energy policies have reduced subsidies and narrowed the potential for wind farm developments to progress through the planning system in England and Wales (DECC, 2016a; DECC, 2015; RenewableUK, 2015a; UK Department for Communities and Local Government (DCLG), 2015; UK Parliament, 2016). This will have a large negative impact on the scale of development in the near future. Procedural planning practice regarding turbines (including bat-related issues) also varies between authorities (Park et al. 2013). These somewhat unpredictable factors introduce some uncertainty into inferences regarding future patterns of wind turbine planning and subsequent interactions with bats.

2.6 Conclusions

No impacts of wind turbine presence or density upon bat roost populations have been identified during this study. This result applied to both current roost populations and roost population changes over a 5 year period, incorporating a range of sustenance zone sizes.

A thorough review of wind turbine planning was undertaken for Wales and SW England. A database was created which radically improves knowledge of turbine installations in the regions, relative to existing reference sources. Using this database, trends in turbine planning have been identified.

With regard to spatial distributions of approved turbines, both concentrations and areas of relative scarcity exist within Wales and SW England. A high ratio of planning approval and consistently high numbers of approved turbines across years were identified. This indicates that wind turbines are and will increasingly be important features to consider for bat conservation. This is particularly the case for single or double turbine installations and sub-micro to small turbine sizes, which were found to represent the large majority of all approved turbine sites. The potential lack of compatibility of the current guidance with small turbine contexts is an issue which has been raised by local planning authorities (Park et al. 2013). Consequently further monitoring and research regarding small and individual wind turbines is urgently required to form appropriate guidance.

A number of recommendations are made for future research. Focused long-term monitoring of selected roosts within closer proximity of turbines (e.g. within 500m) is suggested. This should include intense field observation of activity at the roost and turbine locations. This would improve our ability to confirm a lack of impact from turbines upon long-term roost populations. Impacts from wind turbines must be delineated from any spatially co-varying impacts from anthropogenic landuse (e.g. using geospatial analyses and GLM models). The research could also be repeated for other areas of the UK or other countries to consider regional or national variation.

The findings of this study have shown that progress in the development and proliferation of renewable energy installations does not necessarily have to be to the detriment of wildlife populations. Indeed the wider switch to renewable sources of energy production will likely benefit the same wildlife in future decades, through reducing our greenhouse gas emissions. These initial observations suggest that renewable energy development and bat conservation can be mutually achieved.

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2.8 Chapter 2: Supplementary Materials

Table S2.1 (see next page)

An overview of 6 existing wind turbine databases and a comparison of this study’s collated database against them. This includes the installations database from the UK’s Microgeneration Certification Scheme (MCS), which was launched in 2008 and covers small wind turbines with an energy rating up to 50kw. The MCS database covers turbines registered on the scheme from August 2009 onwards (MCS registration is not a requirement for turbine planning and therefore not all are). This scheme will aid identification of many small turbines in the future (though not necessarily micro rooftop turbines). The comparison reflects the data present in the databases at the time of the study.

The UK DECC now publishes a renewable energy planning database (DECC, 2016a), identifying individual wind turbine site locations. However this database was first published in September 2014 and does not include adequately wide coverage of sites proposed before this date for comparison purposes. Furthermore the database only includes sites of 1MW+ capacity, hence ignoring small and medium scale turbines. For these reasons, the database was not used for comparison against this study’s database.

Table S2.1 A comparison of coverage of external wind turbine planning databases

External dataset	% of records covered by this study's dataset	% of records not covered by this study's dataset	% of records unable to confirm site identify to match records	External database's % coverage of this study's entire dataset	External database's % coverage of a portion of this study's dataset – portion chosen to match focus of external database
UK Department of Energy and Climate Change (DECC) RESTATS: Focuses upon turbine applications including all planning outcomes	94	6	0	12	12
Microgeneration Certification Scheme (MCS): Focuses upon installed turbines with an energy rating up to 50kw. [Coverage only from August 2009]	95	3	2	14.3	Unable to confirm due to lack of energy rating data (closest comparison including all sizes of turbines: 28%, though this will be slightly higher in reality)
RenewableUK Wind Energy Database (WED): Focuses upon approved and installed sites	96	4	0	2.9	5.7
RegenSW database: Focuses upon approved and installed turbines. Coverage for SW England only	64	4	32	7.2 (15.1% for SW England only)	29.4
Country Guardian website data: Focuses upon turbine applications including all planning outcomes. [Coverage only up to August 2007]	86	8	6	5.3	6.6
OFGEM database 2008 extract: Renewables Obligation (RO) and Climate Change Levy (CCL) exemptions, less than 50kw rating [Note this is a subset of the total OFGEM database]: Focuses upon installed turbines with an energy rating up to 50kw. [Coverage only up to April 2008]	90	8	2	1.7	Unable to confirm due to lack of energy rating data (closest comparison including all sizes of turbines: 3.3%, though this will be slightly higher in reality)

Table S2.2: GLM output from the model assessing the impact of turbine presence upon bat roost populations for ‘all species’, applying sustenance zone radii of 5km and 4km, 2010-12 mean roost population counts (all species of bat included) and a negative binomial error distribution. The values for Deviance, AIC, the Likelihood Ratio Test (LRT), degrees of freedom (df) and significance (p) relate to the removal of each variable individually from the full model and testing the difference between the resulting and full models

Fixed Effects	**Estimate**	**Standard Error**	**Deviance**	**AIC**	**Likelihood Ratio Test**	**df**	**p**
Sustenance zone size: 5km (n = 370)							
Intercept	4.70	0.16					
Turbine presence	-0.06	0.13	446.51	4255.00	0.18	1	0.668
Broadleaved woodland % land cover	0.03	0.01	449.75	4258.30	3.42	1	0.064
Urban and suburban % land cover	-0.02	0.01	453.94	4262.40	7.62	1	0.006
Sustenance zone size: 4km (n = 381)							
Intercept	4.64	0.15					
Turbine presence	-0.01	0.13	459.95	4366.20	0.01	1	0.931
Broadleaved woodland % land cover	0.03	0.01	464.61	4370.90	4.67	1	0.031
Urban and suburban % land cover	-0.02	0.01	469.25	4375.50	9.31	1	0.002

Table S2.3 GLM output from the model assessing the impact of turbine presence upon bat roost populations for 'all species', applying sustenance zone radii of 3km and 2km, 2010-12 mean roost population counts (all species of bat included) and a negative binomial error distribution. The values for Deviance, AIC, the Likelihood Ratio Test (LRT), degrees of freedom (df) and significance (p) relate to the removal of each variable individually from the full model and testing the difference between the resulting and full models

Fixed Effects	**Estimate**	**Standard Error**	**Deviance**	**AIC**	**Likelihood Ratio Test**	**df**	**p**
Sustenance zone size: 3km (n = 385)							
Intercept	4.63	0.14					
Turbine presence	0.02	0.14	464.33	4413.60	0.02	1	0.895
Broadleaved woodland % land cover	0.03	0.01	470.00	4419.30	5.68	1	0.017
Urban and suburban % land cover	-0.02	0.01	474.36	4423.60	10.04	1	0.002
Sustenance zone size: 2km (n = 393)							
Intercept	4.62	0.13					
Turbine presence	-0.16	0.17	473.91	4507.50	0.81	1	0.370
Broadleaved woodland % land cover	0.03	0.01	480.73	4514.30	7.62	1	0.006
Urban and suburban % land cover	-0.02	0.01	482.63	4516.20	9.52	1	0.002

Table S2.4: GLM output from the model assessing the impact of turbine presence upon *Rhinolophus* genus bat roost populations, applying sustenance zone radii of 5km and 4km, 2010-12 mean roost population counts and a negative binomial error distribution. The values for Deviance, AIC, the Likelihood Ratio Test (LRT), degrees of freedom (df) and significance (p) relate to the removal of each variable individually from the full model and testing the difference between the resulting and full models

Fixed Effects	**Estimate**	**Standard Error**	**Deviance**	**AIC**	**Likelihood Ratio Test**	**df**	**p**
Sustenance zone size: 5km (n = 205)							
Intercept	4.61	0.17					
Turbine presence	0.10	0.14	236.43	2423.5	0.49	1	0.482
Broadleaved woodland % land cover	0.04	0.02	241.14	2428.2	5.20	1	0.023
Urban and suburban % land cover	-0.02	0.01	240.91	2428.0	4.97	1	0.026
Sustenance zone size: 4km (n = 212)							
Intercept	4.54	0.17					
Turbine presence	0.14	0.14	246.37	2500.4	0.97	1	0.324
Broadleaved woodland % land cover	0.04	0.01	252.96	2507.0	7.56	1	0.006
Urban and suburban % land cover	-0.02	0.01	250.84	2504.9	5.44	1	0.020

Table S2.5: GLM output from the model assessing the impact of turbine presence upon *Rhinolophus* genus bat roost populations, applying sustenance zone radii of 3km and 2km, 2010-12 mean roost population counts and a negative binomial error distribution. The values for Deviance, AIC, the Likelihood Ratio Test (LRT), degrees of freedom (df) and significance (p) relate to the removal of each variable individually from the full model and testing the difference between the resulting and full models

Fixed Effects	**Estimate**	**Standard Error**	**Deviance**	**AIC**	**Likelihood Ratio Test**	**df**	**p**
Sustenance zone size: 3km (n = 215)							
Intercept	4.57	0.16					
Turbine presence	0.15	0.16	249.61	2535.8	0.95	1	0.329
Broadleaved woodland % land cover	0.03	0.01	256.35	2542.5	7.68	1	0.006
Urban and suburban % land cover	-0.02	0.01	253.76	2539.9	5.10	1	0.024
Sustenance zone size: 2km (n = 222)							
Intercept	4.54	0.15					
Turbine presence	-0.16	0.21	256.54	2614.5	0.55	1	0.460
Broadleaved woodland % land cover	0.03	0.01	268.07	2626.1	12.07	1	0.001
Urban and suburban % land cover	-0.02	0.01	260.17	2618.2	4.18	1	0.041

Table S2.6: GLM output from the model assessing the impact of turbine density upon bat roost populations for ‘all species’, applying sustenance zone radii of 5km and 4km, 2010-12 mean roost population counts (all species of bat included) and a negative binomial error distribution. The values for Deviance, AIC, the Likelihood Ratio Test (LRT), degrees of freedom (df) and significance (p) relate to the removal of each variable individually from the full model and testing the difference between the resulting and full models

Fixed Effects	**Estimate**	**Standard Error**	**Deviance**	**AIC**	**Likelihood Ratio Test**	**df**	**p**
Sustenance zone size: 5km (n = 370)							
Intercept	4.66	0.15					
Turbine density	1.02	1.53	446.57	4255.00	0.25	1	0.618
Broadleaved woodland % land cover	0.03	0.01	449.69	4258.10	3.37	1	0.066
Urban and suburban % land cover	-0.02	0.01	454.64	4263.10	8.32	1	0.004
Sustenance zone size: 4km (n = 381)							
Intercept	4.60	0.14					
Turbine density	2.68	2.33	461.52	4366.20	1.73	1	0.189
Broadleaved woodland % land cover	0.03	0.01	464.23	4368.90	4.44	1	0.035
Urban and suburban % land cover	-0.02	0.01	469.92	4374.60	10.13	1	0.001

Table S2.7: GLM output from the model assessing the impact of turbine density upon bat roost populations for ‘all species’, applying sustenance zone radii of 3km and 2km, 2010-12 mean roost population counts (all species of bat included) and a negative binomial error distribution. The values for Deviance, AIC, the Likelihood Ratio Test (LRT), degrees of freedom (df) and significance (p) relate to the removal of each variable individually from the full model and testing the difference between the resulting and full models

Fixed Effects	**Estimate**	**Standard Error**	**Deviance**	**AIC**	**Likelihood Ratio Test**	**df**	**p**
Sustenance zone size: 3km (n = 385)							
Intercepts	4.62	0.13					
Turbine density	1.94	2.01	465.47	4413.60	1.26	1	0.262
Broadleaved woodland % land cover	0.02	0.01	468.84	4417.00	4.63	1	0.031
Urban and suburban % land cover	-0.02	0.01	474.92	4423.10	10.71	1	0.001
Sustenance zone size: 2km (n = 393)							
Intercept	4.60	0.13					
Turbine density	-0.16	1.35	473.18	4507.50	0.01	1	0.907
Broadleaved woodland % land cover	0.03	0.01	481.18	4515.50	8.01	1	0.005
Urban and suburban % land cover	-0.02	0.01	482.93	4517.20	9.76	1	0.002

Table S2.8: GLM output from the model assessing the impact of turbine density upon *Rhinolophus* genus bat roost populations, applying sustenance zone radii of 5km and 4km, 2010-12 mean roost population counts and a negative binomial error distribution. The values for Deviance, AIC, the Likelihood Ratio Test (LRT), degrees of freedom (df) and significance (p) relate to the removal of each variable individually from the full model and testing the difference between the resulting and full models

Fixed Effects	**Estimate**	**Standard Error**	**Deviance**	**AIC**	**Likelihood Ratio Test**	**df**	**p**
Sustenance zone size: 5km (n = 205)							
Intercept	4.65	0.17					
Turbine density	8.46	4.58	239.08	2423.5	3.36	1	0.067
Broadleaved woodland % land cover	0.03	0.02	238.72	2423.2	3.01	1	0.083
Urban and suburban % land cover	-0.03	0.01	242.38	2426.8	6.67	1	0.010
Sustenance zone size: 4km (n = 212)							
Intercept	4.57	0.16					
Turbine density	5.50	3.58	247.82	2500.4	2.54	1	0.111
Broadleaved woodland % land cover	0.04	0.01	250.96	2503.6	5.67	1	0.017
Urban and suburban % land cover	-0.02	0.01	251.00	2503.6	5.72	1	0.017

Table S2.9: GLM output from the model assessing the impact of turbine density upon *Rhinolophus* genus bat roost populations, applying sustenance zone radii of 3km and 2km, 2010-12 mean roost population counts and a negative binomial error distribution. The values for Deviance, AIC, the Likelihood Ratio Test (LRT), degrees of freedom (df) and significance (p) relate to the removal of each variable individually from the full model and testing the difference between the resulting and full models

Fixed Effects	**Estimate**	**Standard Error**	**Deviance**	**AIC**	**Likelihood Ratio Test**	**df**	**p**
Sustenance zone size: 3km (n = 215)							
Intercept	4.60	0.15					
Turbine density	2.96	2.58	249.98	2535.8	1.35	1	0.246
Broadleaved woodland % land cover	0.03	0.01	254.41	2540.2	5.77	1	0.016
Urban and suburban % land cover	-0.02	0.01	253.66	2539.5	5.02	1	0.025
Sustenance zone size: 2km (n = 222)							
Intercept	4.52	0.15					
Turbine density	-0.59	1.52	256.18	2614.5	0.15	1	0.698
Broadleaved woodland % land cover	0.04	0.01	268.57	2626.9	12.55	1	<0.001
Urban and suburban % land cover	-0.02	0.01	260.17	2618.5	4.15	1	0.042

Table S2.10: GLM output from the turbine density vs. roost size change over 5 years model, applying sustenance zone radii of 5km and 4km, changes in mean roost population counts (of all species) over the 2005-07 to 2010-12 period and a Gaussian error distribution . The values for Deviance, AIC, the Likelihood Ratio Test (LRT), degrees of freedom (df) and significance (p) relate to the removal of each variable individually from the full model and testing the difference between the resulting and full models

Fixed Effects	**Estimate**	**Standard Error**	**AIC**	**Likelihood Ratio Test**	**df**	**p**
Sustenance zone size: 5km (n = 243)						
Intercept	-14.94	16.44				
Turbine density	-33.23	168.78	2965.10	0.04	1	0.844
Broadleaved woodland % land cover	2.88	1.55	2968.60	3.45	1	0.064
Urban and suburban % land cover	-1.36	1.07	2966.70	1.62	1	0.204
Sustenance zone size: 4km (n = 250)						
Intercept	-19.23	16.05				
Turbine density	-385.81	457.20	3064.20	0.71	1	0.400
Broadleaved woodland % land cover	2.82	1.38	3067.70	4.17	1	0.042
Urban and suburban % land cover	-0.88	0.97	3064.30	0.82	1	0.367

Table S2.11: GLM output from the turbine presence outcome / roost size predictor (all species) models, including sustenance zone radii of 5km and 4km, 2010-12 mean roost population counts and applying a binomial error distribution. The values for Deviance, AIC, the Likelihood Ratio Test (LRT), degrees of freedom (df) and significance (p) relate to the removal of each variable individually from the full model and testing the difference between the resulting and full models

Fixed Effects	**Estimate**	**Standard Error**	**Deviance**	**AIC**	**Likelihood Ratio Test**	**df**	**p**
Sustenance zone size: 5km (n = 370)							
Intercept	-0.43	0.26					
Roost size	-0.0004	0.0007	500.99	506.99	0.33	1	0.565
Broadleaved woodland % land cover	0.05	0.02	504.60	510.60	3.93	1	0.047
Urban and suburban % land cover	0.03	0.02	505.87	511.87	5.20	1	0.023
Sustenance zone size: 4km (n = 381)							
Intercept	-0.75	0.25					
Roost size	-0.0002	0.0007	504.96	510.96	0.04	1	0.838
Broadleaved woodland % land cover	0.02	0.02	505.56	511.56	0.64	1	0.424
Urban and suburban % land cover	0.04	0.01	512.94	518.94	8.02	1	0.005

Table S2.12: GLM output from the turbine presence outcome / roost size predictor (all species) models, including sustenance zone radii of 3km and 2km, 2010-12 mean roost population counts and applying a binomial error distribution. The values for Deviance, AIC, the Likelihood Ratio Test (LRT), degrees of freedom (df) and significance (p) relate to the removal of each variable individually from the full model and testing the difference between the resulting and full models

Fixed Effects	**Estimate**	**Standard Error**	**Deviance**	**AIC**	**Likelihood Ratio Test**	**df**	**p**
Sustenance zone size: 3km (n = 385)							
Intercept	-1.06	0.26					
Roost size	0.00005	0.0008	450.90	456.90	0.00	1	0.953
Broadleaved woodland % land cover	-0.001	0.02	450.90	456.90	0.00	1	0.944
Urban and suburban % land cover	0.02	0.01	453.11	459.11	2.21	1	0.137
Sustenance zone size: 2km (n = 393)							
Intercept	-1.66	0.31					
Roost size	-0.001	0.001	333.64	339.64	1.64	1	0.201
Broadleaved woodland % land cover	0.0005	0.02	332.00	338.00	0.00	1	0.982
Urban and suburban % land cover	0.02	0.01	333.67	339.67	1.67	1	0.196

Table S2.13 Overview of wind turbine planning outcomes by planning authority

Planning Authority	Total applications received	Total unique turbine site applications	Refusals	Pending or Appeal In Progress	Permission	Temporary Permission	Unknown Decision Status	Total Approved Individual Turbines
Bath and North East Somerset Council	21	17	8		9			11
Blaenau Gwent County Borough Council	17	14	5	4	5			5
Borough of Poole	7	7	3		4			4
Bournemouth Borough Council	3	3	2		1			2
Brecon Beacons National Park Authority	25	20	8		12			13
Bridgend County Borough Council	25	22	5	3	13	1		42
Bristol City Council	29	14	2	1	11			19
Caerphilly County Borough Council	21	18	7	3	8			14
Cardiff Council	11	11	2		9			10
Carmarthenshire County Council	188	167	31	38	99		1	184
Ceredigion County Council	120	106	22	17	67			147
Cheltenham Borough Council	2	2			2			2
Christchurch Borough Council	3	3	1		2			2
City and County of Swansea	22	18	9		9			27
Conwy County Borough Council	80	60	18	7	35			57
Cotswold District Council	28	21	7		14			16
Dartmoor National Park Authority	29	25	7		17		1	18
Denbighshire County Council	74	48	8	2	38			101

Planning Authority	Total applications received	Total unique turbine site applications	Refusals	Pending or Appeal In Progress	Permission	Temporary Permission	Unknown Decision Status	Total Approved Individual Turbines
East Devon District Council	32	26	3	1	22			25
East Dorset District Council	3	3	1		2			3
Exeter City Council	5	5	2		3			8
Exmoor National Park Planning Authority	41	33	9		24			25
Flintshire County Council	44	37	9	3	25			26
Forest of Dean District Council	36	27	4	1	22			25
Gloucester City Council	9	7				7		11
Gwynedd County Council	60	53	17	6	30			35
Isle of Anglesey County Council	108	93	29	21	42	1		117
Isles of Scilly	1	1			1			1
Mendip District Council	83	61	13	7	40		1	43
Merthyr Tydfil County Borough Council	13	11	7	1	3			3
Mid Devon District Council	93	79	23	7	49			56
Monmouthshire County Council	31	28	6	3	19			20
Neath Port Talbot County Borough Council	37	26	11	3	12			129
Newport City Council	37	17	2	3	12			14
North Devon District Council	144	103	30	13	60			93
North Dorset District Council	24	19	6	1	12			12
North Somerset Council	31	25	7	2	16			18
Pembrokeshire Coast National Park Planning Authority	67	50	15	3	31	1		39

Planning Authority	Total applications received	Total unique turbine site applications	Refusals	Pending or Appeal In Progress	Permission	Temporary Permission	Unknown Decision Status	Total Approved Individual Turbines
Pembrokeshire County Council	220	180	59	13	108			125
Plymouth City Council	24	20	5		14	1		24
Powys County Council	189	169	22	23	124			363
Purbeck District Council	17	11	2		9			9
Rhondda Cynon Taf County Borough Council	39	33	9	8	16			60
Sedgemoor District Council	44	34	11	2	20		1	21
Snowdonia National Park Authority	41	36	6	3	27			27
South Gloucestershire Council	43	33	9	3	21			26
South Hams District Council	88	75	17	11	47			54
South Somerset District Council	52	41	18	1	22			23
Stroud District Council	35	30	7	1	21	1		22
Swindon Borough Council	15	13	7		6			7
Taunton Deane District Council	34	27	4	1	22			24
Teignbridge District Council	28	23	5		18			21
Tewkesbury Borough Council	5	4	1		3			3
Torbay Council	5	5	1		4			21
Torfaen County Borough Council	6	6	2		4			6
Torridge District Council	177	140	32	31	77			94
Vale of Glamorgan Council	31	27	16		11			11
West Devon Borough Council	54	44	10	5	29			41
West Dorset District Council	62	48	19		29			29

Planning Authority	Total applications received	Total unique turbine site applications	Refusals	Pending or Appeal In Progress	Permission	Temporary Permission	Unknown Decision Status	Total Approved Individual Turbines
West Somerset District Council	8	7	1		6			6
Weymouth and Portland Borough Council	12	12	3		9			12
Wiltshire Council	54	44	12		31		1	34
Wrexham County Borough Council	12	10	4		6			6

3 Bat fatality and disturbance at small and medium wind turbine sites

3.1 Abstract

The majority of published research concerning the impacts of wind turbines upon wildlife has focused on large scale wind turbines at commercial wind farm locations. Of the species so far acknowledged to suffer impacts at turbine sites, bats have perhaps shown the greatest vulnerability. Bat fatalities and to a lesser extent, disturbance, have been recorded across numerous continents. Only recently has the scope of research into impacts upon bats widened to include those observed at small and medium wind turbine sites. This scale of turbine is often installed in domestic settings and at farms, businesses and community energy schemes. Early studies have confirmed bat fatality and disturbance in the immediate vicinity of small wind turbine sites (Minderman et al. 2012; 2015).

This study aimed to widen the volume of monitoring research at small and medium wind turbines and to provide an updated estimate of fatality rates, based on the use of a trained search dog to locate bat carcasses. Bat activity levels were also compared between the turbine location, linear habitat features and open habitat, to identify any disturbance caused by the turbine. Finally the moderating influence of weather and habitat conditions upon bat activity levels at turbine locations was investigated. Only 3 bat carcasses were observed during monitoring at turbine sites, yielding an average unadjusted fatality rate of 0.81 turbine^{-1} year^{-1} at single micro, small or medium size turbines in the UK. Due to the low volume of observed fatalities and the inherent uncertainty in fatality monitoring, an estimate was produced of the maximum fatality rate that could potentially have occurred at each site and not been observed due to the search protocol applied. This produced a worst-case-scenario maximum fatality rate of 15.15 turbine^{-1} year^{-1}. This is considered likely to represent an unrealistically high rate. Further fatality monitoring using a stringent monitoring protocol may be able to reduce the uncertainty levels in this estimate and

potentially confirm a more realistic, lower fatality rate. A small disturbance effect upon bat activity levels in proximity to turbines during high wind speeds was also identified. This impact dissipated within 33-47m. A number of weather and habitat conditions were found to exhibit significant moderating influences upon bat activity levels at small and medium wind turbine locations. These results support existing calls for updated planning guidance concerning bats at proposed small and medium wind turbine sites.

3.2 Introduction

The current shift towards renewable sources of energy production in the UK and globally has led to increasing numbers of wind turbine installations (RenewableUK, 2015; World Wind Energy Association (WWEA), 2014). This trend is forecast to continue globally into the foreseeable future (WWEA, 2014). Growth in the UK wind energy market has recently slowed due to large-scale changes in Government energy policy, planning policy and funding mechanisms. Wind power is nonetheless the largest energy producer in the UK renewable sector (RenewableUK, 2015). Wind turbines are therefore becoming an increasingly common feature of UK landscapes.

3.2.1 Bat fatalities

Though considered beneficial for the sustainability and security of future energy production, wind turbines have some environmental impacts. This includes their potential to cause bird and bat fatalities (Strickland et al. 2011; Rodrigues et al. 2015). Bat fatalities have been recorded in large numbers at some wind farm sites in the USA (Arnett et al. 2008). As a result, the volume of research into the subject has grown rapidly. This is especially true of monitoring programmes across North America, where magnitudes of bat fatalities have been found to vary significantly across sites (Arnett et al. 2016).

Similar research effort is increasing across Europe, identifying bat fatalities in numerous countries (Rydell et al. 2010a; Ferri et al. 2011; Camina 2012; Georgiakakis et al. 2013). This includes the UK, where initial research, reporting and turbine owner communications have identified fatality occurrences (Rydell et al. 2010a; Jones et al. 2009; Minderman et al. 2015; University of Exeter, unpublished research). The current study aimed to investigate whether small and medium scale wind turbines pose fatality or disturbance risks to UK bat species.

3.2.2 Non-fatal impacts

Few studies have considered non-fatal impacts of turbines upon bats such as disturbance and displacement. A small number have however identified bats' behavioural patterns around turbines including investigation, foraging and roosting (Brinkmann et al. 2006; Horn et al. 2008; Ahlén et al. 2009; Rydell et al. 2010a; Hensen, 2004). A study comparing bat activity at turbines with control sites (in Iowa, USA) showed no significant difference in activity levels, indicating displacement did not occur (Jain et al. 2011). However, as bat species assemblages in Europe are considerably different to North America, it is vital that displacement and disturbance are investigated in the European context.

Disturbance can also occur within sites at a local scale. Reductions in bat activity levels at small turbines in the UK have been observed during high wind speeds, relative to monitoring 20m away (Minderman et al. 2012). A long term study at a wind farm in Germany showed some evidence of displacement of bats, where effect levels varied between species. Deviations from flight paths were also observed at a micro scale within the site (Bach and Rahmel, 2004).

Whilst research concerning non-fatal impacts upon bats is limited, studies concerning effects upon birds are more extensive. It may be possible, therefore, to infer from these studies the potential for non-fatal impacts upon bats from turbines. Research upon birds has observed displacement from turbine development and associated habitat changes, though effects are often moderate or species-specific (Strickland et al. 2011). Displacement often comprises flight avoidance of wind farms (Desholm and Kahlert, 2005; Plonczkier and Simms, 2012; Villegas-Patraca et al. 2014) or, on a micro scale, individual turbine avoidance (Everaert, 2014). Breeding grounds and general bird distributions can also be affected by displacement (Pearce-Higgins et al. 2009; Strickland et al. 2011). Bats are known to be vulnerable to both habitat and roost disturbance (Berthinussen and Altringham, 2012; Arlettaz et al. 2000). Consequently it is reasonable to suggest that bats may be susceptible to impacts similar to those experienced by birds.

3.2.3 Environmental conditions

In addition to research considering fatality and disturbance, efforts are also focused upon understanding why such impacts occur and in which weather and habitat conditions risk levels are highest. Elevated bat activity and fatality levels at wind farms in continental Europe and North America have been found to relate to warmer temperatures, lower wind speeds and higher levels of insect prey (Arnett et al. 2011; Amorim et al. 2012; Georgiakakis et al 2013; Baerwald and Barclay, 2011; Weller and Baldwin, 2012; Gorresen et al. 2015; Arnett et al. 2008; Brinkmann et al. 2006; Kerns et al. 2005; Rydell et al. 2010a; Horn et al. 2008). A significant knowledge gap remains in the context of small turbines.

The effect of habitat and topography is less clear – varying rates of association with fatality and activity levels have been observed in both Europe and North America. Some studies have indicated that wooded hilltops and locations within 100m of woodland (in Europe) as well as forested ridges and heads of ravines (in North America) may represent higher risk habitats (Rydell et al. 2010a; Arnett et al. 2008; Piorkowski and O’Connell, 2010; Dubourg-Savage et al. 2011; Baerwald and Barclay, 2009; Brinkmann et al. 2006).

Observations from a limited number of UK-based studies have indicated similar moderating influences from weather and habitat (Minderman et al. 2012; University of Exeter, unpublished research). Interim guidance concerning bats has been produced for wind turbine planning applications in the UK (Natural England, 2014; Natural England et al. 2009) and Europe (Rodrigues et al. 2015) based upon current research findings. However this guidance focuses primarily upon wind farms and large turbines and has yet to be field-validated in the UK. Furthermore, inconsistencies exist in the application of guidance in the context of small wind turbines (Park et al. 2013).

3.2.4 Study aims

The current study aimed to reduce the knowledge gap in the UK, by investigating whether small and medium scale individual wind turbines present any fatality or disturbance risks to UK bat species. Environmental variables were analysed to improve our understanding of the factors influencing bat activity levels at small and medium single turbines. The study aimed to provide monitoring evidence to aid planning guidance development for small wind turbine installations in the UK.

3.3 Methods

3.3.1 Study area

The chosen study area was Wales and the south west (SW) region of England – areas with relatively large, species-diverse populations of bats (Bat Conservation Trust, no date). Potential study sites were identified from wind turbine planning applications. Sites with no more than three installed turbines were selected, with a total height to blade tip <100m. Each turbine was required to be mounted on a standalone mast (not building-mounted) and to have a horizontal axis (Figure 3.1). Differing numbers of blades were acceptable. If multiple turbines were installed at a site, only one was monitored; selection was random unless constrained by access.

Sites were selected to obtain a suitable geographical spread across the study area (at least one site in each county across SW England and a spread across Wales). Site selection aimed to include at least one turbine within each size classification from the UK renewable energy industry's representative body RenewableUK (RenewableUK, 2013). Turbine blade-tip heights are classified as follows: micro (10-15m); small (15-30m); medium (30-55m); large (>55m) (RenewableUK, 2013). An additional category was also added – sub-micro (<10m).

Following contact with turbine and land owners, permission was granted to access and monitor 31 turbine sites. 28 featured a single turbine and 3 featured two turbines. The turbines monitored fell into the following size categories: sub-micro (3), micro (7), small (13), medium (5) and large (3). The proportions of turbines within each size category and geographical area provided a representative sample of approved wind turbine sites within the study area (Figure 3.2), with the exception geographically of slight under-sampling in Wales and over-sampling in Devon. Large turbines were intentionally under-sampled due to the focus of this study on small turbines. It was felt beneficial to include the 3 large individual wind turbines within the sample as a partnering wind farms project (University of Exeter) included only sites with at least 5 turbines.

Figure 3.1: Examples of horizontal axis (left) and vertical axis (right) format wind turbines (image sources: C&F Green Energy (2015) (left), VWT Power (2014) (right))

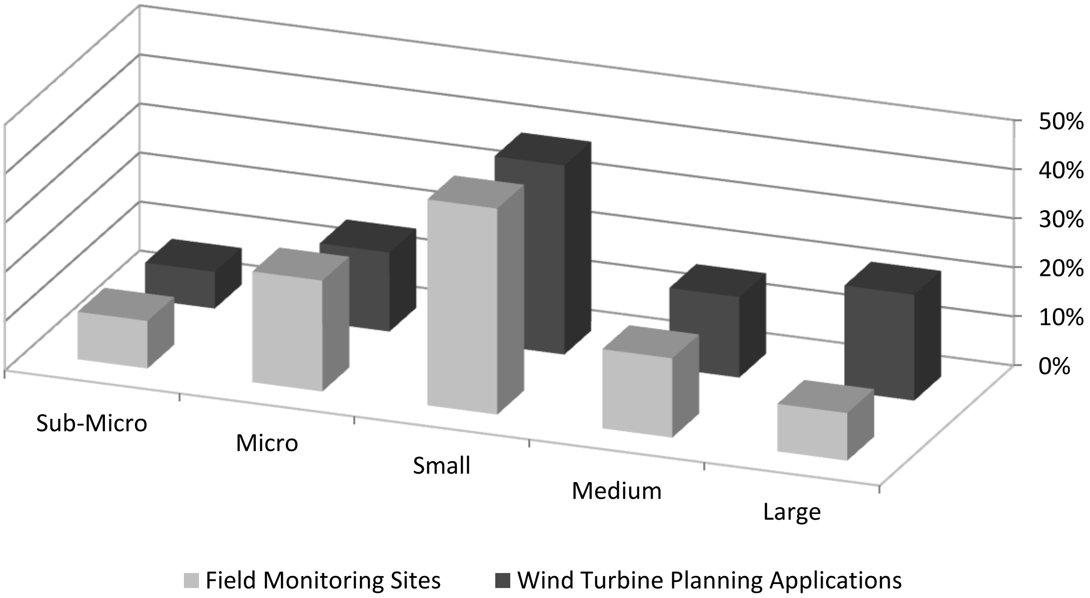

Figure 3.2: A comparison of the percentage of wind turbines falling within each turbine size category (RenewableUK, 2013) from: field-monitored wind turbines (n=31) (grey) vs. a sample (n=348) of wind turbine site applications received up to 2013 by 12 local planning authorities within the study regions (black). For the latter, each site is treated as a single turbine size regardless of numbers of turbines present.

3.3.2 Field monitoring protocol

Field monitoring was carried out during May-October in 2012 (13 sites) and 2013 (14 sites) and June-July in 2014 (4 sites), with monitoring taking place concurrently at groups of 2-4 sites at a time. Monitoring was planned for four weeks at each site with five visits per site, applying the monitoring schedule described below; required modifications due to fieldwork logistics are listed in Table 3.1. Bat carcass searches were conducted at approximately equal intervals (5 at each site during 2012 and 2014, 3 during 2013) using a professionally-trained sniffer search dog (trained specifically for bat carcass searches) and handler. The handler worked the dog along parallel 100m transects spaced approximately 5-10m apart (depending upon habitat density), traversing a 100x100m square centred upon the turbine. The dog was allowed to deviate from these transects in order to follow scents and was subsequently returned to the last point reached, before continuing.

A search efficiency trial following Mathews et al. (2013) was conducted at most sites (25/31) to assess the dog and handler's search performance. In addition, rates of carcass removal by predators were estimated by monitoring, at each visit, whether 3-5 bat carcasses remained where they had been placed on the first monitoring day, within a 100x100m area.

Nine tripod-mounted Batbox Baton frequency division bat detectors linked to Zoom H2n audio-recorders and external batteries were planned to be installed at each site, in a 3x3 grid centred on the turbine; each detector being 33.3m apart (see Figure 3.3). Three detectors were utilised in this study, whilst the full grid was the focus of a separate study (Chapter 4). One Wildlife Acoustics Song Meter 2 (SM2) full spectrum bat detector (also powered by an external battery) was installed with its microphone attached to a 2.5m tripod at the base of the turbine. A weather station was installed, located in open space to reduce wind shading or turbulence due to vegetation and buildings. Due to varying spatial configurations of sites and land ownership limits, installation of the full grid of 9 Baton detectors was not always possible, in such instances fewer detectors were installed (Table 3.1). Installation of a full or partial grid of detectors was possible at all but one site (the latter featured just the SM2 detector and weather station). Detectors' external battery levels, use of recording storage capacities and any damage to equipment were recorded during each site visit.

Table 3.1: Details of site monitoring programme. Sites 12 and 13 are excluded as the turbine had yet to be constructed at the sites, which were monitored to carry out pilot pre-construction monitoring observations

Site Number	Number of monitoring nights (day span of carcass searches if different)	Number of carcass searches	Carcass removal test	Search efficiency test	Number of Baton detectors
1	28	4	Yes	Yes	6
2	28	5	Yes	Yes	9
3	28	5	Yes	Yes	0
4	28	5	Yes	Yes	5
5	28	5	Yes	Yes	9
6	28	5	Yes	Yes	9
7	25	5	Yes	Yes	9
8	27	4	Yes	Yes	9
9	28	5	Yes	Yes	5
10	28	4	Yes	Yes	6
11	28	5	Yes	Yes	6
14	29	5	Yes	Yes	9
15	29	5	Yes	Yes	7
16	Batons: 28, SM2: 21	5	Yes	Yes	5
17	Batons: 26, SM2: 21	5	Yes	Yes	8
18	25 (20)	3	Yes	Yes	9
19	27 (0)	0	Yes	NA	9
20	28 (30)	3	Yes	Yes	9
21	28 (20)	3	Yes	Yes	9
22	28 (14)	3	Yes	No	9
23	27 (15)	3	Yes	Yes	9
24	29 (14)	3	Yes	Yes	9
25	28 (14)	3	Yes	No	8
26	Batons: 20, SM2: 28	3	Yes	No	9
27	28	3	Yes	No	9
28	Batons: 20, SM2: 13	2	Yes	No	9
29	27 (28)	5	Yes	Yes	9
30	21 (28)	5	Yes	Yes	9
31	20	4	Yes	Yes	9
32	30 (28)	3	Yes	Yes	9
33	28	5	Yes	Yes	9

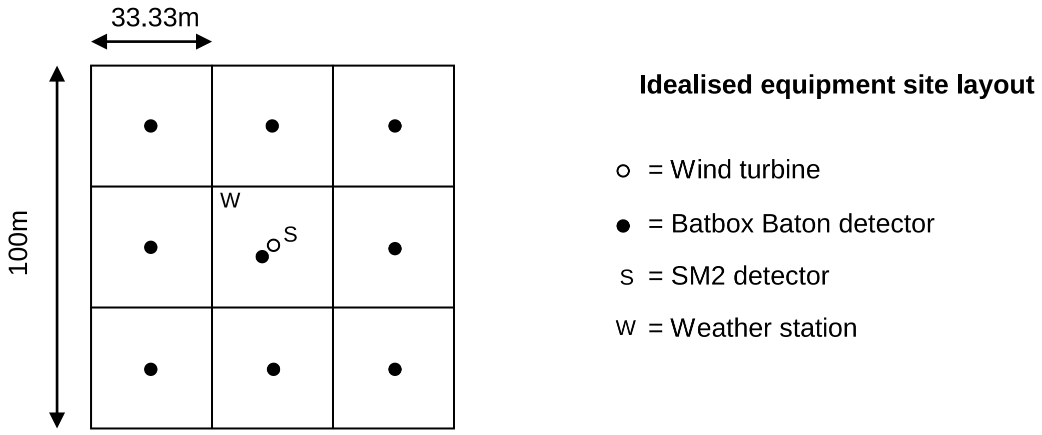

Figure 3.3: An idealised diagram of equipment layout at monitored wind turbine sites

3.3.3 Bat sound analysis

Recording nights started half an hour before sunset and ended half an hour after sunrise (daily sunrise/set times were used). Wildlife Acoustics ‘Songscope’ software was used to complete a species auto-identification scan on the Baton detector recordings, using reference ‘recogniser’ files built from sampled Baton bat recordings where species had been identified. Recordings from the Baton detectors exceeding 1 minute were first manually checked for presence of any bat passes using the Pettersson Elektronik ‘Batsound’ viewer software. This was due to the extensive auto-ID scanning time required for long files. Almost all such files were identified as noise recordings (predominantly rain) and consequently were excluded from further processing. Any long files with bat passes were retained and scanned.

Wildlife Acoustics’ ‘Kaleidoscope Pro’ software was used to undertake automated species identification for the SM2 recordings. For both detector types, all non-*Pipistrellus* genus classifications were manually checked, as the relative accuracy of recognisers for those genera was low. The Kaleidoscope Pro *Pipistrellus* recogniser accuracy is 86% (Wildlife Acoustics, 2014). For the Baton recordings, any noise-classified files with a high proportion of sound sections indicating a potential bat classification were also manually checked. A single bat pass was defined as at least 2 echolocation calls within 1 second of one another.

Using equipment status information recorded during monitoring, each detector recording night was flagged as either suitable or unsuitable. This was based upon detector and recorder battery levels, recording file capacity, equipment damage observations and recorded weather conditions. Suitable weather conditions were defined as nights with mean wind speed <= 8m/s, mean temperature >=10^{o}C and mean hourly rainfall <= 2.5mm. Nights with large fluctuations in these weather conditions were also removed. Weather conditions were not used to filter recording nights for the analysis of environmental conditions' effect upon bat activity.

3.3.4 Statistical analyses

3.3.4.1 Estimating levels of bat fatality

Due to a low volume of observed fatalities, an estimate was produced of the total fatalities that could potentially have occurred at each site and not been observed due to the search protocol used. Two sites were removed from the calculations due to no searches being carried out at one site and an insufficient number of searches (2) at the other for carrying out fatality calculations. 29 sites were therefore analysed. The 'Evidence of Absence' (EoA) software (Dalthorp et al. 2014a) was used to calculate fatality estimates. EoA is suitable for use with zero or low fatality sites whereas other estimators are not (e.g. the *carcass* package (Korner-Nievergelt et al. (2014, 2015)) within the 'R' software (R Core Team, 2014)). The software uses Bayes' formula to estimate credible intervals of fatality totals (Dalthorp et al. 2014b; Huso et al. 2015) and accounts for the uncertainty in carcass persistence and search efficiency data using repeated simulations across distributions. *Carcass* is still suitable for use in understanding the probability of observing carcasses (and as such is applied in this manner below), whilst being unsuitable for the latter derivation of estimated fatalities in the context of low observed fatalities. EoA requires the following input for each site:

1. Carcass count: The number of observed carcasses

2. Sampling coverage: The searchable proportion of the area in which carcasses were likely to fall. All carcasses were assumed to fall within

the 100x100m search area. This assumption was supported by datasets from previous carcass distribution studies (Arnett et al. 2005; Niermann et al. 2011), as supplied within the *carcass* package. Unsearchable areas were digitised from field mapping using ESRI ArcGIS 10 software, referenced against aerial imagery and Ordnance Survey Mastermap data obtained from the Edina Digimap service. The proportion (from 0 to 1) of searchable area was calculated for concentric 10m ring buffers from the turbine up to 50m (the final 40-50m ring also included the 50m+ areas at the corners of the search square). These proportions were multiplied by empirically derived values of the proportion of carcasses that typically fall within each 10m ring (using the results from Niermann et al. 2011 in the *carcass* package). Finally the sum of the resulting values represented the searchable proportion of the site

3. Searcher Efficiency: The search efficiency trial results were used as input in the *carcass* package to calculate estimates of the probability of the searcher finding carcasses, along with upper and lower 95% confidence intervals (CI). EoA also requires a factor by which searcher efficiency changes with each search – efficiency was assumed to stay constant, resulting in a value of 1. For four sites where search efficiency trials were not completed, search efficiency results from another site with the closest matching habitat structure were applied

4. Sampling Dates: The carcass search dates were entered, resulting in a mean search interval and search span in days

5. Carcass Persistence Distribution: The *Estimator* software (Huso et al. 2012) was used to calculate an average carcass persistence probability curve from the combined persistence data from all monitored sites. This is because the data from most individual sites did not provide sufficient information for different persistence timeframes to produce a curve. This is an approach used in previous studies (e.g. Minderman et al. 2015). *Estimator* fits a number of failure time distribution curves to the data to model persistence. In order to identify the best fitting curve, the *carcass* package was used to calculate probabilities of persistence using the

observed data, in order to compare fit against the *Estimator* curves. The Weibull failure time distribution best fitted the observed carcass persistence data. These were used with 10,000 simulations to calculate a mean persistence time (51.34 days, 95% CI = 33.81-99.57) and probability of persistence for a search interval of 8 days (0.84, 95% CI = 0.77-0.9) which were entered in EoA

6. Prior Distribution: A uniform prior distribution of fatalities was used, due to a lack of existing knowledge about fatality at small wind turbines (or turbines in the UK generally)

7. Arrival Function: A uniform arrival function was assumed, due to a lack of knowledge about seasonal or inter-day patterns of fatalities at small turbines (or turbines in the UK). Furthermore as the maximum sampling period at each site was 4 weeks, little variation may be expected

8. Credibility Level: A value of 0.95 was used (i.e. $p = 0.05$)

A posterior probability distribution and maximum estimate of 95% credible total fatalities was produced for each site, along with a probability estimate of observing carcasses (with 95% CI).

3.3.4.2 Differences in bat activity with varying proximity to a wind turbine

The effect of turbine presence upon bat activity rates was tested by comparing measured activity rates from three Baton detectors at each site. The first was located at the base of the wind turbine (‘turbine’ position), the second at a distance of 33.3-47.1m (mean 40m) from the turbine (see adjacent and corner cells in Figure 3.3) and next to a linear habitat feature (‘feature’ position) and the third also located 33.3-47.1m (mean 40m) from the turbine but in open habitat (‘open’ position).

Nights were excluded where poor weather, detector / battery failure or recorder capacity resulted in insufficient monitoring. Sites were excluded where habitat structure (e.g. absence of linear features) restricted comparative analysis.

Activity measured at the three detectors was required to be recorded during the same shared nights between all detectors. A mean of 7 shared monitoring nights were obtained from 26 sites (total nights = 179).

A generalised linear mixed effect model (GLMM) was calculated using the *glmmadmb* package (Skaug et al. 2014) in *R* to assess the effect of turbine presence and habitat type (i.e. detector position: turbine / feature / open) upon recorded nightly levels of bat activity. Total nightly bat passes (of all species) was set as the dependent variable, with an offset for length of monitoring night to account for varying night lengths. Detector position (turbine/ feature / open) was used as a fixed factor variable and was separately nested within site as a random effect. The model used a negative binomial error distribution, due to over-dispersion observed in the data. Mean nightly temperature (^{o}C) and wind speed (m/s) were included as fixed covariates and nightly rainfall occurrence was included as a fixed factor.

The contribution of each variable to the model and its significance was assessed using ANOVA tests, likelihood ratio tests and Akaike information criterion (AIC) values. The contribution of each variable and overall model fit, quality and predictive ability were also assessed using residuals plots for the overall model and each individual variable, in addition to inter-variable correlation plots, measures of over-dispersion, leverage plots to consider outliers, pseudo R-squared values and predictions plotted against observed values. Outliers mutually confirmed via leverage plots, residuals plots and model prediction plots were removed to improve model fit.

As the analysis was focused upon identifying the effect of the turbine and a number of monitored turbines were located close to linear habitat features, a second version of the model was created to investigate the potential modifying effect of distance to linear features from detectors. The same model configuration was used, with the inclusion of an interaction between detector position and distance to the nearest linear habitat feature (hedge or tree line).

In order to identify the remaining effect of turbine presence in the event of any influence from distance to linear features, a third model was additionally produced. The configuration of the first model was again replicated, with distance to nearest linear habitat feature included as a fixed covariate, whilst the detector positions were re-categorised as adjacent to or away from the turbine (i.e. turbine presence / absence). Finally a variant on this model was also calculated, adding an interaction between the turbine presence factor and wind speed in order to test for the wind speed-reliant effect of turbines observed during the only existing small turbine field research (Minderman et al. 2012).

3.3.4.3 Environmental conditions and bat activity

19 environmental variables were recorded for each turbine site, including weather conditions, land cover types, linear habitat feature length, distance to nearest linear habitat feature, turbine dimensions, season and existing bat roost populations (see Supplementary Materials Table S3.1 for a list of the variables).

Weather and turbine variables were based on data collected at site, whilst habitat variables were calculated from Landcover Map 2007 data (LCM) (Centre for Ecology and Hydrology (CEH), 2011), OS Mastermap data and aerial imagery using ESRI ArcGIS 10 and Geospatial Modelling Environment software. Hedges on opposite sides of roads were treated as a single linear feature, except in the case of dual carriageways or motorways. Bat roost variables were calculated from data provided by the UK Bat Conservation Trust.

The relationship of environmental variables with bat activity levels recorded by the SM2 detectors was tested. 27 sites were included after removing 4 due to weather station or detector failure. Weather data was applied to 1 of the 27 sites from a nearby site (approx. 6 km) after weather station failure.

A number of model iterations were calculated to remove unimportant candidate variables, using generalised linear models (GLM) in *R*, assessing at each iteration the significance of effects of included variables, whether the proposed effect of variables was logical, the quality of model fit to the measured data (using methods as described above) and the relative quality of the model assessed against the other models (using AIC values). Upon reaching a subset of variables showing potential for relationships with bat activity, these variables were investigated using both site- and night-level datasets to further refine model configuration (applying GLMs and GLMMs respectively) to reach the minimum adequate model required to explain variability of bat activity.

A GLMM with a negative binomial error distribution was calculated using the *glmmadmb* package to assess the effect of each environmental variable upon nightly levels of bat activity. Total nightly bat passes (of all species) was set as the dependent variable, with an offset for length of monitoring night to account for varying night lengths. Site was set as a random effect. Mean nightly temperature, mean nightly wind speed (log transformed to reduce heterogeneity in model residuals in relation to this variable), distance to nearest linear habitat feature and proportion of built environment landcover within 5km were included as fixed covariates and nightly rainfall occurrence was included as a fixed factor. The same model validation and assessment methods as described above were also applied. Outliers mutually confirmed via leverage plots, residuals plots and model prediction plots were removed to improve model fit. The night-level analyses were repeated for three genera groups (1: *Pipistrellus;* 2: *Nyctalus* and *Eptesicus;* 3: *Myotis, Barbastella, Plecotus and Rhinolophus* ('Woodland bats')).

A second all-species model was created applying the same configuration at site level, though using the *glm.nb* function in *R* (MASS package (Ripley et al. 2015)) to calculate a GLM, applying a negative binomial error distribution. Total bat passes across the monitoring period at each site were used as the dependent variable, alongside total monitoring hours as an offset. All predictor variables used mean values for the monitoring period at site rather than nightly values and the wind variable was not log transformed due to improved residuals at site level. Rainfall was changed to a fixed covariate and represented mean hourly rainfall across the monitoring period. A single outlier site was removed after inspection of leverage, residual and prediction plots.

3.4 Results

3.4.1 Estimating levels of bat fatality

Across the 30 sites where carcass searches were completed, 3 bat carcasses were found in total. Their genera were identified as *Pipistrellus*, *Myotis* and unknown due to decomposition. The dog/handler team achieved an average efficiency of 90.2% in locating trial carcasses. Carcass removal was found to exhibit a bimodal pattern, with half (49.6%) of the trial carcasses persisting for the whole monitoring period and approximately a quarter (24%) being removed within the 1st week. 11.6% persisted for only 1 week, 10.7% for only 2 and 4.1% for only 3. The probability of individual carcass persistence times as modelled within the carcass application was as follows: 7 days: 0.76 (0.69-0.84), 14 days: 0.65 (0.57-0.74), 21 days: 0.56 (0.48-0.66), 28 days: 0.51 (0.43-0.61). The average probability of carcasses persisting during the average search interval (8 days), accounting for differing arrival times during that period, as modelled within EoA was 0.84 (0.77-0.9), (i.e. this does not represent the probability of persistence for the maximum of 8 days). The overall estimated probability that a carcass would be found following fatality as modelled within EoA ranged across sites from 0.38 (0.34-0.41) to 0.86 (0.8-0.91) (mean = 0.74). This accounted for search interval, proportion of inaccessible search area, search efficiency and carcass persistence.

The fatality rate at one site was not estimated due to an insufficient number of carcass searches. The estimated maximum possible number of fatalities that may have occurred across the 29 analysed sites after observing 3 carcasses was 99 ($p = 0.05$) (0.134 fatalities turbine^{-1} night^{-1}). This incorporates the uncertainty produced by the monitoring protocol, which is likely to result in an unrealistically high fatality rate. This dropped to a maximum of 56 ($p = 0.05$) across 27 sites (0.082 fatalities turbine^{-1} night^{-1}) after excluding two sites with very low probabilities of observing carcasses (<0.4; the mean probability from the remaining sites was 0.76). The low probabilities at these 2 sites resulted in large analytical uncertainty and consequentially large potential maximum fatality estimates. The low probabilities were caused by a poor search efficiency rating at one of the sites and a low proportion of accessible search area at the other.

Assuming bat mortality at turbines only occurs between May and October (i.e. excluding the very minor numbers of fatalities previously observed during April and November) (Rydell et al. 2010a; Arnett et al. 2008), the 3 carcasses observed across the reliable survey sets from 27 sites suggest an unadjusted fatality rate of 0.81 turbine^{-1} year^{-1} may occur on average at single micro, small or medium size turbines in the UK, discounting the uncertainty incorporated in the search protocol. The equivalent worst-case scenario, accounting for uncertainty in the search protocol, implies a maximum fatality rate of 15.15 turbine^{-1} year^{-1}. The latter may be unrealistically high and a lower rate (that equally accounts for all monitoring uncertainty) may be confirmed by completing a dedicated set of fatality surveys with very stringent monitoring protocols (e.g. using a very short search interval).

3.4.2 Differences in bat activity with varying proximity to a wind turbine

The results from the GLMMs are shown in Tables 3.2-3.3 and S3.2-S3.4. Detector location was shown to have a significant effect in the first model (Table 3.2), identifying higher levels of activity near linear habitat features than turbine or open habitat positions. Higher activity levels were also recorded at turbine locations than in open habitat. However the second model identified a significant interaction of detector position with distance from linear habitat features (Table S3.2). The significance of distance to linear feature at turbine detectors was also confirmed in a separate verifying model (Table S3.3) where the variable was included as a covariate rather than within an interaction, using a subset of the data only including turbine detectors (where the detector position variable was removed).

Having accounted for the effect of distance to linear features in the third model (Table S3.4), no significant effect was recorded from turbine presence (i.e. now representing the remaining effect of detector position). However, after investigating the influence of wind speed upon the effect of turbine presence, the model was significantly improved (Table 3.3; testing the inclusion of the previously excluded outliers furthermore showed no qualitative change in model outcomes (Table S3.5)). Whilst bat activity was actually higher at the turbine during low wind speeds, the observed pattern reversed during high wind speed periods where activity was reduced from 0.53 (0.12-2.29) to 0.18 (0.02-0.79) passes per hour as a result of turbine presence (an average reduction of 78%) (see Figure 3.4a and 3.4b).

The negative effect upon bat activity levels of increasing distance from linear habitat features is consistent across the models. The inclusion of wind speed, temperature and rainfall occurrence significantly improved all four models, with the exception of a lower level of significance associated with temperature in the latter two models (Tables 3.3 and S3.4). Bat activity rates were found to decrease as a result of rising wind speeds and during nights with rainfall and to increase during warmer nights, with relatively consistent effect sizes across the models.

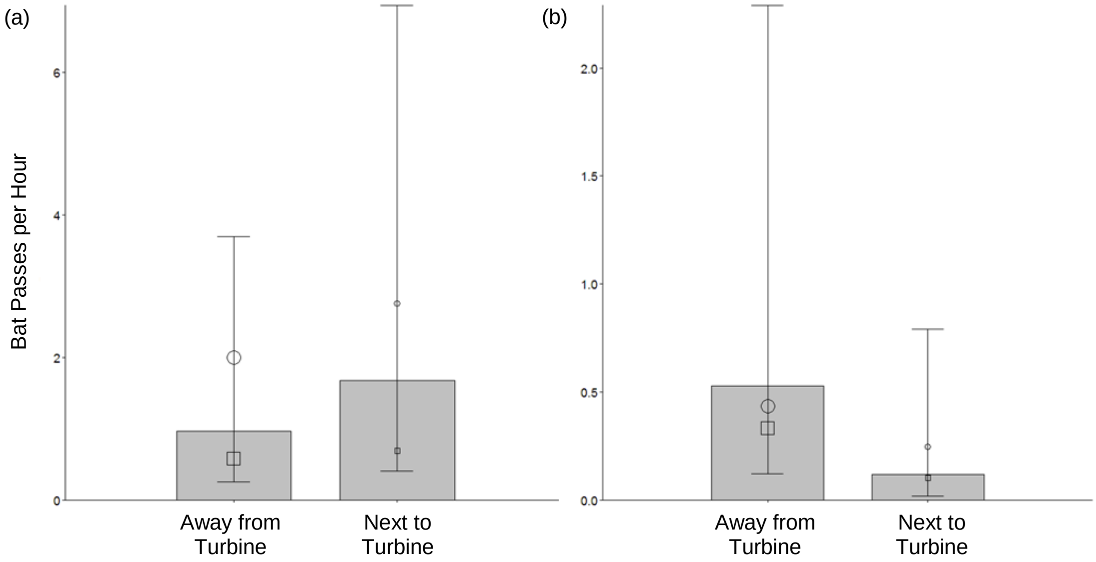

Figure 3.4: Estimated effect from the night level model of turbine presence on bat activity levels at small and medium wind turbine sites (a) during low wind speed conditions (0 m/s) and (b) during high wind speed conditions (3.75 m/s). Bars and CI lines = model prediction; circles = mean observed rate of bat passes; squares = median observed rate of bat passes; relative sizes of squares and circles represent relative contributing levels of data (larger = more data).

Table 3.2: Parameter estimates and likelihood ratio tests of the GLMM analysing the effect of turbine presence and habitat type (linear features and wooded habitat vs. open habitat) upon bat activity. The model used a negative binomial error distribution.

Fixed Effects	**Estimate**	**Standard Error**	**Log Likelihood**	**AIC**	**Deviance (Likelihood Ratio Test)**	**df**	**p**
(Intercept) [Detector Position = Feature]	0.25	0.45					
Mean Nightly Temperature (^{o}C)	0.05	0.03	-1597.8	3211.6	4.12	1	0.042
Mean Nightly Wind Speed (m/s)	-0.35	0.07	-1609.4	3234.7	27.28	1	<0.0001
Rainfall Occurrence During Night	-0.43	0.13	-1601.0	3218.1	10.6	1	0.001
Detector Position			-1607.7	3229.4	23.98	2	<0.0001
Detector Position [Open]	-1.55	0.28					
Detector Position [Turbine]	-0.86	0.27					

Table 3.3: Parameter estimates and likelihood ratio tests of the GLMM analysing the effect of turbine presence upon bat activity, incorporating the effect of distance to nearest linear habitat feature. Detector positions are amalgamated into ‘turbine presence’ and ‘turbine absence’ categories and their interaction with wind speed is tested. The model used a negative binomial error distribution.

Fixed Effects	**Estimate**	**Standard Error**	**Log Likelihood**	**AIC**	**Deviance (Likelihood Ratio Test)**	**df**	**p**
(Intercept)	0.52	0.48					
Mean Nightly Temperature (^{o}C)	0.05	0.03	-1640.1	3298.3	2.68	1	0.102
Rainfall Occurrence During Night	-0.37	0.15	-1641.8	3301.7	6.06	1	0.014
Distance to Nearest Linear Habitat Feature	-0.03	0.003	-1681.2	3380.4	84.84	1	<0.0001
Turbine Presence * Mean Nightly Wind Speed (m/s)	-0.55	0.14	-1646.2	3310.4	14.78	1	0.0001

3.4.3 Environmental conditions and bat activity

The total number of bat passes recorded from all sites (N) was 27,387 across 642 nights of monitoring (mean per detector-night = 42.7, std. dev. = 94.84).

82.9% of calls were identified as belonging to the *Pipistrellus* genus, 9.2% as *Nyctalus* and *Eptesicus*, 6.2% as *Myotis,* 0.7% as *Plecotus*, 0.7% *Barbastella*, 0.1% as *Rhinolophus* and Unclassified recordings comprised only 0.3%. Bat activity was recorded during 91.3% of monitoring nights.

Mean nightly temperature, mean wind speed, rainfall occurrence, proportion of built environment landcover and distance to linear habitat features were all found to have a significant effect upon nightly bat activity levels (Table 3.4). With the exception of temperature's positive association with bat activity, increases in all of these factors were found to have a negative influence on bat activity levels (Figure 3.5 a-e).

As mean nightly wind speeds at ground level (1.5m) increased from 0 to 6 m/s, average bat passes per hour were estimated to fall from 7.75 (2.66-22.59) to 0.61 (0.17-2.12), an average reduction of 92%. At a turbine hub height of 20m, due to wind shear with height this wind speed change represents an increase from approx. 0 to 10.7 m/s, based on a typical arable grassland landcover (applying a log law shear adjustment (Mathew, 2006)). However bat activity levels were not recorded at hub height and equivalent changes in bat activity at this height cannot be guaranteed. Similarly rainfall occurrence during a night was estimated to cause activity to drop from 2.6 (0.84-8.04) to 1.93 (0.61-6.15) passes per hour (an average decrease of 26%), whilst an increase in mean nightly temperature from 4.9^{o}C to 19.5^{o}C resulted in an increase from 0.82 (0.31-2.19) to 6.83 (1.81-25.82) passes per hour.

Differences in habitat structure in the surrounding landscape and at a local level within sites were also found to have an effect (Figure 3.5d and 3.5e). With an increase in proportion of built environment landcover within the surrounding landscape out to a 5km radius from 0.44% to 25%, hourly bat passes were estimated to decrease from 3.03 (1-9.2) to 0.64 (0.11-3.62), an average decrease of 79%. Similarly with an increase in distance from the nearest linear habitat feature of 2m to 100m, bat passes per hour were estimated to drop from 3.81 (1.31 to 11.09) to 0.75 (0.14-3.96) (an average decrease of 80%).

At a species group level, the effects of some environmental conditions were observed to vary. The *Pipistrellus sp.* analysis recorded no significant influence from rainfall or built environment landcover (see Table S3.6). Only wind and temperature were found to have a significant moderating influence upon *Nyctalus* / *Eptesicus* activity (see Table S3.7) though the effect size from wind was reduced relative to the all-species model. Finally, the 'woodland bats' model indicated a lack of significant influence of temperature and distance to nearest linear habitat feature upon activity (see Table S3.8), however an increased negative effect size of rainfall.

No turbine-related variables were found to have any significant effect during development of the models, including height to blade tip, number of blades and number of years since planning approval (a measure of relative approximate length of installation time).

At a site level, only wind speed and proportion of surrounding built environment land cover remained as significant predictors of bat activity levels (Table 3.5).

Table 3.4: Parameter estimates and likelihood ratio tests of the night-level GLMM analysing the effect of environmental variables upon bat activity. The model used a negative binomial error distribution.

Fixed Effects	**Estimate**	**Standard Error**	**Log Likelihood**	**AIC**	**Deviance (Likelihood Ratio Test)**	**df**	**p**
(Intercept)	0.78	0.41					
Mean Nightly Temperature (^{o}C)	0.14	0.02	-2156.2	4326.4	35.86	1	<0.0001
log (Mean Nightly Wind Speed (m/s))	-1.3	0.14	-2179.2	4372.4	81.9	1	<0.0001
Rainfall Occurrence During Night	-0.3	0.13	-2141	4296	5.44	1	0.02
Percentage of Landcover Within 5km Classified as ‘Built Environment’	-0.06	0.03	-2141.1	4296.1	5.62	1	0.018
Distance to Nearest Linear Habitat Feature	-0.02	0.01	-2141.7	4297.4	6.9	1	0.009

Table 3.5: Parameter estimates and likelihood ratio tests of the site-level GLMM analysing the effect of environmental variables upon bat activity. The model used a negative binomial error distribution.

Fixed Effects	**Estimate**	**Standard Error**	**Log Likelihood**	**AIC**	**Deviance (Likelihood Ratio Test)**	**df**	**p**
(Intercept)	1.94	1.45					
Mean Nightly Temperature (^{o}C)	0.12	0.11	-375.03	385.06	30.15	1	0.275
Mean Nightly Wind Speed (m/s)	-1.33	0.29	-383.23	394.75	39.84	1	0.002
Mean Nightly Rainfall Per Hour (mm)	1.64	0.94	-376.42	386.53	31.62	1	0.108
Percentage of Landcover Within 5km Classified as ‘Built Environment’	-0.08	0.03	-381.93	393.06	38.15	1	0.004
Distance to Nearest Linear Habitat Feature	-0.01	0.01	-374.24	384.25	29.34	1	0.527

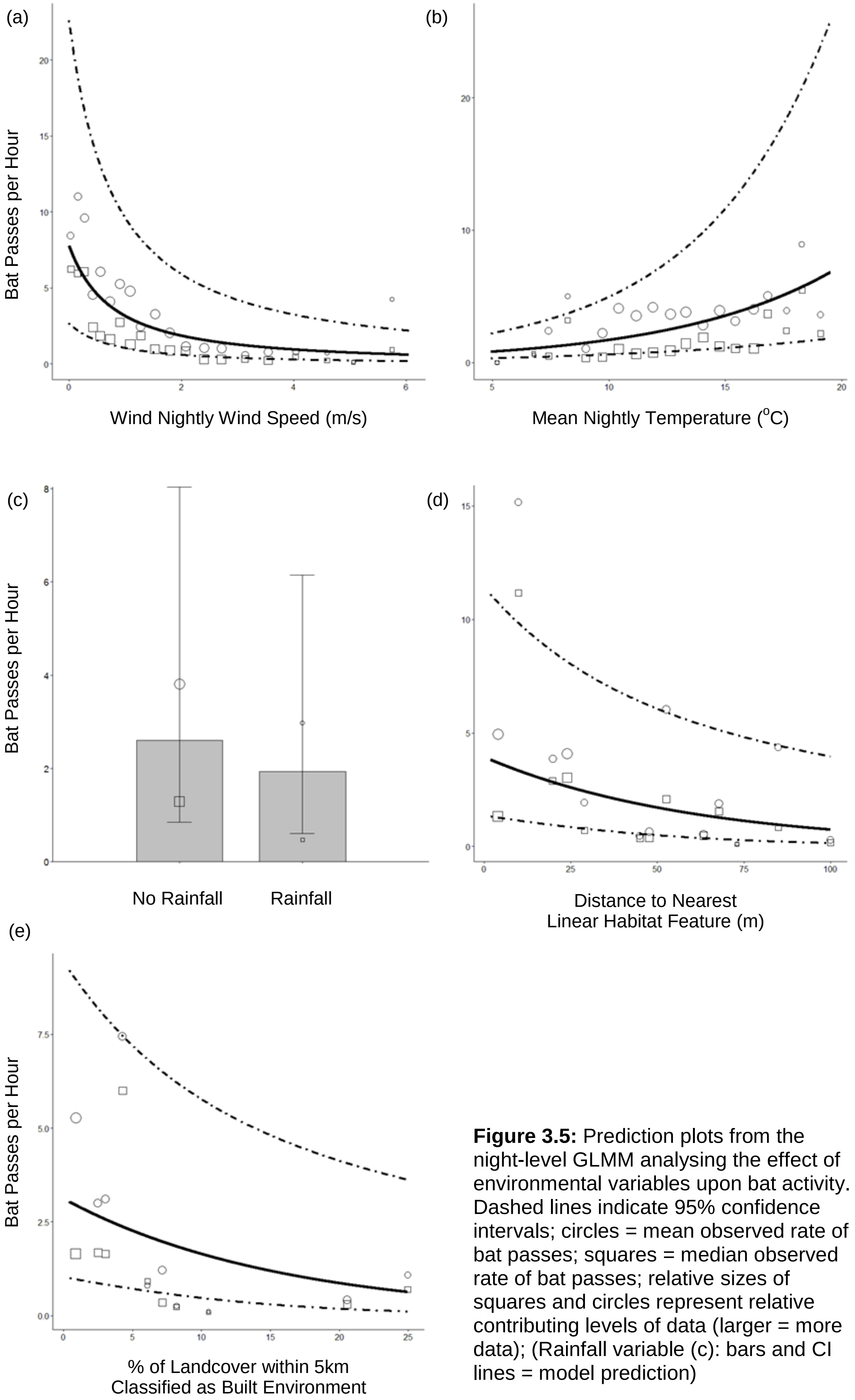

Figure 3.5: Prediction plots from the night-level GLMM analysing the effect of environmental variables upon bat activity. Dashed lines indicate 95% confidence intervals; circles = mean observed rate of bat passes; squares = median observed rate of bat passes; relative sizes of squares and circles represent relative contributing levels of data (larger = more data); (Rainfall variable (c): bars and CI lines = model prediction)

3.4.4 Activity levels at sites and timing of activity

SM2-recorded activity rates at each site ranged from 0.03 to 26.31 passes per hour, with a mean of 12.43 (Table S3.9). However one site’s results were found to heavily skew the mean (the median was 1.72 including all sites). Excluding this site gave a mean of 3.20. This dataset covered a larger number of nights per detector and potentially different nights, relative to the 3 Batons dataset (Table S3.10).

Using recordings from the set of three Baton detectors (number of sites = 26), mean passes per hour were found to be highest at the feature position (2.87 passes per hour (range: 0.05 to 9.43)) and lowest at the open position (0.58 (0.01-5.23)), with moderate activity at the turbine position (1.86 (0-13.52)). Results are shown in Table S3.10.

The distribution of bat activity across the night for all sites is shown in Figure 3.6. Activity is seen to peak 10-20% into the night, before falling until the period 60-90% into the night, at which a smaller peak exists (these patterns are consistent with previous results at wind energy sites (Brinkmann et al. 2006; Limpens et al. 2013)). The same broad pattern is observed at all detector positions, however the second peak occurs slightly earlier in the open position, at 50-70% into the night.

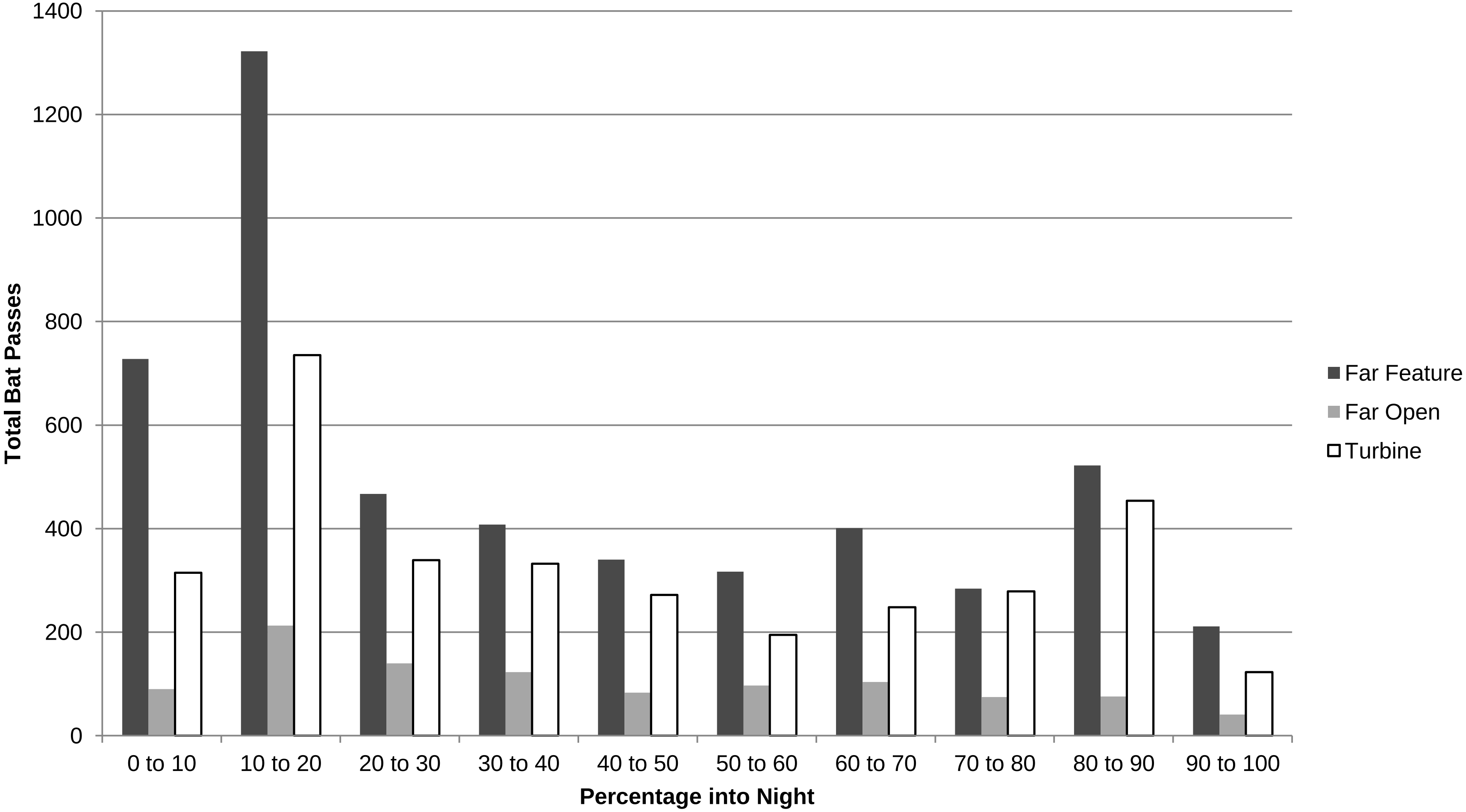

Figure 3.6: Temporal distribution of bat activity (all species) across the night, for all sites (n=26), as recorded by the Baton detectors

3.5 Discussion

This study provides some of the first results investigating the impacts of small and medium wind turbines upon bats. The results are also some of the first from wind turbines of any size in the UK. Bat fatality levels at small and medium wind turbines were measured, in addition to the disturbance impact of turbine presence upon bat activity and the influence of environmental factors in determining levels of bat activity.

Small and medium turbines were found to pose a potential fatality risk to bats. The maximum average fatality rate was estimated as between 0.81 to 15.15 turbine^{-1} year^{-1}. Bat activity was higher at turbine locations than non-turbine locations during low wind speeds, however the pattern reversed during high wind speeds, indicating disturbance. Additionally, nightly bat activity levels at small and medium turbines were found to be significantly affected by a number of weather and habitat conditions.

3.5.1 Estimating levels of bat fatality

Only 3 bat carcasses were observed during approx. 4-week long field monitoring periods at 27 wind turbine sites, in total spanning 2.5 field seasons. On an unadjusted basis, this would yield an average fatality rate of 0.81 turbine^{-1} year^{-1} at single micro, small or medium size turbines in the UK. After accounting for uncertainty inherent in the search protocol, the worst-case maximum fatality rate was estimated to be 15.15 turbine^{-1} year^{-1}. It should be acknowledged that the potential impact is realistically likely to be lower than the latter rate. This could be confirmed by further stringent monitoring to reduce uncertainty whilst observing similar carcass numbers.

The Poisson model can be used to provide a simple comparative estimate to consider alongside the above result. The maximum credible mean number of fatalities likely to occur across 27 sites (the number analysed above), having observed 3 carcasses in total, could be estimated as 7.753 ($P = 0.05$) using the Poisson distribution ($P(x) = \mu^{x}e\text{-}^{\mu}/x!$). Having accounted for average search conditions (i.e. search efficiency, carcass removal, searchable area and search interval) this is equivalent to 10.201 fatalities across 27 sites. The latter implies that the maximum annual fatality rate at a single micro, small or medium size turbine in the UK per year is 2.76. However this approach ignores the uncertainty/credible intervals of fatality estimates at a site level (in addition to uncertainty in the measures of site-level search efficiency and carcass removal), which in reality cumulatively influence the total, 'combined sites' fatality estimate. The Poisson model could again be used to provide a simple comparative estimate. For example, the maximum credible fatality estimate for individual sites, having observed 0 fatalities (the closest integer to the mean observed carcasses per site, 0.111 (i.e. 3 / 27)) is 2.995 ($P = 0.05$) using the Poisson distribution. Multiplying this result to represent 27 sites equals 80.865 fatalities, adjusted to 106.401 having accounted for search conditions. This implies a per-turbine maximum annual fatality rate of 28.79, somewhat higher than the 2.76 found when calculated at a 'combined sites' level. Both of these Poisson model-based methods are a simplification of the calculation methods required to more accurately estimate likely maximum fatality thresholds. These limitations notwithstanding, the mean of the two estimated rates (15.78) is encouragingly similar to that calculated during this study (15.15).

The scope of this study does not include the calculation of cumulative fatalities across all installed small and medium wind turbines in the UK and subsequent population level impacts. The complexity of this subject would require a stand-alone study incorporating numerous demographic measures of bat population structures and regional differences in bat populations and fatality rates. Accurate bat population estimates are very difficult to produce (Barlow et al. 2015; Kunz et al. 2007) and therefore any attempt to infer population impact from cumulative fatality estimates will be subject to large potential error. Any inferred population impacts should consider all turbine sizes and both wind farms and individual turbines.

The use of a professionally trained search dog to locate bat carcasses ensured reliable search efficiency. A high proportion of bat carcasses were also found to persist in the field for relatively long periods of time. These results suggest bat fatality monitoring at turbines in the UK is a feasible, if specialist, task. A low search efficiency result at a single site (excluded from further analyses) substantially increased the estimate of maximum possible fatalities at the site due to uncertainty, highlighting the importance of efficiency tests.

Estimated fatality rates were higher than the only previous study concerning small turbines (Minderman et al. 2015). These differences may be the product of multiple factors, as discussed below. The previous study used anecdotal records of bat fatalities from turbine owners. The search efficiency of turbine owners was likely to have been very low due to a lack of search training (Minderman et al. 2015). In addition it is likely that the ‘searches’ would have comprised a casual walk around a turbine or a chance finding of a carcass. Search efficiency rates from trained professionals following a strict search protocol were however applied in the study’s estimates (Minderman et al. 2015). This is likely to significantly underestimate uncertainty regarding searcher efficiency and therefore potential fatality estimate ranges.

Minderman et al. (2015) also used a monitoring length equal to the installed lifetime of turbines and treated any visit to the turbine by owners as a search. In reality such visits would not normally consist of a search. As many turbine owners reported zero fatalities, this method would report zero observed carcasses over a long time period, significantly reducing measures of observed carcasses per night. It is unlikely in reality that this could be treated as reliable long term monitoring. Furthermore, there is an inherent potential bias in fatality reporting from turbine owners due to concern regarding impacts on protected species. Consequently this method risks underestimation of fatalities due to under-reporting (Minderman et al. 2015). Finally the study applied the *carcass* software to estimate fatalities from sites with very low observed carcasses, a purpose for which the software is unsuitable and which may produce erroneous fatality rates.

Having observed fatalities at small wind turbines, it can be confirmed that bats will not always avoid small turbines. This raises questions as to the consistency of their ability to detect turbines. The hypothesis that bats may not echolocate as frequently at height (Cryan and Barclay, 2009) – proposed as a potential explanation for fatalities at wind farms – does not explain these fatalities at small turbines, at heights where frequent echolocation may be expected.

Without further sampling at a large number of sites, it is difficult to judge the potential variation in fatality levels between species due to low numbers of observed fatalities. Long term monitoring at sites with observed fatality occurrence may provide further information regarding species-specific patterns.

3.5.2 Differences in activity with varying proximity to a wind turbine

Habitat type had a significant impact upon resulting bat activity measures at sites, finding significantly higher activity near linear habitat features than in open habitat. This has important implications for approaches to monitoring at small and medium wind turbine sites (and potentially at large turbine sites), whereby classification of sites' bat activity could be altered due to detector positioning. Furthermore this result is consistent with typical expectations of bats' habitat use (Downs and Racey, 2006; Verboom and Huitema, 1997; Vaughan et al. 1997), verifying this assumption for turbine sites.

During low wind speed conditions, bat activity levels were higher at turbine locations relative to non-turbine locations. However during increased wind speeds, activity levels were lower at turbine locations than non-turbine locations. It therefore appears that the presence of a non-moving or slow-moving turbine is not a deterrent to bat activity and may even provide a feature of interest for foraging, navigation or other purposes. In contrast, during operation in high wind speeds, small to medium turbines appear to have a negative impact upon bat activity levels. This finding is consistent with previous small turbine research (Minderman et al. 2012). The observation of lower bat activity levels at turbines during high wind speeds is also consistent with previous research at large wind farms (Arnett et al. 2008; Brinkmann et al. 2006; Kerns et al. 2005; Rydell et al. 2010a; Amorim et al. 2012).

The results suggest turbines have a non-fatal disturbance impact upon bat activity during high wind speeds. The significantly different levels of activity 33-47m away indicate that the impact of turbines dissipates within this distance. The impact distance is likely to be even lower than this, on the basis of previous observations that effects on activity diminish within 20m (Minderman et al. 2012). Limited amounts of evidence-based planning guidance regarding bats at small turbines are currently available. The main national statutory guidance often used in England by default is therefore guidance regarding wind farms (Natural England, 2014). This suggests a minimum separation distance of 50m between turbines and habitat features of value to bats. This guideline is often impossible or impractical to meet in the context of small to medium turbines placed within domestic or small agricultural land holdings. Based on the monitoring findings regarding disturbance distances discussed above, it seems viable to suggest a reduction of separation distances to 20m in the context of small and medium turbines.

The decreased activity during high wind conditions may suggest bats are either able to avoid turbines with fast-spinning blades, or are deterred by the blades' movement or the resulting effect on the auditory and/or airflow environment near the turbine. Alternatively this could suggest that bats favour the shelter provided by linear features during high-wind conditions. The occurrence of high activity levels near turbines during low wind speeds is however potentially a matter of concern, due to the higher rates of bat fatalities during low wind speeds reported from many large wind farms (Arnett et al. 2008; Brinkmann et al. 2006; Kerns et al. 2005; Rydell et al. 2010a; Amorim et al. 2012).

All bat monitoring for this analysis was carried out just above ground level (1.5m). It is unknown if activity at the nacelle level will reflect similar patterns, particularly at medium-scale turbines. Future studies may be able to explore this issue using paired monitoring. It is nonetheless probable that activity at hub height at small (and to a lesser extent, medium) scale turbines will be detected by ground mounted detectors due to the limited vertical separation distance. Whilst acoustic monitoring has been possible at hub height at large turbines by installing detectors within nacelles, small turbines do not typically feature adequate room in the nacelle area to mount any equipment, therefore hub height monitoring is likely to be difficult. The interim nacelle size, or in some cases hub-height maintenance platforms, of medium turbines may or may not offer monitoring potential.

3.5.3 Environmental conditions and bat activity

The observed effects of weather upon bat activity levels are consistent with previous research at wind energy sites and wider assumptions regarding bat activity (Amorim et al. 2012; Georgiakakis et al 2013; Baerwald and Barclay, 2011; Gorresen et al. 2015; Arnett et al. 2008; Rydell et al. 2010a; Limpens et al. 2013). The recorded effects of habitat conditions provide an improved level of clarity relative to the inconsistent patterns found in previous research (Rydell et al. 2010a; Arnett et al. 2008; Piorkowski and O'Connell, 2010; Dubourg-Savage et al. 2011; Baerwald and Barclay, 2009; Brinkmann et al. 2006). The results appear to show that bats use wind turbine sites in a very similar manner to their use of normal landscapes, in close proximity to linear habitat features, during warm, low wind speed nights with no rain (Verboom and Huitema, 1997; Anthony et al. 1981; Erickson and West, 2002; Scanlon and Petit, 2008).

The only existing small turbine study considering weather variables in relation to bat activity (Minderman et al. 2012) found no relationship with rainfall or temperature. The method used could however be considered limited, due to use of mean daily weather values rather than conditions at night, thereby incorporating skewing effects from diurnal weather variation. Furthermore the study used weather data from meteorological stations at a mean distance of 13km from sites. This does not allow for site-level weather conditions and sheltering. Finally bat activity was measured in a binary manner per hour (i.e. activity/no activity), therefore detailed variation in activity with weather conditions could not be analysed.

At a site level, only mean wind speed and proportion of built environment landcover remained as significant predictors of bat activity. These variables may therefore provide an early indication as to the likely relative magnitude of bat activity at a proposed wind energy site. However bat activity is known to vary considerably between nights, as are fatalities at wind energy sites (Hayes, 1997; Baerwald and Barclay, 2011; observations from this study), as such, the nightly model results may also be considered at proposed sites.

The variables in the night level model above could be adopted into algorithm-based curtailment of turbines at sites where risk to bats is high (which can react to conditions on a nightly or hourly basis), particularly in the case of large and possibly medium turbines. However such flexible curtailment programs are less likely to be possible at small wind sites due to the simpler functionality of small turbines (i.e. typically not incorporating such advanced control units). Therefore simpler measures such as siting of turbines within appropriate habitat, habitat management, or increasing turbine cut-in wind speeds may be the most practical solutions in these contexts (Baerwald et al. 2009; Arnett et al. 2011; Arnett et al. 2013; Hein et al. 2013; Hein et al. 2014; Peste et al. 2015; Millon et al. 2015). However the latter two mitigation approaches have yet to be tested at small turbine sites.

Increased cut-in speeds (and to an extent, siting) may be sensitive to consequential energy yield and financial impacts, particularly as small turbines are not exposed to the high wind speeds found at larger heights (Mathew, 2006). Therefore low wind speeds incorporated in proposed curtailment strategies are likely to comprise a larger proportion of available wind resource for energy generation, relative to large turbines. This energy impact will be exacerbated in lower wind speed areas at both a local and national level (e.g. England has lower average wind speeds than Scotland).

An important variable that may help to account for a portion of the variability in bat activity at turbine sites in the UK is the volume of available insect prey (Rydell et al. 2010b; Rydell et al. 2016; Cryan and Barclay, 2009). Though this variable is likely to correlate to an extent with existing variables (e.g. temperature, wind speeds, distance to habitat features), completion of insect monitoring at turbine sites alongside bat monitoring may help to understand this association.

This approach would bring many benefits. By doing so, we may be able to identify the reasons for bats' activity patterns at wind turbines and potentially the underlying cause for their presence at turbines (Horn et al. (2008); Cryan and Barclay (2009); Rydell et al. (2010b); Valdez and Cryan (2013); Rydell et al. (2016)). Such studies may increase our understanding of bats' echolocation abilities and consistency of echolocation when hunting insects at height (and species-specific adaptations that may moderate turbine-risk (Rydell et al. 2010b)), in an environment with other moving features (i.e. turbine blades). This would simultaneously aid in addressing the infrequent-echolocation theory for bats' vulnerability to turbines at height – particularly for bats known to migrate (Cryan and Barclay, 2009). Insect monitoring may discover a particular group of insect prey for bats that are preferentially available at wind turbine features, perhaps attracted due to height or heat emissions (Rydell et al. 2010a; Rydell et al. 2016). In identifying prey niches we may be better placed to design mitigation strategies to draw such insects in the vicinity of turbines away from direct proximity. Habitat management mitigation schemes for bats may offer shared potential in this respect (Peste et al. 2015). If early indications of greater foraging around the lower blade tips (Rydell et al. 2010b) are supported by further insect monitoring, mitigation strategies (e.g. bat monitoring linked to automatic curtailment) may be efficiently designed.

Associated with the monitoring of insects are however a range of challenges. Insect monitoring at hub height is a non-trivial difficulty and no widely accepted method has yet been designed. Methods known to have been applied so far at turbines include sticky traps (Rydell et al. 2016) and Malaise traps (University of Exeter, unpublished research), however the latter are limited to ground-level monitoring and both methods require extensive post-sampling periods of insect-identification by experts with identification knowledge. Thermal imaging has also been used for ground level-only insect monitoring during hub-height monitoring of bats (Horn et al. 2008), though equipment costs are high. Access to maintain insect monitoring equipment at hub height has been found to be restricted at operational turbines (Rydell et al. 2016), limiting long-term monitoring strategies. Aerial monitoring methods such as helium balloons and drones could also be considered, however a multitude of restricting factors are likely to render these methods impractical, e.g. manual operation, operator time, expense and health and safety/blade collision concerns for turbine operators. Whilst investigation of the insect stomach-contents of bats killed at turbines is possible (Valdez and Cryan (2013); Rydell et al. (2016)), such efforts are limited by the inability to confirm bats' consumption of the insects at the turbine, as opposed to occurring prior to arrival at the turbine (Rydell et al. 2016). Locating the carcasses of smaller bats such as those found in Europe is also often a specialist task requiring trained search dogs and handlers (Arnett, 2006; Mathews et al. 2013).

Issues in application may remain even after insect monitoring. For example the subsequent application of any insect volume variable in active turbine curtailment mitigation could be problematic (i.e. automatic detection of insect volumes at turbines is likely to be technically challenging, though identifying insect-weather associations may aid such efforts). The confounding factor of a shared preference for tall features between bats and insects (e.g. hill-topping (Rydell et al., 2010b)) may additionally complicate efforts to isolate the reason for bats' presence at turbines. On balance, whilst a small number of dedicated studies of insects and bats at turbines may aid our understanding of bat behaviour, the wider application of insect monitoring at turbines is likely to be problematic and to offer minimal returns from high monitoring effort requirements.

The very low levels of observed carcasses restricted any analysis of associations between fatalities and environmental conditions. Future long term studies at high risk sites may be able to identify significant predictors of fatalities after observing larger volumes of fatalities.

3.6 Conclusions

This study observed bat fatalities in low numbers at small wind turbine sites in the UK. After observing only 3 bat carcasses during turbine monitoring, an unadjusted average fatality rate for single micro, small or medium turbines in the UK was estimated as 0.81 turbine^{-1} year^{-1}. After accounting for uncertainty in search protocols, the worst-case-scenario maximum fatality rate was estimated as 15.15 turbine^{-1} year^{-1}. The latter is however unlikely to be representative of actual fatality rates and indicates further monitoring dedicated solely to observing fatalities is required, to reduce uncertainty levels and likely confirm a lower maximum fatality rate.

Bat activity at small and medium turbine sites was found to be higher near linear habitat features than in open habitat. Turbine presence was only found to reduce bat activity during high wind speeds; this result is consistent with previous small turbine research (Minderman et al. 2012). Whilst bats' apparent avoidance of turbines during these conditions is positive with regard to reducing fatality risk, the observed small scale displacement of bats represents a non-fatal disturbance impact (though this effect dissipates within 33-47m or less). Whilst this small displacement seems unlikely to cause wider population-level impacts, this can only ultimately be confirmed by long term studies incorporating monitoring before and after turbine construction.

Wind speed, temperature, rainfall occurrence, distance to linear habitat features and proportion of built environment landcover within 5km were all found to have a significant influence upon bat activity levels at turbine sites. The use of these variables within algorithm-based curtailment of turbines may help to mitigate impacts upon bats in the UK. However due to the more limited technology in small turbines, such advanced curtailment methods are not likely to be possible. As such, simpler mitigation methods such as appropriate siting of turbines and habitat management (and only if still required, increasing turbine cut-in speeds) are likely to provide a more practical solution in the context of small turbines.

No statutory national guidance is currently available for assessment of risk to bats at small and medium wind turbines in England and available guidance elsewhere in the UK and Europe for small and medium turbines is very limited and largely not evidence based. Even with the current uncertainty in the UK wind energy industry as a result of Government policy, planning and funding changes, the number of small and medium wind turbines deployed is likely to continue to grow from its current estimated total of over eight thousand turbines. As a result, appropriate planning guidance is required to clarify bat assessment recommendations at small and medium turbines, rather than inappropriately applying onerous requirements based on large wind farm assessment guidelines, or applying no assessment due to a lack of guidance (issues previously highlighted by Park et al. (2013)). This study’s results, along with the previous small turbine studies (Minderman et al. 2012; Minderman et al. 2015) can be used as an evidence base from which guidance can be shaped. Future studies – particularly long term studies at small and medium turbine sites – are required to build upon these results as described above.

As suggested by Minderman et al. (2012), it is recommended guidance includes the use of a separation distance of 20m between small and medium turbines and linear habitat features or other important bat habitats. Furthermore it is recommended that guidance regarding mitigation strategies for risk to bats at small and medium turbines focuses on appropriate siting of turbines. Finally it is emphasised that monitoring of bat fatalities in the UK (e.g. in research programmes) should be carried out using professionally trained search dogs and should account for levels of carcass persistence and search efficiency, in order to produce reliable estimates of total possible fatalities.

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3.8 Chapter 3: Supplementary Materials

Table S3.1: Original 19 candidate variables for the ‘Environmental Conditions and Bat Activity’ analysis

Temperature (°C)
Absolute Pressure (Hpa)
Wind Speed (m/s)
Mean rainfall per hour (mm/hr)
(Mean) number of days since 1st January (parentheses = site level model)
Percentage of landcover within 5km classified as ‘Built Environment’ (%) – percentages not including marine area
Percentage of landcover within 5km classified as ‘Water’ (%) – percentages not including marine area
Percentage of landcover within 5km classified as ‘Broadleaved woodland’ (%) – percentages not including marine area
Distance to nearest Bat Conservation Trust (BCT)-recorded roost (records up to and including 2012) (m)
Mean of 3-year mean roost counts from Bat Conservation Trust (BCT)-recorded roosts (records up to and including 2012) within 5km
Mean of 3-year mean roost counts from Bat Conservation Trust (BCT)-recorded roosts (records up to and including 2012) within 2km
Density of Bat Conservation Trust (BCT)-recorded roosts (records up to and including 2012) within 5km
Density of Bat Conservation Trust (BCT)-recorded roosts (records up to and including 2012) within 2km
Total length of linear habitat features (i.e. hedgerows and tree lines) within 500m (m)
Total length of linear habitat features (i.e. hedgerows and tree lines) within 50m (m)
Distance to nearest linear habitat feature (i.e. hedgerow or tree line) (m)
Wind turbine height to upper blade tip (m)
Wind turbine number of blades
Number of years since wind turbine planning approval

Table S3.2: Parameter estimates and likelihood ratio tests of the GLMM analysing the effect of turbine presence and habitat type (linear features and wooded habitat vs. open habitat) upon bat activity, incorporating an interaction between detector position and distance to nearest linear habitat feature variables. The model used a negative binomial error distribution.

Fixed Effects	Estimate	Standard Error	Log Likelihood	AIC	Deviance (Likelihood Ratio Test)	df	p
(Intercept) [Detector Position = Far(Feature)]	0.86	0.48					
Mean Nightly Temperature (^{o}C)	0.05	0.03	-1589.7	3201.5	4.02	1	0.045
Mean Nightly Wind Speed (m/s)	-0.34	0.06	-1601.1	3224.2	26.7	1	<0.0001
Rainfall Occurrence During Night	-0.42	0.13	-1592.7	3207.4	9.98	1	0.002
Detector Position [Turbine] * Distance to Nearest Linear Habitat Feature	0.01	0.01	-1595.7	3202.9	16	3	0.001

Table S3.3: Parameter estimates and likelihood ratio tests of the GLMM analysing the effect of distance to nearest linear habitat feature upon bat activity using a subset of the data only including detectors in the ‘turbine’ position. The model used a negative binomial error distribution.

Fixed Effects	Estimate	Standard Error	Log Likelihood	AIC	Deviance (Likelihood Ratio Test)	df	p
(Intercept)	1.20	0.80					
Mean Nightly Temperature (^{o}C)	0.05	0.05	-531.39	1074.8	0.98	1	0.322
Mean Nightly Wind Speed (m/s)	-0.71	0.11	-548.3	1108.6	34.80	1	<0.0001
Rainfall Occurrence During Night	-0.46	0.23	-532.89	1077.8	3.98	1	0.046
Distance to Nearest Linear Habitat Feature	-0.03	0.01	-535.48	1083.0	9.16	1	0.002

Table S3.4: Parameter estimates and likelihood ratio tests of the GLMM analysing the effect of turbine presence upon bat activity, incorporating the effect of distance to nearest linear habitat feature. Detector positions are amalgamated into ‘turbine presence’ and ‘turbine absence’ categories. The model used a negative binomial error distribution.

Fixed Effects	**Estimate**	**Standard Error**	**Log Likelihood**	**AIC**	**Deviance (Likelihood Ratio Test)**	**df**	**p**
(Intercept)	0.79	0.49					
Mean Nightly Temperature (^oC)	0.05	0.03	-1647.4	3310.7	2.36	1	0.125
Mean Nightly Wind Speed (m/s)	-0.33	0.07	-1655.5	3327.0	18.64	1	<0.0001
Rainfall Occurrence During Night	-0.36	0.15	-1649.0	3314.0	5.58	1	0.018
Turbine Presence	-0.15	0.2	-1646.5	3308.9	0.56	1	0.454
Distance to Nearest Linear Habitat Feature	-0.03	0.003	-1687.2	3390.3	81.94	1	<0.0001

Table S3.5: Parameter estimates and likelihood ratio tests of the GLMM analysing the effect of turbine presence upon bat activity, incorporating the effect of distance to nearest linear habitat feature. Detector positions are amalgamated into ‘turbine presence’ and ‘turbine absence’ categories and their interaction with wind speed is tested. The model used a negative binomial error distribution and no outliers were excluded.

Fixed Effects	**Estimate**	**Standard Error**	**Log Likelihood**	**AIC**	**Deviance (Likelihood Ratio Test)**	**df**	**p**
(Intercept)	1.00	0.49					
Mean Nightly Temperature (^oC)	0.03	0.03	-1698.8	3415.6	0.9	1	0.343
Rainfall Occurrence During Night	-0.36	0.15	-1701.2	3420.4	5.66	1	0.017
Distance to Nearest Linear Habitat Feature	-0.03	0.003	-1740.9	3499.7	85.02	1	<0.0001
Turbine Presence * Mean Nightly Wind Speed (m/s)	-0.52	0.14	-1705.4	3428.8	14.1	1	0.0002

Table S3.6: Parameter estimates and likelihood ratio tests of the night-level, *Pipistrellus* genus GLMM analysing the effect of environmental variables upon bat activity. The model used a negative binomial error distribution

Fixed Effects	**Estimate**	**Standard Error**	**Log Likelihood**	**AIC**	**Deviance (Likelihood Ratio Test)**	**df**	**p**
(Intercept)	0.39	0.48					
Mean Nightly Temperature (^{o}C)	0.16	0.03	-1951.73	3917.46	33.84	1	<0.0001
log (Mean Nightly Wind Speed (m/s))	-1.51	0.16	-1976.32	3966.64	83.02	1	<0.0001
Rainfall Occurrence During Night	-0.20	0.14	-1935.83	3885.66	2.04	1	0.153
Percentage of Landcover Within 5km Classified as ‘Built Environment’	-0.05	0.03	-1936.02	3886.04	2.42	1	0.120
Distance to Nearest Linear Habitat Feature	-0.02	0.01	-1938.08	3890.16	6.54	1	0.011

Table S3.7: Parameter estimates and likelihood ratio tests of the night-level, *Nyctalus* and *Eptesicus* genera GLMM analysing the effect of environmental variables upon bat activity. The model used a negative binomial error distribution

Fixed Effects	**Estimate**	**Standard Error**	**Log Likelihood**	**AIC**	**Deviance (Likelihood Ratio Test)**	**df**	**p**
(Intercept)	-3.01	0.69					
Mean Nightly Temperature (^{o}C)	0.17	0.04	-1052.64	2119.28	22.30	1	<0.0001
log (Mean Nightly Wind Speed (m/s))	-0.72	0.19	-1048.28	2110.56	13.58	1	0.0002
Rainfall Occurrence During Night	-0.30	0.18	-1042.77	2099.54	2.56	1	0.110
Percentage of Landcover Within 5km Classified as 'Built Environment'	-0.00	0.05	-1041.49	2096.98	0.00	1	1
Distance to Nearest Linear Habitat Feature	-0.01	0.01	-1042.28	2098.56	1.58	1	0.209

Table S3.8: Parameter estimates and likelihood ratio tests of the night-level, *Myotis, Barbastella, Plecotus and Rhinolophus* genera GLMM analysing the effect of environmental variables upon bat activity. The model used a negative binomial error distribution

Fixed Effects	**Estimate**	**Standard Error**	**Log Likelihood**	**AIC**	**Deviance (Likelihood Ratio Test)**	**df**	**p**
(Intercept)	-0.20	0.47					
Mean Nightly Temperature (^{o}C)	0.02	0.03	-998.68	2011.37	0.82	1	0.366
log (Mean Nightly Wind Speed (m/s))	-1.37	0.17	-1030.01	2074.02	63.47	1	<0.0001
Rainfall Occurrence During Night	-0.77	0.15	-1010.71	2035.42	24.87	1	<0.0001
Percentage of Landcover Within 5km Classified as 'Built Environment'	-0.09	0.03	-1001.84	2017.68	7.13	1	0.008
Distance to Nearest Linear Habitat Feature	-0.01	0.01	-998.53	2011.06	0.51	1	0.477

Table S3.9: SM2 detector bat monitoring results from all sites (n=31), sorted by total passes per hour (in descending order). Data has been filtered to include only nights that featured suitable weather conditions (as defined above), adequate equipment battery levels and equipment in working order.

Site Number	Total bat passes (all species)	Total hours of monitoring (including half an hour before sunset and after sunrise each night)	Total bat passes per hour (all species)
5	4958	188.42	26.31
7	1882	163.38	11.52
10	2657	251.73	10.55
2	613	63.15	9.71
1	1360	159.67	8.52
20	2014	242.05	8.32
24	2208	301.88	7.31
31	1117	167.12	6.68
21	1418	234.60	6.04
19	781	175.17	4.46
11	895	242.28	3.69
15	856	240.63	3.56
25	978	290.85	3.36
17	125	43.88	2.85
30	228	108.72	2.10
22	349	203.28	1.72
6	379	224.93	1.68
3	195	150.95	1.29
23	262	291.05	0.90
4	180	204.10	0.88
33	87	119.78	0.73
32	133	228.82	0.58
27	155	296.90	0.52
29	96	228.75	0.42
9	102	280.58	0.36
16	17	52.22	0.33
26	77	303.98	0.25
8	55	252.80	0.22
28	16	161.77	0.10
18	10	109.73	0.09
14	6	213.15	0.03
All Sites	24209	1947.17	12.43

Table S3.10: Baton detector bat monitoring results from all sites (n=26). Data has been filtered to include only nights that featured suitable weather conditions (as defined above), adequate equipment battery levels and equipment in working order.

Site Number	**Total bat passes (all species) – Far(Feature) detector position**	**Total bat passes (all species) – Far(Open) detector position**	**Total bat passes (all species) – Turbine detector position**	**Total bat passes (all species) – All 3 positions combined**	**Total hours of monitoring (including half an hour before sunset and after sunrise each night)**	**Total bat passes per hour (all species) – Far(Feature) detector position**	**Total bat passes per hour (all species) – Far(Open) detector position**	**Total bat passes per hour (all species) – Turbine detector position**	**Total bat passes per hour (all species) – All 3 positions combined**	**Total monitoring nights at site**
2	204	11	113	328	35.33	5.77	0.31	3.20	9.28	4
5	362	54	281	697	51.65	7.01	1.05	5.44	13.49	6
6	3	8	22	33	59.78	0.05	0.13	0.37	0.55	7
7	406	225	582	1213	43.05	9.43	5.23	13.52	28.18	5
8	562	45	526	1133	92.97	6.05	0.48	5.66	12.19	10
9	169	55	51	275	77.55	2.18	0.71	0.66	3.55	8
10	508	164	677	1349	118.65	4.28	1.38	5.71	11.37	12
11	115	31	62	208	118.65	0.97	0.26	0.52	1.75	12
14	52	11	81	144	109.37	0.48	0.10	0.74	1.32	9
15	607	3	119	729	155.83	3.90	0.02	0.76	4.68	13
16	6	4	0	10	26.25	0.23	0.15	0	0.38	3
17	21	11	13	45	17.82	1.18	0.62	0.73	2.53	2
18	98	114	39	251	118.35	0.83	0.96	0.33	2.12	14
19	13	2	27	42	24.77	0.52	0.08	1.09	1.70	3
20	272	41	287	600	59.35	4.58	0.69	4.84	10.11	7
21	260	73	111	444	68.15	3.82	1.07	1.63	6.52	8
22	31	28	0	59	79.03	0.39	0.35	0	0.75	8
23	55	24	4	83	100.47	0.55	0.24	0.04	0.83	10
24	97	43	20	160	38.87	2.50	1.11	0.51	4.12	4
25	25	35	75	135	50.13	0.50	0.70	1.50	2.69	3
26	7	7	6	20	48.13	0.15	0.15	0.12	0.42	4
27	161	7	6	174	74.82	2.15	0.09	0.08	2.33	6
29	612	1	13	626	67.85	9.02	0.01	0.19	9.23	8
30	45	12	16	73	75.32	0.60	0.16	0.21	0.97	9
32	308	30	161	499	39.32	7.83	0.76	4.09	12.69	3
33	3	3	0	6	8.53	0.35	0.35	0	0.70	1

4 Spatial activity patterns of bats at wind turbine sites

4.1 Abstract

The fatality risk posed by wind turbines to bats is a well documented phenomenon. The non-fatal impacts of turbines upon bats have however received less research attention. Disturbance and displacement effects of wind turbines upon birds have been observed, including flight avoidance of whole wind farms and micro-avoidance of individual turbines within wind farms. Early research has shown that domestic-scale small wind turbines impose a disturbance effect upon bat activity in the immediate turbine vicinity during high wind speeds (Minderman et al. 2012).

Presented here are some of the first investigations into spatial bat activity patterns within small and medium wind turbine sites in the UK. Social Network Analysis (SNA) methods were used to analyse bat movement networks within a small grid of bat detectors centred on each turbine. Each detector location was treated as a ‘node’ within the detector grid’s ‘network’. The analysis incorporated the wind turbine within the network and considered whether its presence represented a disturbance source that is avoided, or an additional navigable feature and target for investigative behaviour. Individual observations of longer flights paths between detectors were also analysed and categorised by behaviour type.

Both network-wide and node-level measures of connectivity were calculated to assess the density and fragility of movement networks and the importance of individual locations for bat movement. The importance of habitat type at each detector location for bat movement was also considered.

Associations were identified between bats’ movement routes and habitat structures present at sites. Furthermore bats were found to actively use the turbine area rather than avoid it, indicating disturbance from turbines does not

occur in all conditions. Foraging appeared to be the most prevalent behaviour type displayed by bats at wind turbine sites, including in the direct vicinity of turbines.

Important movement linkages within sites provided by linear habitat features (e.g. hedges and tree lines) appeared to represent vulnerable locations within sites with sparse habitats. If these were disrupted, activity at sites could be reduced to weakly connected networks. Consequently it is suggested that non-fatal disturbance impacts should be considered in assessments of proposed wind turbine sites where a high level of risk to bats is predicted.

4.2 Introduction

Recognition of the impacts of climate change and reducing global energy security has prompted a large increase in global renewable energy production. This has included the installation of increasing numbers of wind turbines. Wind turbines are known to present a mortality risk to bats due to blade strikes and barotrauma, with fatalities recorded in many studies in North America and Europe (Arnett et al. 2008; Baerwald and Barclay, 2011; Bicknell and Gillam, 2013; Rydell et al. 2010; Dubourg-Savage et al. 2011; Georgiakakis et al. 2012; Lehnert et al. 2014; Minderman et al. 2015). Early fatality results have also been reported across other continents (Hull and Cawthen, 2013; Doty and Martin, 2013; Kumar et al. 2013; Escobar et al. 2015; Barros et al. 2015).

Reported patterns of spatial bat activity near wind energy sites often concern landscape scales and inter-site variations (Arnett et al. 2008; Baerwald and Barclay, 2009; Piorkowski and O’Connell, 2010; Rydell et al. 2010; Dubourg-Savage et al. 2011). This study aims to contribute to our understanding of bats’ spatial activity patterns within wind turbine sites, their behaviour in proximity to turbines and the occurrence of any non-fatal disturbance or avoidance impacts. These topics have received little research attention to date.

4.2.1 Spatial activity patterns and non-fatal impacts

Thermal imaging observation has confirmed bat flight in proximity to turbine blades (Horn et al. 2008; Ahlén et al. 2009; Cryan et al. 2014), as well as collisions and avoidance behaviour (Horn et al. 2008). Bats' presence at turbines has been attributed to investigation of turbines, foraging, responses to turbine-altered air currents and roost searching (Horn et al. 2008; Ahlén et al. 2009; Cryan et al. 2014; Gorresen et al. 2015).

Small numbers of studies have provided insights into spatial activity patterns within turbine sites. The construction of a wind farm in Germany appeared to cause displacement, reducing numbers of *Eptesicus serotinus* (Serotine bat) present over 5 years (Bach and Rahmel, 2004). In contrast, *Pipistrellus pipistrellus* (common pipistrelle) numbers increased, perhaps attracted by the turbines. Spatial distributions of foraging activity were altered across the site and flight heights along hedgerows changed with varying proximity to turbine blade tips. Avoidance behaviour by *Nyctalus noctula* (Noctule) and Serotine bats was also observed at a nearby wind farm (Bach and Rahmel, 2004).

At some wind farms, concentrations of fatalities have been observed at the ends and centres of turbine strings (Arnett et al. 2008). Very little research is available regarding small, single wind turbine sites. A study in the UK recorded a larger reduction in bat activity in proximity to single wind turbines during periods of increased wind speeds, relative to locations 20m away from turbines (Minderman et al. 2012). Small numbers of bat fatalities have also been observed at small turbines (Minderman et al. 2015).

Whilst research concerning bats is limited, previous studies focusing upon birds indicate the types of non-fatal impacts that bats may experience from turbines. Immediate and delayed displacement by and avoidance of turbines has been confirmed during bird studies (Strickland et al. 2011; Plonczkier and Simms, 2012; Leddy et al. 1999; Johnson et al. 2000a; Shaffer and Johnson, 2008; Deshold and Kahlert, 2005). Impact levels vary by species and activity can increase near turbines (Devereux et al. 2008). Avoidance of whole wind farms can occur as well as micro-avoidance of individual turbines within wind farms

(Plonczkier and Simms, 2012; Villegas-Patraca et al. 2014; Everaert, 2014). Destruction or disruption of important bird habitats during wind farm construction may also cause disturbance and reduce bird numbers (Zeiler and Grünschachner-Berger, 2009; Beck et al. 2011).

4.2.2 Social network analysis

An effective approach for analysing animal movements and interactions is Social Network Analysis (SNA). It has been applied to identify social roosting networks between individual bats (Fortuna et al. 2009; August et al. 2014; Silvis et al. 2014), bat groupings during foraging (Dechmann et al. 2009) and networks present between bat roost trees (Rhodes et al. 2006). Little evidence is available from SNA regarding bats' movements between locations on a fine temporal scale (i.e. on the scale of seconds). Analogous movement studies using SNA have however analysed use of coral reef by fish (Fox and Belwood, 2014) and shark movements recorded by acoustic arrays; a similar concept to monitoring with acoustic bat detectors (Jacoby et al. 2012).

SNA analyses focus upon networks comprised of units of interest ('nodes') and relationships between them ('edges') (Dube et al. 2011). Network-wide SNA measures help to define whether target species' movement / association networks are widespread or focused upon particular locations, individuals or habitats. Furthermore they can indicate whether the network is robust and well connected or sparse and vulnerable to disruption. Individual node-level measures quantify the importance and functionality of each node or its characteristics for connectivity within a network (Dube et al. 2011; Dale and Fortin, 2010). Table S4.1 (Supplementary Materials) provides reference definitions of the SNA measures applied within this study. Previous studies have provided overviews of the principles and terminology associated with SNA (e.g. Dube et al. 2011).

4.2.3 Study aims

Through the application of SNA approaches, this study aimed to investigate the use of sites and habitat by bats during their movement between a small network of bat detectors, installed at single small and medium wind turbine sites. The analysis incorporated the wind turbine within the network and considered whether its presence represented a disturbance source that is avoided, or an additional navigable feature and target for investigative behaviour. Individual observations of bat movement between detectors were also analysed and categorised by behaviour type, providing a complementary analysis to Horn et al.'s (2008) observations of movement around the rotor-swept area.

4.3 Methods

4.3.1 Data collection

Field monitoring was carried out at 30 sites across Wales and south-west England with a single small or medium wind turbine installed. These 2 regions represent areas within the UK with high bat populations and diversity (Bat Conservation Trust, no date). 3 of the sites had a 2nd turbine installed, though only 1 turbine was monitored. Selection of the monitored turbine was random unless constrained by access. All turbines included in the study were >5m and <100m to blade tip height (>5m and <70m to hub height) and featured blade diameters of >1.5m and <60m. 23 sites featured a turbine with 3 blades, 6 had 2 blades and 1 had >3 blades. All turbines were of a horizontal axis design and mounted on a standalone mast (not on a building).

Monitoring was carried out during May-October in 2012 (12 sites) and 2013 (14 sites) and June-July in 2014 (4 sites), with monitoring taking place concurrently at groups of 2-4 sites at a time. The 'ideal' monitoring set up is described below and in Figure 4.1. Due to varying site configurations, access constraints, habitat structures and equipment availability, alterations to the 'ideal' monitoring set up were often required. This included reductions in bat detector numbers which could be installed. Table 4.1 summarises the main changes that were made to the monitoring schedule at each site.

Table 4.1: Details of site monitoring programme. Sites 12 and 13 are excluded as the turbine had yet to be constructed at the sites, which were monitored to carry out pilot pre-construction monitoring observations

Site Number	**Number of monitoring nights**	**Number of Baton detectors**
1	28	6
2	28	9
3	28	0
4	28	5
5	28	9
6	28	9
7	25	9
8	27	9
9	28	5
10	28	6
11	28	6
14	29	9
15	29	7
16	28	5
17	26	8
18	25	9
19	27	9
20	28	9
21	28	9
22	28	9
23	27	9
24	29	9
25	28	8
26	20	9
27	28	9
28	20	9
29	27	9
30	21	9
31	20	9
32	30	9
33	28	9

Each site was ideally monitored for 4 weeks and visited 5 times. During each visit, all equipment, clock settings and batteries were checked. 9 tripod-mounted Batbox Baton frequency division bat detectors linked to Zoom H2n audio-recorders were installed at each site, arranged in a 3x3 grid centred on the turbine, with each detector being 33.3m apart (Figure 4.1).

Using equipment metadata recorded in the field, each planned recording night at each detector was flagged as either suitable or unsuitable. This was based upon the battery level of the detector and recorder (above or below threshold operating level), available file capacity of the recording device, any damage suffered by the equipment and weather conditions recorded by the weather station. Suitable weather conditions were defined as nights with mean wind speed <= 8m/s, mean temperature >=10^{o}C and mean hourly rainfall <= 2.5mm. Nights with large fluctuations in these weather conditions were also removed. Recording nights started half an hour before sunset and ended half an hour after sunrise (daily sunrise/set times were used). The clock/recording timestamp settings for all Zoom H2n recorders were synchronised to the second against a single, consistent reference time source. Recording timestamps were proportionally corrected for any small time drift in the recording unit clock relative to the reference time source, noted during each visit.

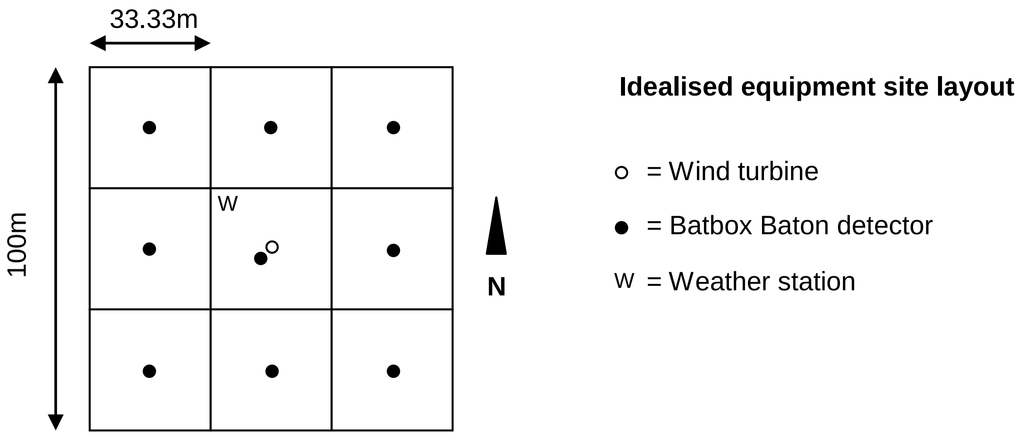

Figure 4.1: An idealised diagram of equipment layout at monitored wind turbine sites

4.3.2 Bat sound analysis

Wildlife Acoustics ‘Songscope’ software was used to complete a species auto-identification scan on the recordings, using reference ‘recogniser’ files built from sampled Baton bat recordings where species had been identified. Recordings from the Baton detectors exceeding 1 minute were first manually checked for presence of any bat passes using the Pettersson Elektronik ‘Batsound’ viewer software. This was due to the extensive auto-ID scanning time required for long files. Almost all such files were identified as noise recordings (predominantly rain) and consequently were excluded from further processing. Any long files with bat passes were retained and scanned.

All non-*Pipistrellus* genus classifications were manually checked, as the relative accuracy of recognisers for those genera was lower. Any noise-classified files with a high proportion of sound sections indicating a potential bat classification were also manually checked. A single bat pass was defined as at least 2 echolocation calls within 1 second of one another.

Individual species’ echolocations were identified using standard bat identification procedures (e.g. as detailed in Russ (2012) and Fisher et al. (2005)), based on call characteristics including frequency, shape, duration, interpulse interval, rhythm, characteristic call patterns (e.g. ‘chip-chop’ patterns), amplitude, habitat structure around the detector, geographical location of site and time of night. Bat species within the *Myotis* and *Plecotus* genera were not individually identifiable using acoustic methods alone and therefore were identified only at the genus level. Bat species within the *Nyctalus* and *Eptesicus* genera were only individually identified where call characteristics allowed a high degree of confidence, due to clear frequency or call pattern separation relative to the other species (with additional validation via consideration of habitat and geographical location). The remainder of the candidate *Nyctalus* and *Eptesicus* recordings were identified only as ‘*Nyctalus*/*Eptesicus’*.

4.3.3 Statistical methods

4.3.3.1 Bat movement analysis using SNA

Only sites with 9 Baton detectors installed were considered for analysis (21 sites). Due to stringent data quality requirements (using only 'suitable' monitoring nights, as defined above), the need for all 9 detectors to be working suitably concurrently and recorders frequently reaching their storage capacity due to high levels of noise from inclement weather, only a small number of sites and associated nights provided suitable data. This was not considered a limitation, with the study having been designed for detailed activity analysis across short time periods. This approach has been employed by previous behavioural studies of bat activity near turbines and in network analyses of foraging bats (e.g. Horn et al. 2008; Ahlén et al. 2009; Dechmann et al. 2009). In total, 30 suitable recording nights were obtained across 10 sites (mean per site = 3, std. dev. = 2.3).

An SNA approach was used to analyse bat movement between the Baton detectors within each site. The 9 detectors represented the 'network' and each detector a 'node' within the network. Each movement between the detectors represented an 'edge'. Each monitoring night was divided into a series of 5 second monitoring periods. Two or more bat recordings were considered linked and representative of bat movement between detectors (an 'edge'), if they were recorded during the same or adjacent 5 second periods. Recordings were only linked if they featured either the same species, or the associated genus for recordings only identified to genus-level. The choice of 5 second periods was considered appropriate for the detectors' spatial configuration (min. detector separation: 33.3m, max.: 47.1m (diagonal); see Figure 4.1) and bats' typical flight speeds (see Supplementary Materials for further information).

Each detector node in the network was labelled with its compass direction location, relative to the central wind turbine location (i.e. N, NE, S etc.), which was labelled 'T'. Each detector node was also categorised in relation to the dominant habitat in its square cell area (see Figure 4.1). The habitat categories comprised ‘open’ habitat, ‘feature’ habitat (e.g. linear hedgerows and tree lines) and ‘turbine’.

The R software (R Core Team, 2015) and R package ‘igraph’ (Csardi et al. 2015) were used to carry out SNA of bat activity. Activity data from each site and night were structured as adjacency matrices to identify associations (‘edges’) between detectors (‘nodes’), representing bat movement between the detectors. *igraph’s* ‘graph.adjacency’ function was applied to calculate an undirected network graph from each matrix, allowing multiple edges between node pairs, as well as ‘loops’ (self-association at a single detector). A second network was calculated to identify movements between and preferential use of habitat types.

4.3.3.2 SNA measures

Measures of overall connectivity and network structure across each night were assessed, identifying the overall size of the graph and the graph density. To calculate a graph density measure, igraph’s ‘simplify’ function was used to remove duplicate edges (only for this statistic), as this measure is poorly defined for duplicate edges (Csardi et al. 2015). Fragmentation within the network was also assessed, identifying the number of exclusive node groups, the global cluster coefficient and graph adhesion. Furthermore the characteristic path length and diameter of the graph were calculated.

At a detector node-level, the nodes’ ‘degree’ of association, ‘betweenness’, ‘closeness’ and ‘Eigenvector centrality’ within the network were identified. These node level measures quantified the importance of individual locations or habitat types for bat movement and connectivity within the wind turbine sites.

The activity network at each site was plotted using the *igraph* package, creating layouts based on the geographical site configuration as well as the ‘Kamada Kawai’ and ‘Fruchterman Reingold‘ layout algorithms used to optimise representation of SNA graphs. UCINET network analysis software was used to carry out any statistical tests upon the network data, applying repeated permutations to account for the non-independent nature of network data. Movement bottlenecks were identified using the software’s ‘Bi-Components’ tool. The network data were additionally compared against a theoretical ‘regular’ model representing equal bat activity across a network. Subsequently the networks were compared against 3 random models of bat activity, assessing whether bats’ spatial use of turbine sites can be considered regular, random or non-random.

4.3.3.3 Bat flight behaviours

Longer flight paths were analysed to consider bat behaviour and use of habitat around turbine sites. Where multiple movement edges were recorded for the same species/genus (as above) in successive 5 second periods, the overall flight path between detectors was recorded. Flight paths with 3 or more successive edges were selected for further analysis. The flight path was classified to a probable behaviour category (e.g. foraging, commuting, turbine investigation) based on its shape, species recorded, movement duration and relationship to habitat. Existing studies have frequently applied such manual classifications at turbine sites (Horn et al. 2008; Ahlén et al. 2009; Ahlén, 2003; Bach and Rahmel, 2004; Cryan et al. 2014; Gorresen et al. 2015). The flight path was also classified as either ‘expected’ or ‘unexpected’. For example if a Common Pipistrelle was recorded flying along a hedgerow crossing the monitoring area this was classified as ‘expected’. Alternatively if it deviated away from the hedgerow into open habitat to avoid or investigate a turbine, this was classified as ‘unexpected’. Total occurrence rates of behaviour types and unexpected flight paths are reported, alongside qualitative analysis of the flight behaviours.

4.4 Results

4.4.1 Observed activity levels

3292 bat recordings were made during the 5 second periods monitored, across all 30 monitoring nights (mean = 109.73 bat recordings night^{-1}, or 12.19 detector^{-1} night^{-1}). The species composition of the recorded bat activity is illustrated in Table 4.2. Bat movements were recorded between all potential pairs of detectors in the overall study's detector grid at least once during the 30 nights of monitoring across the 10 sites (Figure 4.2). 585 inter-detector movements were recorded (mean 19.5 night^{-1}), in addition to 546 intra-detector movements (i.e. successive recordings of flight around a single detector) (mean 18.2 night^{-1}) and 2308 isolated recordings at single detectors (mean = 76.9 night^{-1}).

Table 4.2: Species-specific breakdown of the recorded bat activity

Species / Genus	Number of recordings	As a % of all species
Common pipistrelle	881	26.8%
Soprano pipistrelle	1314	39.9%
Nathusius pipistrelle	3	0.1%
Pipistrellus sp.(unknown)	642	19.5%
Myotis	343	10.4%
Noctule	49	1.5%
Leisler	24	0.7%
Serotine	25	0.8%
Leisler / Serotine	8	0.2%
Noctule / Leisler / Serotine	3	0.1%
Pipistrellus	2840	86.3%
Myotis	343	10.4%
Nyctalus / Eptesicus	109	3.3%
Total	3292	

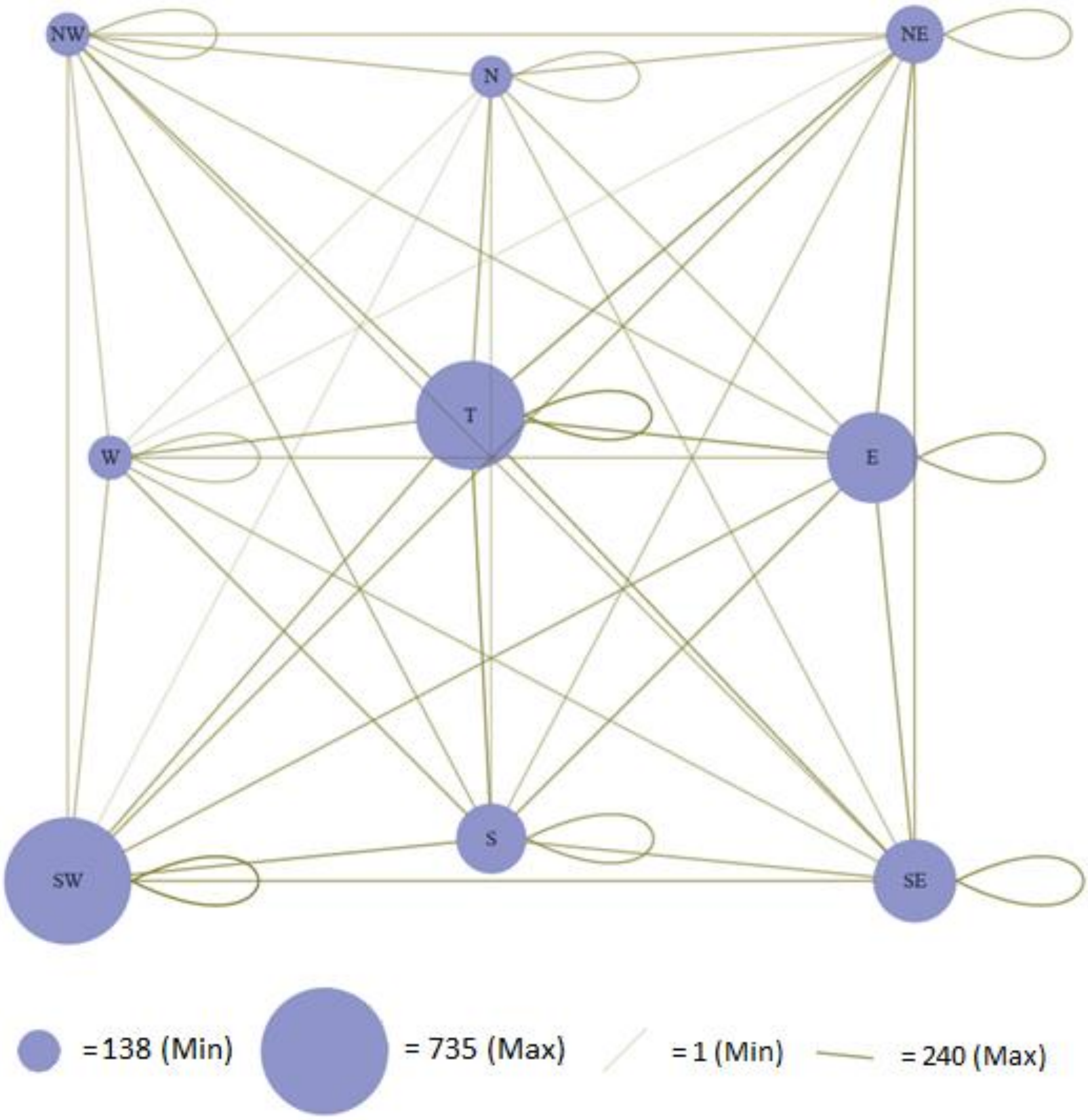

Figure 4.2: Combined distribution of recorded bat movements and individual bat recordings from all 30 monitoring nights at all 10 sites. Lines between detector positions represent recorded bat movements (boldness increases with number of records); circles at detector locations represent individual bat recordings (size of circle increases with number of records); looped lines attached to detector locations represent successive bat recordings at that location (i.e. concentrated bat movement around the detector location)

Bat movement networks varied between sites and nights, both in volume of activity and spatial configuration of connectivity. Figure 4.3 illustrates recorded movements during 4 individual monitoring nights at 4 different sites, using the geographic layout of the detectors. Table 4.3 (a-c) exemplifies the inter-night variations observed.

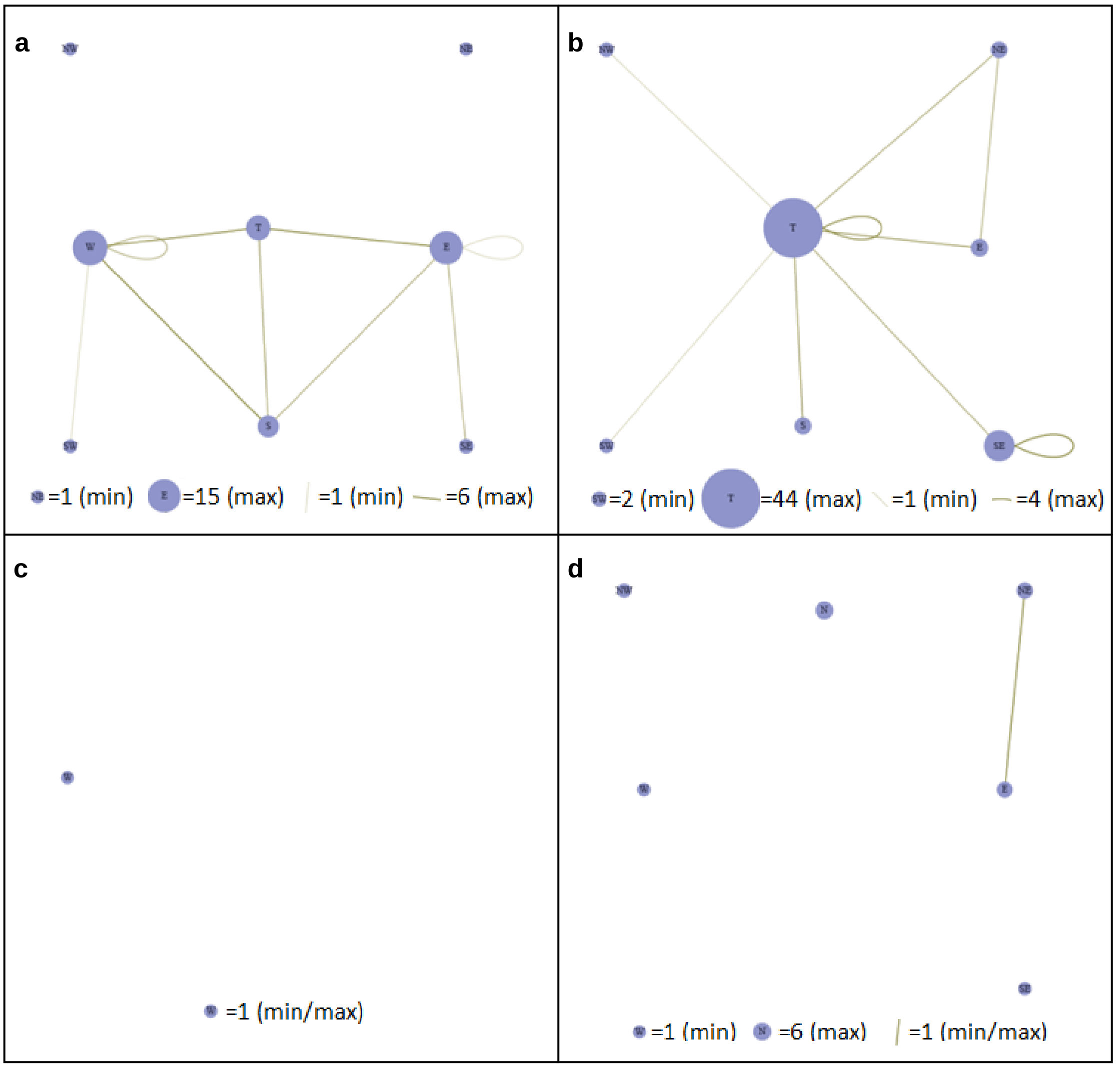

Figure 4.3: Bat movement networks recorded on individual nights at 4 different sites. Lines between detector positions represent recorded bat movements (boldness increases with number of records); circles at detector locations represent individual bat recordings (size of circle increases with number of records); looped lines attached to detector locations represent successive bat recordings at that location (i.e. concentrated bat movement around the detector location)

Not all detector locations were actively used at each site (mean active nodes per night = 7.5, range = 4-9, std. dev. = 1.6), though activity was recorded at the turbine location at 8 of the 10 sites. Where movement edges were observed (not all nights featured edges), total edges per night at each site ranged from 3 to 122.

Table 4.3 a, b and c: Association matrices between detector locations – illustrating numbers of bat movements recorded between detectors. Results are shown illustrating Soprano Pipistrelle recordings from 3 individual, successive monitoring nights (nights 12, 13 and 14) from the same, single site (no. 5)

Table 4.3a: Night 12

	E	**N**	**NE**	**NW**	**S**	**SE**	**SW**	**T**	**W**
E	5								
N	0	0							
NE	5	0	0						
NW	0	0	0	0					
S	2	0	0	0	0				
SE	1	0	0	0	0	0			
SW	6	0	7	0	7	6	94		
T	5	0	4	0	0	0	4	12	
W	0	0	0	0	0	0	0	1	0

Table 4.3b: Night 13

	E	**N**	**NE**	**NW**	**S**	**SE**	**SW**	**T**	**W**
E	0								
N	0	0							
NE	2	0	0						
NW	0	0	0	0					
S	0	0	0	0	1				
SE	1	0	1	0	0	7			
SW	0	0	1	0	1	3	6		
T	0	0	2	0	7	2	1	12	
W	0	0	0	0	0	0	0	0	0

Table 4.3c: Night 14

	E	**N**	**NE**	**NW**	**S**	**SE**	**SW**	**T**	**W**
E	3								
N	0	0							
NE	0	0	0						
NW	0	0	0	0					
S	0	0	0	0	0				
SE	0	0	0	0	0	0			
SW	6	0	2	0	4	3	111		
T	2	0	0	0	0	0	1	0	
W	0	0	0	0	0	0	0	0	0

4.4.2 Site level network analyses

4.4.2.1 Network measures

Table 4.4 sets out all site-level statistical network results for all bat species combined. A higher mean network density (0.45) was observed at sites with a cluttered habitat structure (sites with ≥50% of non-turbine detector habitat types categorised as 'feature') relative to those with an 'open' habitat structure (0.17) (<50% 'feature' types). Both site types featured a mean site monitoring length of 3 nights. At a species-level Serotine, *Nyctalus leisleri* (Leisler's bat) and *Myotis (sp.)* bats featured the lowest mean monitoring night network density and *Pipistrellus pygmaeus* (soprano pipistrelle) and common pipistrelle the highest.

Table 4.4: Overview of site-level network statistics describing connectivity and complexity, activity density and clustering and network strength monitored at each site. All values are mean values per night to account for differing monitoring lengths between sites

Site number (No. of nights)	**Mean network measures per night**							
	Total active nodes	**Total edges**	**Graph density**	**Node groups**	**Cluster coefficient**	**Graph adhesion**	**Diameter**	**Character-istic Path Length**
5 (5)	8.8	122.4	0.57	1.4	0.6	1	2.8	1.54
6 (2)	7	25	0.18	3	0.51	0	2.5	1.47
7 (1)	5	8	0.08	3	0	0	2	1.33
8 (2)	8.5	50	0.32	3.5	0.56	0	3	1.55
14 (8)	7.75	29.5	0.25	3.63	0.17	0.88	2.25	1.31
18 (5)	7.2	6.8	0.08	5.6	0	0	1	0.73
19 (1)	4	3	0.08	2	0	0	2	1.33
20 (3)	6.67	23.33	0.25	2.33	0.32	0	2.33	1.44
22 (1)	8	5	0.06	7	0	0	1	1
26 (2)	7	4.5	0.10	4	0	0	2.5	1.45

Mean nightly global clustering coefficient values at sites ranged from 0 (low clustering) to 0.6 (moderate clustering) (Table 4.4), however the overall nightly mean of 0.25 represented a lack of overall cohesion within networks. Higher clustering coefficients were frequently recorded in concurrence with lower numbers of node groups. However site 8 displayed a relatively high mean nightly coefficient of 0.56 whilst featuring a mean of 3.5 node groups. The latter case was the result of individual detectors recording occurrences of isolated bat activity that were not connected by movement to the remaining network detectors, which themselves showed high levels of interconnected clustering. Multiple node groups occurred at both sparse and cluttered habitat site types (as defined above) and the large numbers of node groups (Table 4.4) indicate fragmentation of habitat use is common at turbine sites.

A mean of 20.6% of detector nodes at a site-level represented key movement ‘bottlenecks’ between otherwise unconnected areas of sites. These node locations highlighted fragile elements of connecting habitat within sites, which if removed may result in greater fragmentation of bat activity. Correspondingly, graph adhesion values were found to be very low across most sites (nightly mean across all sites = 0.4), indicating that the majority of nightly activity networks at the sites were already weakly connected. For the few nights (17%) where activity was found to be strongly connected (i.e. a graph adhesion value >=1), the low graph adhesion values illustrated that a small number of habitat disturbances at the turbine sites would result in weakly connected networks.

The diameter measure was similar between sites (nightly mean = 2.17, range of nightly means = 1-3), however these diameters were created from combined species’ use of each site. Mean individual species diameters for those species recorded on >5 nights ranged from 0.6 (Leisler’s bat) to 2.78 (common pipistrelle). Leisler’s bats may therefore be more likely to use straighter flights across turbine sites and to interact less with site features. Acoustic monitoring success is also likely to be lower for this species, given the mean diameter is less than 1. Common pipistrelles may rely on less direct, longer paths along features such as hedgerows.

4.4.2.2 Movement network visualisations

The movement network visualisations using the ‘Kamada Kawai’ and ‘Fruchterman Reingold‘ layout algorithms illustrated ‘clusters’ of detector locations featuring good within-group connectivity (a group of nodes connected by edges) (Figure 4.4). The visualisations highlighted any strength or lack of between-group connectivity (the number or lack of linking edges between different node groups). Detector node locations within these layouts do not represent geographic space, instead connectivity and association. The associated numbers of node groups are recorded in Table 4.4, illustrating that a cohesive network of site-wide activity was observed to be rare. Instead, most sites featured compartmentalised, unconnected groups of activity and in some cases, just scattered bat passes at separate locations.

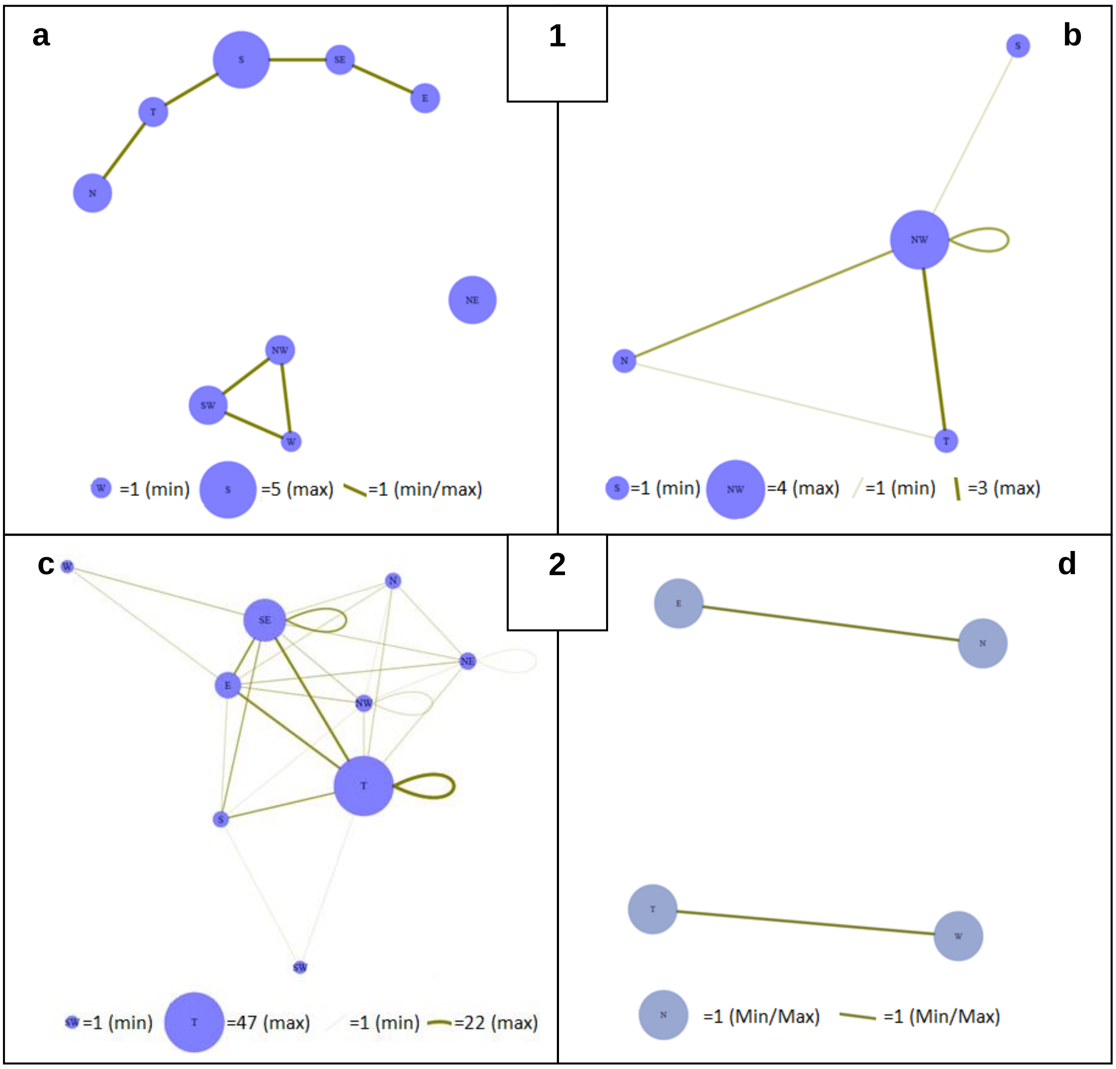

Figure 4.4: Examples of network visualisations using the Fruchterman Reingold and Kamada Kawai algorithms, suggesting (1: a and b) unconnected areas of Common Pipistrelle (a) and Leisler (b) bat flight activity within 2 different monitoring sites; (2) well-connected networks of flight activity

4.4.2.3 Regular and random network models

All sites' network densities were found to be significantly different to a regular model of movement (assuming equal use of all site areas), regardless of differences in monitoring length (Table 4.5). Individual, supplementary site networks were furthermore constructed for each of the 7 sites with at least 2 monitoring nights, using 2 randomly chosen nights. A comparison of these against 3 random models of graph density (constructed from the mean number of edges present in the 7 comparison networks) illustrated only a small number of significant differences for individual sites (Table 4.5). Whilst a non-uniform structure of site use was found, the ability to describe bat activity at turbine sites as non-random was limited.

Table 4.5: Comparison of 2-night site level networks with regular and random theoretical networks

Site number (No. of nights)	**Comparing density to a regular theoretical model (20,000 iterations)**		**Comparing density to random network 1 (20,000 iterations)**		**Comparing density to random network 2 (20,000 iterations)**		**Comparing density to random network 3 (20,000 iterations)**	
	Z	p	t	p	t	p	t	p
5 (5)	-2.66	0.01	1.29	0.09	1.03	0.15	1.65	0.05
6 (2)	-5.48	<0.0001	-1.13	0.13	-1.22	0.11	-0.64	0.27
7 (1)	-13.69	<0.0001	-	-	-	-	-	-
8 (2)	-5.05	<0.0001	-0.78	0.21	-1.08	0.13	-0.31	0.38
14 (8)	-1.91	0.03	-0.88	0.18	-0.15	0.12	-0.58	0.28
18 (5)	-7.62	<0.0001	-3.24	0.001	-3.40	0.0004	-2.43	0.0096
19 (1)	-13.68	<0.0001	-	-	-	-	-	-
20 (3)	-4.21	<0.0001	-1.12	0.13	-1.40	0.08	-0.72	0.23
22 (1)	-18.63	<0.0001	-	-	-	-	-	-
26 (2)	-11.28	<0.0001	-2.18	0.02	-2.41	0.006	-1.62	0.06

4.4.3 Node-level network analyses and habitat type analyses

Table 4.6 shows the node-level statistical network analysis results for all species combined. Movement links were found between all three habitat types (open / feature / turbine) at almost all sites. No activity was recorded at the turbine location at two sites, though both featured only a single monitoring night. A further single site did not record movement between the ‘open’ and ‘turbine’ habitat types, though activity was recorded at both.

When analysing detector habitat types for all species and sites, differences in degree centrality (feature = 1136, open = 550, turbine = 532) were not significant (F = 1.98, df = 2, p = 0.16, 20,000 iterations). The ‘feature’ habitat type was assigned an eigenvector centrality value of 1, relative to 0.41 for turbine locations and 0.24 for open habitats. No significant differences in associations between habitat types were found (e.g. feature-open vs. feature-turbine). The composition of habitat-type to habitat-type movements was: 43.6% ‘feature-feature’; 17.4% ‘open-open’; 12.5% ‘feature-turbine’; and 12% ‘open-turbine’; 11.7% ‘turbine-turbine’; and 2.8% ‘feature-open.

The ‘turbine’ location featured the highest eigenvector centrality score of all detectors in the site-level network at half of the sites (and 3/10 sites on a mean nightly basis). The difference between the turbine and pooled non-turbine locations, using individual monitoring night samples, was significant at two of the five sites where this pattern was observed (t = -0.752, p = 0.007 (one tailed); t = -0.828, p = 0.003 (one tailed)) and approaching significance for a third (t = -0.244, p = 0.06 (one tailed)). Similarly the turbine location frequently featured high ‘betweenness’ and ‘degree’ values in the node-level networks (Table 4.6) – i.e. recording many flights through the turbine location and many connecting movements to and from the turbine from the other sections of the site.

Degree centrality was only significantly different between detector nodes at one of the seven sites with 2+ monitoring nights (F = 3.12, df = 8, p = 0.011, 20,000 iterations). Preferential use of and reliance upon single detector portions of sites was therefore rarely observed. Significant between-detector differences were similarly only observed at a species-level at two sites for soprano pipistrelles (F

= 3.40, df = 8, p = 0.004, 20,000 iterations; F = 2.37, df = 8, p = 0.04, 20,000 iterations) and one site for common pipistrelles (F = 2.17, df = 8, p = 0.05, 20,000 iterations).

Table 4.6: Network node-level measures of bat activity and detector location connectivity at each monitoring site. The data are displayed geographically within each site in relation to the geographic detector location they represent, as exemplified by the first set of 9 results in the top left of the table (i.e. within each 3x3 grid of results, the detector locations are organised as follows: top row left = north west (NW), top centre = N, top right = NE; middle row left = W, middle centre = Turbine (T), middle right = E; bottom row left = SW, bottom centre = S, bottom right = SE)

Site Number (No. of nights)	Degree			Betweenness			Closeness			Eigenvector Centrality		
5 (5)	1.80 (NW)	2.80 (N)	15.60 (NE)	0.36	0.09	2.36	0.05	0.06	0.08	0.04	0.02	0.21
	1.80 (W)	37.60 (T)	27.60 (E)	0	7.55	1.05	0.06	0.10	0.08	0.04	0.35	0.24
	105.60 (SW)	17.60 (S)	34.40 (SE)	2.08	1.92	1.77	0.08	0.08	0.08	0.54	0.24	0.53
6 (2)	8.00	5.00	0	2.10	0	0	0.05	0.02	0.01	0.52	0.15	0
	0.50	32.00	0.50	0	2.40	0	0.04	0.02	0.04	0.23	0.50	0.003
	1.00	2.50	0.50	0	1.00	0	0.03	0.05	0.04	0.43	0.52	0.02
7 (1)	5	2	0	1	0	0	0.083	0.077	0.05	0.697	0.274	0
	0	0	0	0	0	0	0.05	0	0	0	0	0
	0	9	0	0	0	0	0	0.077	0	0	1	0
8 (2)	0	4.00	0	0	0	0	0.02	0.03	0.01	0	0.02	0
	14.00	33.50	18.50	2.50	3.86	2.65	0.03	0.04	0.04	0.47	1.00	0.48
	2.00	26.50	1.50	0	0.99	0	0.03	0.04	0.02	0.13	0.87	0.02
14 (8)	2.50	2.75	5.13	0.01	0.13	0.92	0.03	0.04	0.04	0.23	0.34	0.37
	1.88	17.88	8.63	0.12	2.48	2.50	0.02	0.05	0.03	0.14	0.58	0.44
	4.63	4.88	10.75	0.02	1.26	0.57	0.03	0.04	0.05	0.26	0.46	0.72

Site Number (No. of nights)	**Degree**			**Betweenness**			**Closeness**			**Eigenvector Centrality**		
	1.00	0.20	0.40	0	0	0	0.02	0.03	0.02	0.40	0.20	0.40
18 (5)	1.20	0.60	0.60	0	1.00	0.60	0.03	0.02	0.01	0.24	<0.001	0.20
	1.80	7.60	0.20	0	0	0	0.02	0.01	0.03	0.40	0.50	0.20
	1	0	0	0	0	0	0.143	0	0	0.5	0	0
19 (1)	0	4	1	0	1	0	0	0.167	0.143	0	1	0.5
	0	0	0	0	0	0	0	0	0.0833	0	0	0
	4.00	1.00	7.67	1.33	0	2.22	0.03	0.02	0.04	0.10	0.01	0.25
20 (3)	5.00	21.00	1.33	1.05	2.00	0	0.07	0.07	0.06	0.56	1.00	0.36
	3.33	3.67	0	1.67	1.07	0	0.04	0.07	0	0.05	0.06	0
	0	1	0	0	0	0	0.018	0.02	0.018	<0.001	0.236	<0.001
22 (1)	0	0	9	0	0	0	0.018	0	0.02	<0.001	0	1
	0	0	0	0	0	0	0.018	0.018	0.018	<0.001	<0.001	<0.001
	0.50	0.50	0.50	0	0	0	0.01	0.03	0.03	<0.001	<0.001	0.35
26 (2)	0	0	1.50	0	0	0.50	0	0.03	0.04	0	<0.001	0.59
	1.00	3.00	2.00	0	1.00	1.00	0.03	0.01	0.04	0.29	0.50	0.67

4.4.4 Bat flight behaviours

147 long flight paths of all species were observed across the sites (≥3 consecutive recordings). A mean of 4.9 detector recordings were linked for each path (range = 3 to 41, std. dev. = 4.94) and at least one flight path was recorded at every site.

Flight paths were recorded for the common pipistrelle, soprano pipistrelle, Nathusius' pipistrelle, Leisler's bat, serotine, noctule and *Myotis (sp.)* bat species. Interpreted behaviours comprised foraging (n = 104), commuting (12), possible investigation (21) and 'unknown' (10). During foraging activity, 72.1% of flight paths incorporated at least some movement in the vicinity of linear hedgerow and woodland features. Only 3.8% displayed mixed use of open and feature habitats. A large proportion of foraging flights (41.3%) included the turbine area. Of the 27.9% of foraging flight paths in open habitat, approximately half (12.5% of the total foraging flights) also incorporated the turbine area.

The frequency of looping and repeating flight patterns was high (71.4% of all flights, defined as including ≥2 consecutive recordings at the same location), indicating substantial foraging activity. 33.3% of the 105 repeating/looping flights were recorded at the turbine location – lending weight to hypotheses of foraging around or investigation of the turbine feature. Within the 35 repetitive behaviour observations at the turbine, the majority (26) featured extended activity (defined as ≥3 consecutive recordings at the same location). One occurrence comprised 24 consecutive recordings at the turbine.

Flights categorised as 'expected' behaviour only reached 55.8% of the total. One record (0.7%) was unclassified. 23 of the 64 'unexpected' flight behaviours represented flights in open space by species not usually associated with this habitat. 40 were classified due to flight patterns involving the turbine. Activities comprising 'unexpected' behaviours included (1) flights passing directly through the turbine area; (2) paths to and from the turbine during flight, sometimes in a repeated manner; (3) repeated flight at the turbine location; and (4) recordings from a flight path finishing at the turbine location.

4.5 Discussion

4.5.1 Social network analysis

This study investigated bats' spatial activity patterns within small and medium wind turbine sites and analysed whether turbines disturbed bat activity or encouraged investigation by bats. The study applied SNA research methods and furthermore assessed observations of extended flight paths around turbine sites, both based on a small network of bat detectors. The study represented the first use of SNA for analysis of bat activity at wind turbine sites, as far as the author is aware. Additionally, the study is one of the first to specifically analyse bat movement networks using SNA (following initial investigations regarding movements between roosts and bats' social networks (Rhodes et al. 2006; Silvis et al. 2014; Fortuna et al. 2009; August et al. 2014)).

Bat movement networks' activity levels and spatial configurations varied considerably between sites and nights, a finding consistent with existing observations (Brinkmann et al. 2006; Horn et al. 2008; Baerwald and Barclay, 2009; Baerwald and Barclay, 2011; Weller and Baldwin, 2012). Typical species-specific patterns of abundance and habitat use were observed, finding higher network densities for common and soprano pipistrelles and lower densities for serotine, Leisler's and *Myotis* (sp.) bats (Verboom and Huitema, 1997; Russ et al. 2003). This suggests species-specific use of space is not modified by small turbine presence. Typical habitat use by bats also appears to occur, as shown by higher network densities at sites with cluttered habitat (Downs and Racey, 2006; Verboom and Huitema, 1997; Vaughan et al. 1997). Furthermore the significantly non-uniform patterns of bat movements within sites as observed also indicate selective use of site structure by bats. Recommendations for preferential selection of turbine development sites with sparse habitats, to reduce risk of bat presence (Natural England, 2014), are therefore supported.

Movements were observed between all habitat types present at almost all sites, including the turbine location. This suggests bats do not generally avoid small and medium turbines – a result which is consistent with observations of activity and fatality at small turbines during previous studies (Minderman et al. 2012; Minderman et al. 2015; unpublished studies, University of Exeter).

The observed differences in degree centrality (non-significant) and eigenvector values between habitat types imply bats may use linear and wooded habitat features as core network linkages through turbine sites. This was supported by the relatively high proportion of ‘feature-feature’ movements (44%). Additionally, bats may be reluctant to deviate from linear/wooded features; only 2.8% ‘feature-open’ movements were observed. These findings are consistent with previously recorded use of linear and hedgerow features by bats (Verboom and Huitema, 1997). Whilst such habitat may be preferable, paths across open space were still seen to be used (17.4% of movements).

Turbine locations also recorded higher eigenvector values than open habitat locations, indicating bats may perceive turbines as providing preferential navigational and foraging value relative to surrounding sparse environments. Bats’ movements illustrated connections with the turbine from both ‘feature’ and ‘open’ habitat types (12.5% and 12% of habitat type associations respectively). This is supported by the concerning finding that detectors at the turbine location featured the highest eigenvector value of all detectors at half of the sites (at a site network level). Furthermore the high ‘betweenness’ and ‘degree’ values frequently attributed to the turbine portray extensive movements both connecting to and travelling through the turbine vicinity. This presents a risk that turbines may be hub structures for bat activity at some sites. Some of the turbines were however adjacent to linear habitat features; therefore the eigenvector value for the turbine habitat type may be artificially elevated.

Foraging or investigation may be likely bat activities at turbines, as multiple consecutive recordings occurred at the turbine (11.7% of habitat associations). These behaviours have been proposed by Kunz et al. (2007a) and Cryan and Barclay (2009). Observations of the high likelihood of insect presence on turbine surfaces strengthen the foraging hypothesis (Rydell et al. 2016).

The results indicated a risk to bats from habitat disruption at turbine sites. This was particularly the case at sites with low clustering coefficients (indicating division of activity into groups) and at habitat locations representing bottlenecks. Similarly habitat linkages may be fragile (as recorded by the graph adhesion analyses) – particularly at sites featuring isolated linear features (as this habitat types exhibited high eigenvector values). Sites with high clustering coefficients may be less vulnerable due to the availability of alternative movement routes.

Vulnerability to habitat disruption will likely vary by species, as suggested by the differing network diameters identified at species-level. The straighter observed flight lines for example of the Leisler’s bat, relative to the longer, linear habitat-associated paths of the common pipistrelle bat (matching the species’ expected format of habitat use (Shiel et al. 1999; Russ and Montgomery, 2002; Verboom and Huitema, 1997; Downs and Racey, 2006)) suggest lower vulnerability of the former species to habitat change.

4.5.2 Long flight paths

Long flight path formats considered likely to represent foraging were the most frequently observed activity type. The frequent looping activity recorded at individual nodes, together with looping and repeating flight paths support this assessment. Bats’ disproportionately high reliance upon linear habitat features was again highlighted, by use of these features during 72.1% of foraging flight paths. This further underlines the importance of turbine placement away from these habitat features, to avoid non-fatal impacts upon bats.

Similarly, the large proportions of foraging flights and repeating/looping flight paths including the turbine support hypotheses of foraging at and/or investigation of turbines (Cyran and Barclay, 2009; Horn et al. 2008). The large proportion of ‘unexpected’ flights through the turbine vicinity indicates not all bat flights near turbines are fatal or suffer from disturbance. Other behaviour included apparent investigation, represented by paths to and from the turbine during flight and repeated activity at the turbine. Bats may also therefore utilize micro-avoidance of the turbine at close proximities. Such behaviour is consistent with previous investigations of both bats and some bird species at turbine sites (Minderman et al. 2012; Everaert, 2014).

Flights terminating at the turbine may be interpreted in a number of ways. This may represent occurrence of fatality, or a failure of detectors to record flight away from the turbine. Alternatively an increase in flight height at the turbine, to avoid the structure, may have reduced the ability to record bat flight away from the turbine. Finally bats' echolocation activity may have reduced upon encountering the turbine.

4.5.3 Evaluation

A small amount of the activity classified as movements will have in reality comprised recordings of individual bats at different locations in adjacent 5 second periods. This is a factor commonly encountered during bat research when attempting to define bat populations at a site (e.g. defining whether 10 recordings represent 10 passes from a single bat, or less than 10 passes each from 2 or more bats) and is very difficult to resolve using just acoustic monitoring (Kunz et al. 2007b). However the use of very short (5 second) activity recording windows and classifications by species/genus imply a high likelihood that the majority of adjacent recordings in time represented a single bat movement.

Finally the manual classification of long flight paths was a subjective process relying on researcher-interpretation. However as all flights were interpreted by a single researcher and a consistent process was used to define the flight types, this analysis was not subject to unequal bias during classification. Furthermore this manual approach has been used in most previous studies of bat behaviours and activity types in proximity to turbines (Horn et al. 2008; Ahlén et al. 2009; Ahlén, 2003; Bach and Rahmel, 2004; Cryan et al. 2014; Gorresen et al. 2015).

4.5.4 Future research

The use of SNA methods was beneficial for gaining an in-depth understanding of activity configurations at wind turbine sites. The approach extracted and quantified activity patterns from a collection of acoustic datasets that would otherwise prove challenging to handle and analyse in combination. Its use was particularly of value in identifying the most important locations within sites for bats' movement through the site areas, the use of different habitat types by bats, the interaction of bats with turbines, the density of movement networks and the fragility of habitat linkages.

Future studies may consider increasing the number of sampling nights, to identify seasonal variations in bat activity. Seasonal mating, migratory or roosting behaviours may alter bats' use of turbine sites and interaction with turbines. Use of detector models that are able to operate over long time periods with minimal maintenance is furthermore recommended – this element was limited by financial constraints in the current study.

Future studies could apply SNA approaches to further test hypotheses of habitat disruption, by removing individual habitat nodes and modelling the impact upon bat movement networks. Field validation could be completed by experimentally applying the same changes at the modelled sites, e.g. the experimental removal of a section of hedgerow before repeated monitoring. Post-alteration monitoring may need to be repeated over consecutive years to allow for lagged behavioural responses by bats to the disruption (as previously observed (Bach and Rahmel, 2004)). The same methods offer potential for evaluating the effectiveness of habitat management for mitigation of turbine impacts upon bats. Management may in this case comprise habitat removal to deter bats from turbines, or habitat production to attract bats to non-turbine areas or offset disruption from turbine development (Peste et al. 2015; Millon et al. 2015).

4.6 Conclusions

This study investigated bats' spatial activity patterns within small and medium wind turbine sites using SNA, identifying strong associations between bats' movement routes and habitat structures present at sites. Furthermore bats were found to actively use the turbine area rather than avoid it, indicating a lack of consistent disturbance from the turbine itself. Foraging appeared to be the most prevalent behaviour type displayed by bats at wind turbine sites, including in the direct vicinity of turbines. Important movement linkages within sites provided by linear features (e.g. hedges) and wooded habitat appeared to represent vulnerable locations within sites with sparse habitats. If these were disrupted activity at sites could be reduced to weakly connected networks.

These outcomes exemplify opportunities to assess and plan turbine placement in a more advanced manner, using SNA. Of particular concern are changes to habitat features as a result of site development and the installation of wind energy infrastructure. Non-fatal impacts upon bats such as habitat loss and the breakdown of movement/foraging networks could occur in these situations.

These results represent some of the first research outcomes investigating non-fatal impacts of small and medium turbines (and indeed of any size of turbine) upon bats. The lack of avoidance of small and medium turbines by bats and displays of foraging activity in their vicinity suggest that current assumptions within development guidance (e.g. Natural England (2014)) to place turbines away from linear habitat features are valid. Increased risk of fatality may otherwise occur due to the observed lack of turbine avoidance and focused use of such habitats by bats.

SNA methods may be applicable to gain a greater understanding of activity networks and vulnerable locations within sites. However the large survey effort and detailed analysis approaches required suggest such methods may be better suited to high risk sites, major developments and research environments. Future studies may consider repeating such analyses at large turbine sites or wind farms to assess whether the same patterns are repeated in these environments.

On the basis of the results presented, future studies and planning guidance should incorporate considerations of the non-fatal impacts of small and medium turbines upon bats in any development guidelines. Where habitat structure is considered to imply a high risk of disruption from turbine development , SNA analysis methods may offer an opportunity to understand bats’ use of sites and improve turbine placement.

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4.8 Chapter 4: Supplementary Materials

Table S4.1: SNA Measures applied within this study. Definitions based on Csardi et al. (2015)

SNA Measure	**Definition**
Characteristic path length	Average path length between any two nodes
Diameter of the graph	Longest path between any two nodes
Graph adhesion	Represents the number of edges which would need to be removed to create a weakly connected network
Overall size of the graph	Total active nodes and edges
Graph density	Total unique edges divided by the number of possible unique edges
Degree measure	Records the number of edges connecting to the concerned node
Betweenness	Represents the number of shortest travel paths which pass through a node
Closeness	Calculates how many steps are required between nodes in the network in order to reach every other node, from the concerned node
Eigenvector centrality	Defined by igraph package authors as “arising from a reciprocal process in which the centrality of each [node] is proportional to the sum of the centralities of those [nodes] to [which it] is connected. In general, vertices with high eigenvector centralities are those which are connected to many other vertices which are, in turn, connected to many others (and so on)” (Csardi et al. 2015).

Bat flight speeds and classifying bat movements

The choice of 5 second periods was considered appropriate for the detectors' spatial configuration (min. detector separation: 33.3m, max.: 47.1m (diagonal)) and bats' typical flight speeds. After incorporating an approximate maximum detection distance of 5-15m by the Baton detector (allowing for differing call amplitudes from different species), bats had to fly a maximum distance of approximately 3-37.1m between detection zones during a 5-10 second period (2 adjacent 5 second periods), in order for the activity to be classified as a movement edge between detectors. Using a mean distance of 20.1m and mean time of 7.5s, this would indicate a *minimum* required flight speed of 2.7 m/s in order for the flight to be linked between detectors. This equates well to typical bat flight speeds recorded by previous studies, e.g. 3.5-5.7 m/s in Aldridge and Rautenbach (1987); 2.5-4 m/s in Thomas et al. (1990); 4.5 m/s in Jones and Rayner (1989); 3.4-11.6 m/s in Grodzinski et al. (2009); 2.9-8.3 in Middleton (2006); 2.1-13.9 m/s in Hayward and Davis (1964); 3.9-8.1 m/s in Jones (1995). If flight speeds were at the higher end of these ranges, they may be recorded at 2 or more detectors within the same 5 second period, which would still be linked using the above method. In the worst-case scenario, using a poor (5m) detection distance and the longest resulting maximum flight distance (37.1m), with the most restricted flight recording window (5 seconds; occurring if a bat is initially recorded at the very end of the 1st 5 second window), this would require a flight speed of 7.4m/s. The latter scenario would likely result in some flights not being classified (though flights would still be recorded from faster flying bats); however the likelihood of such a scenario is also low.

5 Impact of turbine noise on bats

5.1 Abstract

Numbers of wind turbine installations are increasing across the world in response to the growing pressures of climate change. This has had unpredicted negative impacts upon some wildlife species, including the occurrence of bat fatalities at many wind energy sites. A large collection of hypotheses have been proposed to explain bats' presence at wind turbines (Cryan and Barclay, 2009) and a range of research studies have tested a number of these. It has been suggested that wind turbines may furthermore impose non-fatal impacts upon bats, including disturbance and displacement. The hypothesis that turbine noise may either attract (Ahlen, 2003; Cryan and Barclay, 2009) or disturb bats has received little research attention.

An investigation is presented here into the effect of small wind turbine noise upon bat activity in rural agricultural settings, typical of the landscape type in which small wind turbines are often planned. By assessing bats' activity levels in response to a turbine noise playback experiment, the study isolates the impact of turbine noise upon bats without the confounding factors of physical and visual turbine presence. A string of 5 bat detectors was installed along 4 mature, linear hedgerows with an ultrasonic speaker placed at the centre of the string. Turbine noise playback in both human-audible and ultrasonic frequencies was enabled on half of the monitored nights to test its effect upon bat activity levels.

No effect of small turbine noise was identified upon bat activity, including when accounting for an interaction with detector position. Temperature and rainfall were however found to have a moderating influence upon activity. These results represent the first scientific investigation to test the turbine noise hypothesis. Future research may address whether the same result occurs at large turbine sites and in differing habitats.

5.2 Introduction

The occurrence of bat fatalities and their causal factors at wind energy sites have received substantial research attention (Johnson et al. 2003; Arnett et al. 2008; Rydell et al. 2010a; Dubourg-Savage et al. 2011; Baerwald and Barclay, 2011; Georgiakakis et al. 2013; Minderman et al. 2015; Rydell et al. 2016). Whilst non-fatal impacts and disturbance to bats from wind turbines have been recorded (Minderman et al. 2012; Jain et al. 2011; Bach and Rahmel, 2004), this subject requires further research attention.

5.2.1 Hypotheses for bats' interactions with turbines

Numerous behavioural theories to explain bats' interactions with turbines have been proposed. Proposed theories include attraction to turbines for foraging, roosting, mating or investigation purposes, avoidance of moving blades and attraction or avoidance due to noise emissions (Cryan and Barclay, 2009; Cryan et al. 2012; Ahlén, 2003; Kunz et al. 2007; Gorresen et al. 2015; Szewczak and Arnett, 2006; Minderman et al. 2012; Rydell et al. 2016). All of these may cause alterations to bats' flight activity and behaviours. The latter hypothesis regarding acoustic attraction of bats due to turbine noise was first proposed by Ahlén (2003) and later highlighted by Cryan and Barclay (2009). Both studies suggested that playback of turbine noise and concurrent monitoring of bat activity could be used to test the hypothesis. The current study therefore adopted this approach to investigate the effect of small wind turbine noise upon bat activity.

5.2.2 Bats and noise

5.2.2.1 Environmental noise

Playback of noise associated with roads, vegetation movement and broadband computer frequencies has been found to disturb and repel bat species that forage with gleaning strategies (Schaub et al. 2008). Foraging success was also found to decrease with increasing proximity to road noise during a second playback experiment, where foraging search time required by bats to locate prey was found to dramatically increase closer to the noise source (Siemers and Schaub, 2011). The latter experiment deduced that bats' echolocation detection distance may also reduce in the presence of noise. Not all noise sources meanwhile have been found to have a large effect upon bats, for example a study of aircraft noise could not identify any notable impact (Le Roux and Waas, 2012).

5.2.2.2 Turbine noise

Only a single pilot experiment has been completed so far utilising playback of turbine noise to understand impacts upon bats. The study found inconclusive results from largely unstructured behavioural observation, though it was stated that the impression gained by the author was one of a lack of impact (Ahlen, 2003). Bats may more generally struggle to process more than one stream of acoustic information at a time (Barber et al. 2003); therefore if turbine noise occurs within their foraging habitat, avoidance of the affected area may be a logical response.

5.2.2.3 Bat echolocation and noise

Changes in bats' echolocation behaviour are also known to occur as a result of interaction with other sources of noise. Bats will often change their echolocation frequencies in order to avoid acoustic jamming i.e. confusion with similar sound frequencies to their own echolocation. This has been observed to occur in the presence of other bat calls and chorusing insects (Gillam et al. 2007; Chiu et al. 2009; Gillam and McCracken, 2007). The relative frequency of jamming noise to that of bat echolocation appears to be an important factor in defining noise impact extents. Noise with frequencies below that of bats' echolocation has been found to have a larger impact than equal or higher frequencies, causing upward shifts in echolocation frequency (Takahashi et al. 2014). Indications that most turbine noise emissions are also of lower frequencies (Szewczak and Arnett, 2006; Long, 2011; Dooling, 2002) therefore suggest noise impacts from wind turbines are worthy of investigation. Some high frequency noise can also be created by wind turbines, particularly at blade tips (Twidell, 2003) and from blade defects (Dooling, 2002).

5.2.2.4 Acoustic deterrents

A final key area of research that has improved our understanding of noise impacts upon bats is that of the development and testing of ultrasonic acoustic deterrents for bats at wind turbines. An initial lab experiment provided indications that ultrasonic noise could have potential use as a deterrent method for bats, after they were recorded being repelled by the emitted signal, causing reduced activity and foraging in the vicinity (Spanjer, 2006).

Initial field tests of ultrasonic acoustic deterrents at wind farm sites reported limited impacts upon bat activity; however this was attributed to the size of the noise envelope created by the device (Horn et al. 2008; Szewczak and Arnett, 2008). Ultrasound is known to attenuate quickly across air volumes, particularly at high frequencies (Griffin, 1971; Lawrence and Simmons, 1982). Consequently propagation of ultrasonic noise emissions from turbines may similarly be limited, particularly in high wind conditions at hub heights. One of the deterrent studies did however record large reductions in bat activity within the effective range, with activity reducing to 2.5-10.4% of that recorded during control conditions (Szewczak and Arnett, 2008).

Further evidence of the acoustic impact of ultrasound upon bats was provided by testing of deterrents at pond sites in the USA, prior to wind farm implementation. A 17% reduction in bat activity was observed (Johnson et al. 2012). A later study implementing an acoustic deterrent at a wind farm, observed small reductions in fatalities. Humidity level was furthermore raised as a moderating factor on signal propagation (Arnett et al. 2013).

5.2.2.5 Summary and study aims

Existing observations regarding bats’ behavioural and echolocation reactions to environmental noise and acoustic devices indicate that turbine noise could feasibly impact upon bat activity and behaviour. The height of small turbines suggests that most, if not all, of their noise emissions will reach ground level and the typical foraging heights of many common bat species in the UK. This makes small turbines an excellent case study in the context of noise impacts upon bats.

This study investigated the effect of small wind turbine noise upon bat activity in rural agricultural settings, typical of the landscape type in which small wind turbines (up to ~30m blade tip height) are often planned. By assessing bats' activity patterns in response to a turbine noise playback experiment, the study isolated the impact of turbine noise upon bats without the confounding factors of physical and visual turbine presence.

5.3 Methods

5.3.1 Study area

Four sites were sought with a mature, linear and largely uninterrupted hedgerow of at least 200m in length. Each site was required to not have a wind turbine installed within the site's land parcel or within 2km. Three sites were obtained within Wiltshire (all agricultural fields) and one within Gloucestershire (a domestic smallholding). The habitat type at two of the sites was pasture grass, the third was a recently harvested arable crop field, whilst the fourth comprised a ploughed arable field with a grass margin. Three of the sites featured either agricultural or domestic buildings within 200m, though all sites were located in rural landscapes. Each site was monitored for at least 8 consecutive nights during mid-August to mid-October 2014.

5.3.2 Turbine noise

The study method required the acquisition of a recording of emitted wind turbine noise representative of that occurring at a small wind turbine site. Therefore a Wildlife Acoustics Song Meter 2 (SM2) full spectrum bat detector powered by an external battery was installed at the base of an operational small wind turbine, with a blade tip height between 10 and 15m and a rotor diameter of between 4 and 8m. The turbine model that was chosen is one of the most frequently installed models in the UK (University of Exeter, unpublished data) and as such was considered an optimum choice for representing a typical small turbine site.

The SM2's microphone was installed at the top of a tripod at a height of 2.5m and the detector was set to record using the full frequency spectrum available (up to 96kHz; sampling frequency 192kHz) in order to record turbine noise in both human-audible and ultrasonic frequencies, in field conditions. A recording of 4.1 seconds length featuring continuous turbine noise was selected as a representative recording of noise conditions and was saved onto an SD card. The majority of the turbine noise in the recorded sample was of frequencies below 25kHz, with an additional notable noise component reaching 36kHz (these frequencies are similar to those recorded by Szewczak and Arnett (2006)).

5.3.3 Monitoring protocol

At each experimental study site, five SM2 detectors were installed on 1.5m tripods with external batteries, along a 200m stretch of the selected hedgerow, separated using 50m spacing (Figure 5.1). An ultrasonic speaker (or 'bat lure') (BatLure, Apodemus Field Equipment) was installed on a 1.5m tripod (powered by an external battery) adjacent to the central detector in the string. This was able to playback sound between 5kHz and 100kHz in frequency. The speaker was set to playback the turbine recording stored on the SD card on a continuous loop, with volume set to the maximum level not considered damaging to the equipment (31/40, based on the equipment's parameters). Noise playback was disabled using a timer switch (Conrad Electronics) for the 1st night at each site to enable bats to familiarise themselves with the installations. Nightly noise playback over the duration of the 8 nights was set as follows: Night 1: Off, 2-3: On, 4-5: Off, 6-7: On, 8: Off. This provided 4 nights of ambient noise conditions and 4 nights with turbine noise introduced. For any additional monitoring nights obtained at the end of the cycle, the pattern restarted. The monitoring night was treated as 30 minutes before sunset to 30 minutes after sunrise.

A weather station with internal batteries was also installed at each site in open habitat within the same land parcel and recorded weather variables over 30 minute periods. Batteries were tested for all equipment immediately before installation and following the end of monitoring. No equipment suffered battery failure or inadequate battery power levels.

5.3.4 Bat sound analysis

At one site, recording capacity was exceeded for multiple detectors by the final night, reducing monitoring to 7 nights (one detector’s capacity was exceeded after 5 nights of monitoring). At this site, due to the extremely large volumes of data recorded (including insect noise), the analysed period each night was reduced to the first 2 hours after the start of monitoring, in order to achieve a logistically feasible volume of sound analysis. For all other sites, the entire night was analysed. Two additional monitoring nights were obtained at one of the sites relative to the 8 nights planned and a single additional night obtained at another. 34 monitoring nights were completed in total (7, 8, 9 and 10 nights at the four sites) providing a mean of 8.5 monitoring nights at each site.

Figure 5.1: An example of an SM2 detector installed along a linear mature hedgerow during the turbine noise experiment

Detector recordings were analysed using the Wildlife Acoustics Kaleidoscope Pro software (version 2.3). Pre-constructed ‘classifier’ files were used to attempt to identify the species of each recording, or to categorise the recording as noise. Classifiers are composite reference files built from large numbers of individually identified bat species recordings, which are used for comparison and matching when classifying unknown recordings. In the case of bats of the *Myotis* genus, the resolution of the classifiers restricted identification to genus only. The classifier set is an existing standard reference source integrated into the software (at the time of use, this was the ‘Bats of United Kingdom 2.1.0’ classifier set version). Given the confidence levels attributed to each species classifier by Wildlife Acoustics (Wildlife Acoustics, 2014) and communication regarding past experience of their use in related projects (unpublished data, University of Exeter), it was considered acceptable to assume all classifications of *Pipistrellus pipistrellus* (Common pipistrelle) and *Pipistrellus pygmaeus*

(Soprano pipistrelle) were correct. It is acknowledged that this will introduce a small, but acceptable level of error into the method. Levels of classification accuracy for all other species were considered inadequate and as such all remaining classifications of species were manually verified using the Kaleidoscope Pro software's viewer tool.

A bat pass was identified as 2 or more echolocation pulses within less than 1 second of each other. Multiple passes were recorded as groups of echolocation pulses split by a gap of 1s or more; however the recording of more than 1 pass within a file was found to be extremely infrequent during processing for species requiring manual verification. Therefore recordings classified as Common pipistrelle and Soprano pipistrelle were assumed to be a single pass.

5.3.5 Statistical analyses

The effect of turbine noise on bat activity was assessed using generalised linear mixed effect models (GLMMs) in R (R Core Team, 2014) using the '*GLMMadmb'* package (Skaug et al. 2014). The number of bat passes per hour was used as the outcome variable in order to account for variation in weather conditions during the night. A negative binomial error distribution was assumed to account for overdispersion in the bat passes count data (identified using the residual deviance vs. residual degrees of freedom ratio during the building of models).

Wind speed (m/s), hourly rainfall (mm) and temperature (^{o}C) were treated as fixed covariates, whilst noise playback (on/off) and pooled detector positions (1 = non-speaker detectors; 2 = speaker detector) were set as fixed factors. An interaction effect between noise and detector position was also included, to account for the expected decrease in the effect of noise with increasing distance from the noise source. Nested effects of 'monitoring night' within 'site' were included as random effects to account for lack of independence of records from the same site and night. The analyses were repeated for three genera groups (1: *Pipistrellus;* 2: *Nyctalus* and *Eptesicus;* 3: *Myotis, Barbastella, Plecotus and Rhinolophus*).

The significance and contribution of each variable was measured using ANOVA and likelihood ratio tests, evaluating the deletion of each term from the model with main-effects only. The interaction term was evaluated by comparing the main-effects-only model with the full model including the interaction. Model fit and model assumptions (normality of residuals, homogeneity of residuals' variance, independence of variables and no overly-influential observations) were verified using model residuals plots (normal QQ plot, histogram of residuals, plots of standardised residuals vs. fitted values, variable correlation plots, plots of residuals vs. individual variables and leverage plots) and plots of model-predicted outcome variable values vs. observed values for each predictor variable. Data representing 9 detector hours (of a total 1,706, i.e. <1%) were removed from the model as outliers, to improve model quality, after verifying their effect using leverage plots, model residuals plots and prediction plots.

5.4 Results

5.4.1 Bat activity recorded

The total number of bat passes recorded from all sites (N) was 13,959 across 34 nights of monitoring (mean per detector-night = 83.1, std. dev. = 91.5). 73% of calls were identified as belonging to the *Pipistrellus* genus, 15.8% as *Myotis,* 4.7% as *Nyctalus* and *Eptesicus*, 4.1% as *Barbastella,* 1.7% as *Rhinolophus* and 0.5% as *Plecotus*. Unclassified recordings comprised only 0.1%. Bat activity was recorded during all 34 monitoring nights.

5.4.2 Weather conditions

Good weather conditions were experienced for bat monitoring during the observation period. Mean nightly wind speeds were below the 8 m/s threshold used for bat monitoring in previous research (University of Exeter, unpublished data) during all monitoring nights; the mean wind speed across all nights was 1.7 m/s (std. dev. = 1.3). All mean nightly rainfall records were also below the

2.5 mm / hour threshold previously used (mean hourly rainfall across all nights was 0.1 mm, std. dev. = 0.3). Mean nightly temperatures were above the 10^{o}C threshold for 85.3% of the nights (mean temperatures across the remaining 5 nights ranged from 6.8-9.4 ^{o}C); the mean temperature across all nights was 12.8 ^{o}C (std. dev. = 3.2).

5.4.3 Noise Impacts

Hourly rainfall and temperature were found to have a significant effect upon bat activity levels within the model (Table 5.1). The former had a negative effect and the latter a positive effect. As hourly rainfall levels increased from 0 to 3.9 mm, average bat passes per hour were estimated to fall from 6.37 (confidence intervals (CI) 1.61-25.12) to 0.48 (CI 0.08-2.72), an average reduction of 92%. Activity levels were predicted to increase from 0.69 (CI 0.19-2.47) to 32.18 (CI 7.12-145.49) passes per hour with an increase in temperature of 14.7^{o}C (from 4.5 ^{o}C to 19.2 ^{o}C).

Turbine noise, wind speed and the detector position (next to or away from the noise source) were not estimated to have any significant effect in the ‘all species’ model (Table 5.1); in addition no significant effect was found from the noise/detector position interaction. Prediction plots of the significant variables’ estimated effects upon observed bat activity levels are shown in Figures 5.2 (a to c), overlaid upon observed data.

Similar overall observations were made during genera group analyses (See Supplementary Materials Tables S5.1 to S5.3). *Nyctalus/Eptesicus* activity was not however related to rainfall occurrence in contrast to the all-species model. The effect of turbine noise (estimate (noise on) = -0.45, SE = 0.26, p = 0.098) was close to significance in the *Pipistrellus Sp.* analysis and detector position was found to have a significant influence (estimate (by noise source) = -0.23, SE = 0.14, p = 0.039)), however their effect sizes were small. Woodland bat activity (*Myotis/Rhinolophus/Plecotus/Barbastella*) was significantly negatively affected by rainfall occurrence, whilst temperature was found to have no significant effect. A negative effect of detector positioning next to the speaker was significant (estimate: -0.32, SE: 0.14, p = 0.02), however the small effect size and the lack of significant effect from turbine noise or the interaction between these variables rendered this result largely inconsequential.

Table 5.1: Parameter estimates and likelihood ratio tests of the GLMM analysing the effect of turbine noise and environmental variables upon bat activity. The model used a negative binomial error distribution. The variable evaluation measures represent the deletion of each term from the model with main-effects-only, with the exception of the interaction term for which the deletion was compared between the main-effects-only model and the model including the interaction term.

Fixed Effects	**Estimate**	**Standard Error**	**Log Likelihood**	**AIC**	**Deviance (Likelihood Ratio Test)**	**df**	**p**
(Intercept)	-1.17	0.56					
Wind Speed (m/s)	-0.003	0.04	-4691.70	9399.40	0.00	1	1
Hourly Rainfall (mm)	-0.66	0.15	-4700.60	9417.20	17.80	1	<0.0001
Temperature (^{o}C)	0.26	0.02	-4751.69	9519.38	119.98	1	<0.0001
Noise [On]	-0.27	0.20	-4692.49	9400.98	1.58	1	0.209
Detector Position [By speaker]	-0.21	0.12	-4693.37	9402.74	3.34	1	0.068
Noise*Detector Position	0.12	0.16	-4691.70	9401.40	0.56	1	0.454

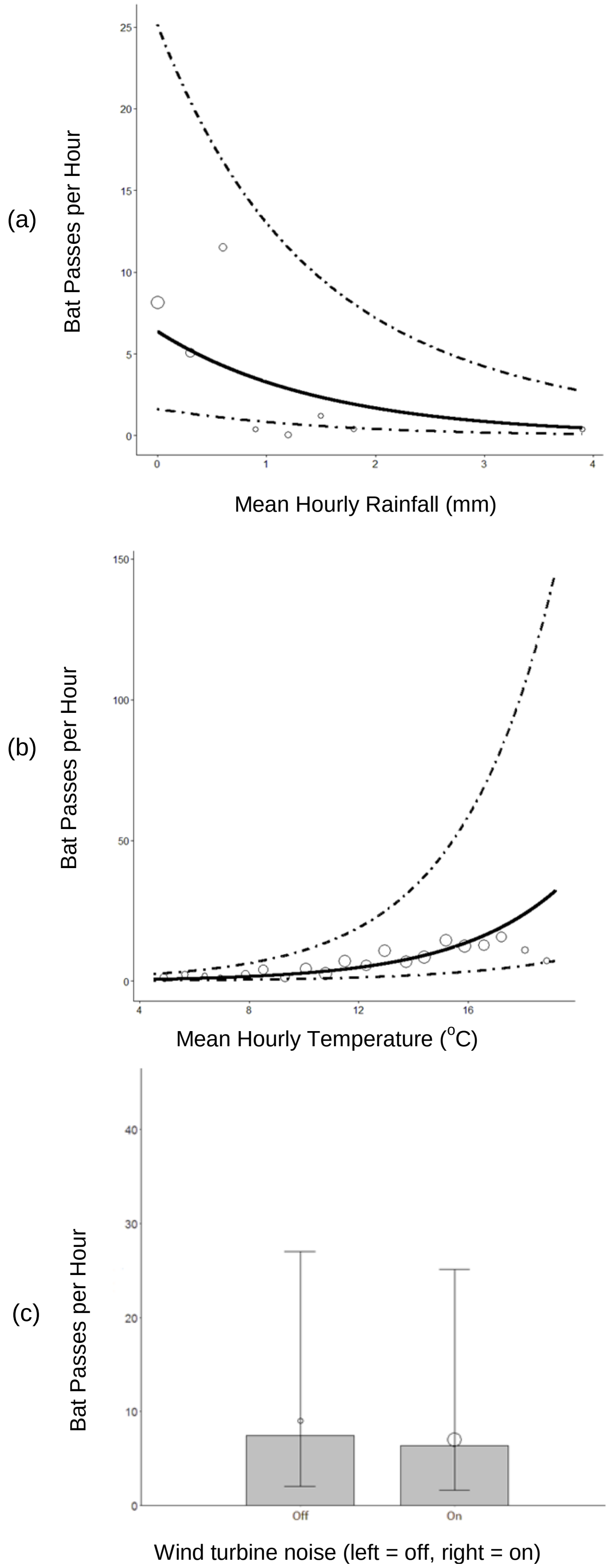

Figure 5.2: Prediction plots from the temperature, rainfall and wind turbine noise variables from the GLMM analysing the effect of turbine noise and environmental variables upon bat activity. Dashed lines indicate 95% confidence intervals (CI); circles = mean observed rate of bat passes; relative sizes of circles represent relative contributing levels of data (larger = more data); (Noise variable (c): bars and CI lines = model prediction)

5.5 Discussion

This study investigated the impact of small wind turbine noise upon bat activity levels in rural environments typical of those used for small wind turbine installations. The results provide an opportunity to evaluate existing noise-related hypotheses for bats' presence at and disturbance by turbines. In doing so the study reduces the number of unknown factors regarding this conservation issue and contributes to our wider understanding of the potential conflicts between wind energy development and bat conservation.

5.5.1 Turbine noise

No effect of small turbine noise upon bat activity levels was found. This result was also not found to be modified by the proximity of detectors to the noise source, or to vary by species group. It is therefore suggested that (1) bats are not attracted to small wind turbines due to their noise emissions and (2) bats are not disturbed or displaced by small wind turbines' noise emissions. The lack of any noise impact is consistent with the only other research observation regarding turbine noise and bat activity (Ahlén, 2003). The hypothesis of acoustic attraction of bats by turbine noise proposed by Ahlén (2003) and Cryan and Barclay (2009) therefore appears to be unsupported on the basis of this study's results.

5.5.2 Further discussion

5.5.2.1 Variability in turbine noise emissions

This study only used playback noise recorded at a single turbine model, though one which was considered very common in the UK. Individual wind turbine models and different sizes of turbine will feature varying levels of noise emissions and as such noise impacts on bats may vary at different turbine sites. Turbine manufacturers (particularly of large turbines) also incorporate optional noise-reduced operation modes in many turbine models. The use of these modes has an associated energy loss. These modes are frequently used on a per-turbine basis to comply with noise limits proposed by planning authorities on environmental health grounds (for example in proximity to residential properties), often in alignment with adopted industry practice guidelines (The Working Group on Noise from Wind Turbines, 1996). Noise emissions may therefore also vary between individual turbines of the same model. Future research projects may consider repeating this analysis using noise recordings of different turbine models (and potentially different noise-reduced modes) to verify the lack of impact observed here across a wider range of turbine types.

The playback of turbine noise through a speaker was unlikely to emit the same volume as would be produced by a real wind turbine. However the maximum possible safe volume of the ultrasonic speaker was used and without highly specialist equipment it is unlikely this issue can be mitigated. As bats have highly sensitive hearing, it is considered likely that any such noise source would be clearly prominent to bats.

As Figure 5.3 shows, the frequency response of the SMX-US microphone (Wildlife Acoustics) used to record the turbine noise is reasonably level. The microphone does not suffer any notable signal degradation bias across the low frequencies typical of wind turbine noise generation (in fact the minimal attenuation present is focused largely across frequencies above 60 kHz). Therefore the recording can reasonably be expected to have sampled the turbine noise frequencies appropriately, whilst it is acknowledged that recordings of any type will always loose at least a minor proportion of the sound characteristics produced at a source.

Future experiments may choose to further improve verification of recorded turbine noise samples and their playback through an ultrasonic speaker, by additionally recording the playback using an ultrasonic microphone and assessing the quality of reproduction of the original recording’s frequency distribution and volume within the playback.

As noise disturbance to humans is a key issue considered at the planning determination stage, industry improvements may lead to reduced noise output from turbines (particularly concerning low frequency noise). The fact that noise

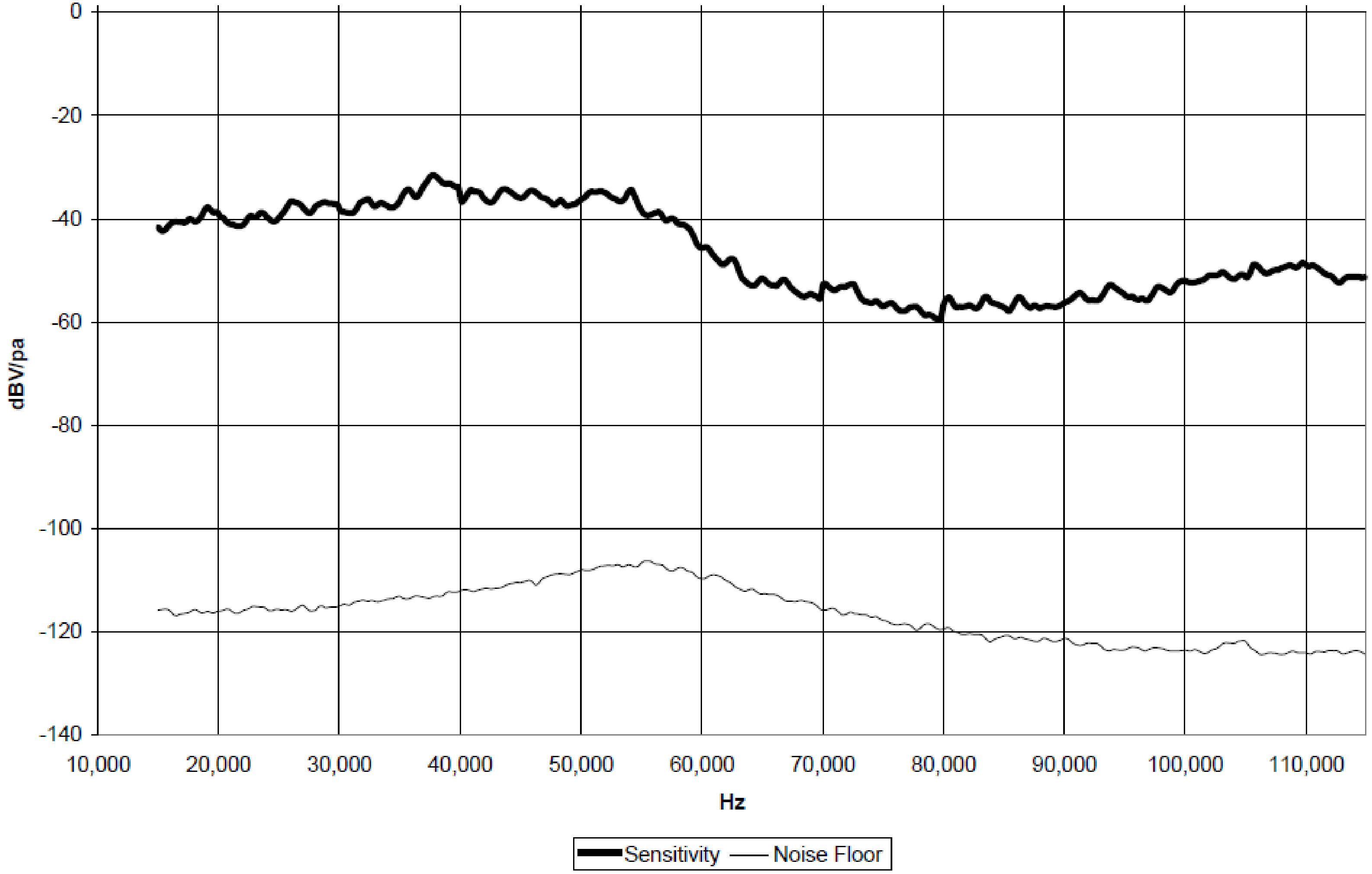

Figure 5.3: The frequency response of the SMX-US microphone (Wildlife Acoustics, 2011)

emissions from turbines can also be a sign of inefficiency and manufacturing defects (Dooling, 2002; Twidell, 2003) also implies that turbine design developments may reduce noise. However the extent to which turbine noise can be reduced is likely to be limited by the simple principle that turbines are large obstructing features with moving mechanical parts, in high speed and sometimes turbulent wind flows. The complete removal of noise in this situation therefore seems unlikely.

Larger turbines are likely to produce more noise than small turbines due to their larger gearboxes, the larger physical size of their moving components, and their greater levels of friction with larger and faster-moving volumes of air at height. However small wind turbine noise is focused within a relatively small auditory environment. This may produce a larger contrast in noise conditions relative to nearby habitat, as opposed to dispersed noise propagation from large turbines in open air. The resulting noise impact upon bats at large turbines therefore has the potential to vary from that observed during this study. Future research may consider undertaking sound sampling at different size turbines to improve understanding of potential differences in noise emissions. Similarly bat activity levels, species composition, echolocation activity, behaviour types and turbine-caused fatality levels have been observed to vary with height (Barclay et al. 2007; Collins and Jones, 2009; Ahlén et al. 2009; Baerwald and Barclay, 2009; Rydell et al. 2010a; Weller and Baldwin, 2012). Consequently bats' interaction with noise at greater heights could vary.

5.5.2.2 Other noise sources

This study's results contrast with some previous investigations that have identified impacts upon bats from other sources of noise, such as roads, vegetation movement and amplified music (Schaub et al. 2008; Siemers and Schaub, 2011; Shirley et al. 2001) and additionally acoustic deterrents at wind turbines (Szewczak and Arnett, 2008; Johnson et al. 2012). This may be due to differences in the noise sources' frequency composition, amplitude, propagation distance or habitat setting. Wind turbines' noise emissions have previously been found to primarily comprise low frequency sounds, with minimal production of ultrasound (Szewczak and Arnett, 2006; Long, 2011; Dooling, 2002), as also noted during this study. This may explain the lack of impact upon bats' auditory senses and resulting activity levels. Confirming the cause of differing responses to other noise sources is challenging without further investigating the range of noise types produced by each source (including turbines) and bats' subsequent auditory perception and response to each. Future research may consider these factors in order to aid our understanding.

5.5.2.3 Environmental moderating factors

Bat activity in this study was only monitored in one main habitat type (along mature, linear hedgerow features in rural environments). This is considered to represent a primary, important habitat type for bats, therefore suggesting activity and disruption in such locations is largely representative of that in the surrounding local area. Future studies may nonetheless consider testing noise impacts in open/sparse habitat types – particularly focusing on bat species adapted to flying in open habitat.

Bat activity levels were found to feature a positive significant association with temperature and a negative significant association with rainfall. Whilst previous research findings at wind turbines have observed a negative significant association between bat activity and wind speed (Brinkmann et al. 2006; Baerwald and Barclay, 2011; Bach et al. 2011; Weller and Baldwin, 2012; Cryan et al. 2014; Gorresen et al. 2015), this study observed no significant effect. It is suggested however, that the low wind speed conditions experienced during the monitoring period (mean 1.7 m/s, max. 7.5 m/s) were not likely to have provided the opportunity to observe negative impacts upon activity from high speeds. In addition, the placement of detectors along mature hedgerows will have recorded activity in an environment with a high relative level of wind shelter, potentially reducing the impact of wind speed (Verboom and Spoelstra, 1999). The greater susceptibility of the 'woodland bat' grouping (*Myotis, Barbastella, Plecotus* and *Rhinolophus* genera) to rainfall reflects their recognised sensitivity with regard to foraging environment requirements.

With the exception of wind speed as discussed, these results are consistent with existing research observations of bat activity and weather at wind energy sites. This supports previous assertions that variations in bat activity at turbines could to an extent be predicted and that such methods may be used to improve mitigation, via incorporation into turbine curtailment programming (Arnett et al. 2013; Weller and Baldwin, 2012). The slight variations in association with weather variables between species groups – as highlighted above – may provide opportunities to further refine the conditions during which curtailment could be used, in order to account for species-specific risk from turbines. It should however be noted that advanced turbine curtailment using algorithms incorporating weather conditions is unlikely to be possible at small turbines, due to technological and financial limitations.

5.5.2.4 Impacts upon bats from small turbines

The lack of impact from turbine noise upon bat activity at small turbines aligns with previous research that has found relatively low levels of conflict between small turbines and bats, with regard to both activity and fatality (Minderman et al. 2012; Minderman et al. 2015; unpublished studies, University of Exeter). The primary impact upon bat activity at small turbine sites appears to be an avoidance of the immediate turbine vicinity during high wind speed conditions (Minderman et al. 2012; unpublished study, University of Exeter). A recent study (unpublished study, University of Exeter) has identified that more stringent monitoring programmes are required at small turbines, in order to confirm that the seemingly low fatality levels indicated in previous research (Minderman et al. 2015; unpublished study, University of Exeter) are indeed representative of actual fatality levels at small turbines.

5.6 Conclusions

This study investigated the impact of small wind turbine noise upon bat activity in the UK and found no impact, concluding that hypotheses of acoustic attraction (Ahlén, 2003; Cryan and Barclay, 2009) and/or displacement of bats by small turbine noise are unsupported. This study provides the first structured analysis on this topic, as far as the author is aware.

Following this result, it is suggested that future research should focus upon testing the remaining hypotheses for bats' presence at and disturbance by wind turbines. These include attraction due to the presence of insect prey and the physical tree-like presence of turbines and disturbance due to loss of habitat and turbine avoidance (Rydell et al. 2010b; Cryan and Barclay, 2009). The impacts of noise from large turbines may also be considered due to the potential contrasts in noise emissions, auditory environments and behavioural responses by bats relative to small turbines. It is recommended on the basis of this study's results, that bat-related planning guidance for the development of small wind turbines should not consider turbine noise as a relevant factor in decision making.

With the exception of a need to confirm the low fatality levels indicated by available studies, existing research to date has shown a relatively low impact of small turbines upon bats in the UK. This study continues that observed trend. Investigation of cumulative impacts from turbines is nevertheless an important outstanding research priority (Arnett et al. 2016; Voigt et al. 2015) and the impact from both small and large turbines needs to be considered in tandem. Though challenging to undertake, cumulative impact calculations should ideally also incorporate impacts from other key sources of risk to bats (e.g. roads, habitat loss and white nose syndrome – the latter primarily concerning North America). Progress in this area is currently at an early stage with only a handful of studies completed, some of which focus upon extrapolation of site-level results (Roscioni et al. 2013; Kunz et al. 2007; Arnett and Baerwald, 2013; O'Shea et al. 2016).

As a result of the wider research context discussed, the outlook for balancing small-scale renewable wind energy generation with bat conservation priorities appears to be positive in the UK.

5.7 References

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5.8 Chapter 5: Supplementary Materials

Table S5.1: Parameter estimates and likelihood ratio tests of the *Pipistrellus* Genus GLMM analysing the effect of turbine noise and environmental variables upon bat activity. The model used a negative binomial error distribution. The variable evaluation measures represent the deletion of each term from the model with main-effects-only, with the exception of the interaction term for which the deletion was compared between the main-effects-only model and the model including the interaction term.

Fixed Effects	Estimate	Standard Error	Log Likelihood	AIC	Deviance (Likelihood Ratio Test)	df	p
(Intercept)	-2.95	0.72					
Wind Speed (m/s)	0.04	0.05	-3823.32	7662.64	0.44	1	0.507
Hourly Rainfall (mm)	-0.50	0.21	-3825.97	7667.94	5.74	1	0.017
Temperature (^{o}C)	0.36	0.03	-3898.18	7812.36	150.16	1	<0.0001
Noise [On]	-0.45	0.26	-3824.47	7664.94	2.74	1	0.098
Detector Position [By speaker]	-0.23	0.14	-3825.24	7666.48	4.28	1	0.039
Noise*Detector Position	0.04	0.20	-3823.10	7664.20	0.04	1	0.841

Table S5.2: Parameter estimates and likelihood ratio tests of the *Nyctalus/Eptesicus* Genera GLMM analysing the effect of turbine noise and environmental variables upon bat activity. The model used a negative binomial error distribution. The variable evaluation measures represent the deletion of each term from the model with main-effects-only, with the exception of the interaction term for which the deletion was compared between the main-effects-only model and the model including the interaction term.

Fixed Effects	Estimate	Standard Error	Log Likelihood	AIC	Deviance (Likelihood Ratio Test)	df	p
(Intercept)	-6.59	1.06					
Wind Speed (m/s)	-0.14	0.09	-966.70	1949.40	2.37	1	0.124
Hourly Rainfall (mm)	0.002	0.76	-965.51	1947.03	0.00	1	1
Temperature (^{o}C)	0.41	0.05	-1006.88	2029.76	82.73	1	<0.0001
Noise [On]	-0.12	0.28	-965.53	1947.05	0.03	1	0.867
Detector Position [By speaker]	-0.21	0.27	-965.51	1947.03	0.00	1	1
Noise*Detector Position	0.38	0.37	-965.51	1949.03	1.07	1	0.301

Table S5.3: Parameter estimates and likelihood ratio tests of the “Woodland bats” (*Myotis/Rhinolophus/Plecotus/Barbastella* genera) GLMM analysing the effect of turbine noise and environmental variables upon bat activity. The model used a negative binomial error distribution. The variable evaluation measures represent the deletion of each term from the model with main-effects-only, with the exception of the interaction term for which the deletion was compared between the main-effects-only model and the model including the interaction term.

Fixed Effects	Estimate	Standard Error	Log Likelihood	AIC	Deviance (Likelihood Ratio Test)	df	p
(Intercept)	-0.03	0.41					
Wind Speed (m/s)	0.002	0.05	-2847.23	5710.46	0.00	1	1
Hourly Rainfall (mm)	-0.78	0.19	-2857.20	5730.40	19.94	1	<0.0001
Temperature (^{o}C)	0.04	0.03	-2848.20	5712.40	1.94	1	0.16
Noise [On]	-0.13	0.23	-2847.33	5710.66	0.20	1	0.65
Detector Position [By speaker]	-0.32	0.14	-2849.83	5715.66	5.20	1	0.02
Noise*Detector Position	0.18	0.19	-2847.23	5712.46	0.92	1	0.338

6 General Discussion

6.1 Introductory restatement

Bat populations across the world are vulnerable to the pressures of climate change, anthropogenic development, habitat loss and direct fatality risk from numerous hazards. The latter include traffic on road networks, natural predation, White Nose Syndrome (WNS) and wind turbines (O'Shea et al 2016). Bat fatalities at wind energy sites are considered to contribute a large proportion of global fatality totals (O'Shea et al. 2016). Fatality levels at individual wind energy facilities have however been found to vary significantly (Arnett et al. 2008; Rydell et al. 2010a). Impacts upon both local and national populations are therefore a concern. Fatality risk has also been observed to vary by species (Arnett et al. 2008; Rydell et al 2010a; Rodrigues et al. 2015); hence impacts upon populations of individual species may be of particular concern.

All bat species in Europe are protected under the Bonn Convention (EUROBATS) and the Bern Convention, in addition to the European Union (EU) Habitats and Species Directive (EUHSD). As a result, any risk to bat populations is an important matter for conservation efforts and is potentially of legal concern. This is further emphasised for any species listed within Annex II of the EUHSD, for which Special Areas of Conservation (SAC) may be designated. In the UK those species are the Greater Horseshoe, Lesser Horseshoe, Bechstein's and Barbastelle bats. The latter two species are additionally classified as 'Near Threatened' on the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species. All bat species and their roosts in the UK are also protected under a range of national legislation, including the Conservation of Habitats and Species Regulations (2010).

Bats are also an important group of species from a biological and even economic perspective. Significant reductions in bat populations would represent a notable biodiversity loss. Bats are the only flying mammals in the world and comprise approximately 20% of the world’s mammals (Altringham, 2011). Their consumption of vast amounts of insects during nightly foraging provides a valuable ecosystem service of pest control (Kunz et al. 2011; Ghanem and Voigt, 2012; Maine and Boyles, 2015). In some cases this can amount to a significant economic benefit to agricultural areas (Maine and Boyles, 2015); the value of bats’ insect consumption in the USA is estimated at approximately $22.9 billion / year (Boyles et al. 2011). Globally, bats are also important pollinators, in addition to supporting seed dispersal and providing guano for nutrient rich fertiliser (Lundberg and Moberg, 2003; Kunz et al. 2011; Ghanem and Voigt, 2012). In the UK, bat populations are furthermore used as a national bioindicator – a biological reference measure considered representative of the wider biodiversity health in a region or nation (Jones et al. 2009; Barlow et al. 2015).

The conflict between wind energy and bat conservation is a complex matter, on account of the wider need for renewable energy generation to reduce the impacts of climate change. Without wider efforts to reduce our reliance upon fossil fuels, the negative effects of climate change upon bats and other wildlife may outweigh those caused by wind turbines. The volume of renewable energy generation that is required in order to achieve EU and global targets for reductions in carbon and greenhouse gas emissions is significant. Current EU legislation sets out a target of achieving 20% of total energy generation from renewable sources by 2020 (Directive 2009/28/EC of the European Parliament and the Council of the European Union (2009)). More recent UK and European targets (including the 2016 ‘Paris Agreement’) aim to reach an 80% reduction in greenhouse gas emissions relative to 1990 levels by 2050 and net zero emissions during the 2nd half of this century (Committee on Climate Change, 2016). The impact on European-level climate change targets of the recent 2016 UK referendum and its vote to leave the EU, is not yet known.

Renewable energy generation will need to rise by significant levels during these periods in order to meet these targets. The largest renewable energy sector in the UK, as a result of a strong natural resource and a maturing industry, is wind power (RenewableUK, 2015a). Onshore wind energy is also currently the most economical form of energy generation in the UK (Bloomberg New Energy Finance, 2015). The development of new wind energy capacity in the UK is, however, currently limited as a consequence of recent changes in government energy and planning policy and funding channels (RenewableUK, 2015a). However in the context of the above legally-binding climate change targets and the present renewable energy industry structure, it is likely that the installation of turbines will further expand in the UK in coming years.

Bat fatalities at wind turbines have now been recorded across the globe and therefore are not a localised phenomenon. Published studies and reports list occurrences across all 6 continents where bats are present (Arnett et al. 2008; Rydell et al. 2010a; Hull and Cawthen, 2013; Doty and Martin, 2013; Kumar et al., 2013; Escobar et al., 2015; Patraca, 2009), with particularly large volumes of research output produced in North America and, more recently, in Europe. Existing research has focused primarily upon fatalities at turbines, in addition to behavioural studies and the development of potential mitigation techniques (see this Thesis' Literature Review). Few studies have considered non-fatal impacts of turbines or the spatial activity patterns of bats at wind energy sites. Furthermore research effort has almost exclusively considered large turbines at wind farms, with only a very small number of studies investigating small turbines (e.g. Minderman et al. 2012; Park et al. 2013; Minderman et al. 2015; Long et al. 2010). The latter studies also comprise the only published research that has considered the context of risk within the UK.

This thesis aimed to reduce that knowledge deficit, by investigating the impact of small and medium scale wind turbines upon bats in the UK. The research aimed to:

1. Identify the locations of planned wind turbines within Wales and south-west England, including all wind turbine sizes and historical records. Using the collated wind turbine data, identify whether wind turbines have any impact (both individually and cumulatively) upon local bat roost populations

2. Quantify the rate of bat fatalities at small and medium wind turbines and identify whether the wind turbines cause disturbance of bat activity in their immediate proximity. Furthermore investigate whether any

environmental factors moderate bat activity levels at small and medium wind turbine sites

3. Investigate bats’ spatial movements in proximity to small and medium wind turbines and identify bats’ use of habitat structures at the turbine sites

4. Evaluate an outstanding hypothesis proposing that bats’ are attracted to wind turbines’ noise emissions. Furthermore identify whether wind turbine noise has any negative impact upon bat activity levels

At a wider level, the thesis aimed to provide research evidence to support the production of updated small turbine planning guidance in relation to bats. Guidelines in this area are currently severely lacking (Park et al. 2013), hindering the efficiency of both bat conservation and small turbine development.

6.2 Consolidation of research space

6.2.1 Turbine planning

A number of wind turbine planning and installation databases exist within the UK, including the RenewableUK Wind Energy Database (RenewableUK, 2016), the Microgeneration Certification Scheme database (Microgeneration Certification Scheme, 2016) and the DECC Renewable Energy Planning Database (DECC, 2016a) (which superseded the DECC RESTATS database in September 2014). Further government and industry reporting channels also record total numbers of turbine installations in the UK and its regions (DECC, 2016b and 2016c; RenewableUK, 2015b), however the latter do not include planning, location or installation data for individual turbines/sites.

Chapter 2 of this thesis included a comprehensive review of planned wind turbines in Wales and South West (SW) England up to the end of 2013, which in turn produced a database recording each of those turbines.

The database was subsequently compared against 6 of the main existing reference sources that recorded individual sites. In doing so it was illustrated that each of these existing databases severely underestimated the total number of planned wind turbines in the region. This has considerable implications for any bat conservation projects that require information detailing turbine locations and consequently base analyses of impacts on these existing databases. Impacts upon bats (or indeed other wildlife) are as a result likely to be underestimated. This is of particular concern for studies that focus upon small and medium turbines, which generally comprise the largest proportion of underestimation of turbine numbers. The importance of this issue is also exacerbated by the current stage of bats and wind turbines research, which is leading towards understanding of cumulative and population impacts at the level of both local landscapes and national populations (Arnett et al. 2016; O’Shea et al. 2016; Voigt et al. 2015; see this Thesis’ Literature Review). Deficiencies in reference turbine data may therefore introduce inaccuracies into analyses. This principle of data quality and uncertainty and the subsequent impact upon research outcomes is further highlighted in the analysis of bat fatality rates at small and medium turbines in Chapter 3. The analysis showed the importance of considering the quality and nature of input data in deriving accurate outputs, such as the moderating influences of carcass removal, search efficiency and search interval factors upon fatality rate estimates at wind turbines. In the same vein, if poor quality turbine planning data are applied to estimate cumulative fatality impacts across regions, inaccurate results may be produced. This study, in contrast, has provided a comprehensive reference database of turbine planning for Wales and SW England that may be used to investigate wildlife conservation in these areas.

Existing bat research to date has primarily focused upon impacts from large turbines at commercial wind farms (e.g. Arnett et al. 2008; Brinkmann et al. 2006; Rydell et al. 2010a; Georgiakakis et al. 2013; Barros et al. 2015). This study however found that 95% of approved wind turbine sites in the sampled regions featured only a single turbine or a pair of turbines. Based on a sample of planning applications that was further explored to consider turbine size, close to half of all planned turbines were categorised as sub-micro to medium in size (45%), whereas this increased to 87% for sites with only a single turbine or a pair of turbines proposed. As a result, this study has illustrated that knowledge regarding impacts upon bats at a large proportion of wind turbine sites in the UK is severely limited, due to the very small number of studies considering small to medium turbines. This thesis has subsequently provided new research considering bat fatality levels and non-fatal impacts upon bats at small and medium turbine sites in the UK (Chapters 2, 3, 4 and 5), reducing the knowledge gap in this area.

This study has also expanded upon the only turbine planning-focused research already published (Park et al. 2013), in identifying a high overall planning approval rate for turbines. Approval rates were also observed to fall with increasing turbine size, further emphasising that smaller turbines are more likely to proliferate rapidly across the UK and therefore require research focus. However government planning, energy and subsidy policies were also highlighted as important moderating factors on wind turbine installation rates. These factors have led to a current decline in the rate of wind energy expansion in the UK (RenewableUK, 2015a). This highlights an opportunity for UK-focused bat research to 'catch-up' with wind energy developments. Little UK research has previously been available to judge potential impacts, during which time large numbers of turbines have been planned, as observed by this study.

6.2.2 Bat fatalities

Only one scientific study has been published in the UK assessing bat fatality rates at turbines of any size (Minderman et al. 2015). That study suggested rates of bat fatalities at small turbines were very low (0.008–0.169 turbine^{-1} year^{-1}), after recording only three fatality observations from turbine owners, in addition to zero carcasses during fatality searches. However as detailed in Chapter 3 of this thesis, the methods used to reach this conclusion left the results open to criticism and may not have produced a robust estimate of fatality rate.

The present study in Chapter 3 of this thesis incorporated fatality monitoring using a professionally trained search dog at 30 small and medium wind turbine sites. It was concluded that, on the basis of the monitoring programme applied, fatality rates lower than 15.15 turbine^{-1} year^{-1} could not be confirmed without more rigorous monitoring. Without adjusting for the uncertainty in the monitoring method, the rate would have equalled 0.81 turbine^{-1} year^{-1}. Three bat carcasses were observed in total during the fatality searches across all of the monitored sites.

This study has therefore shown that fatality rates at small and medium turbines are likely to be higher than previously reported in the research literature (Minderman et al. 2015). Furthermore it was proposed that a rigorous monitoring protocol would be required during future research to reduce the uncertainty remaining in the fatality rate estimate and to confirm if the rate is in reality, lower.

The fatality rate presented, inclusive of the described uncertainty, was similar to some of the higher rates of fatality observed at turbines in wind farms in northern Europe (Rydell et al 2010a). The result of this comparison may of course vary if future research is able to confirm lower rates of fatality at small-medium turbines. Regardless of the exact rate, it is clear small and medium turbines should be incorporated in wider considerations of cumulative population impacts. This approach was taken during the analysis of turbine impacts upon bat roost populations presented in Chapter 2 of this thesis. The latter study found no relationship between the presence or density of turbines (of all sizes combined) and bat roost population sizes. Additionally, no impact was identified from turbine presence or density on roost population changes over time. These outcomes represented some of the first research results in the field considering local-population-level impacts upon bats using measured bat population data. The analyses of turbine density similarly represented one of the first investigations of cumulative impacts from turbines. A final analysis identified no significant preference for the placement of turbines close to roosts with successful (i.e. large) populations. The latter hypothesised pattern could otherwise have occurred due to e.g. shared requirements for landscape structure or similar likelihoods of placement in rural/urban fringe areas. The use of 5 year time periods to analyse roost population changes allowed for the population impact lag times that have been observed during previous bird research (Strickland et al. 2011).

No previous studies have considered the impact of turbines – individually or cumulatively – upon bat roost populations. These results therefore represent an original contribution to this field. The closest comparative results to this study were the observations of overlaps between wind farm locations and portions of bats' modelled core habitat and probable movement corridors in a region of Italy (Roscioni et al. 2013; Roscioni et al. 2014). The majority of existing analyses of potential population impact comprise simply of the extrapolation of site-level fatality rates to regional/national areas (Kunz et al 2007; Arnett and Baerwald, 2013; Voigt et al. 2015). It has been stated in previous research that no conclusive studies have been completed to confirm whether turbines have an impact upon bats at a population level (Voigt et al. 2015).

Power analyses were used to assess the ability of the regional-scale roost population impact modelling (Chapter 2) to detect fatality rates of the scale identified in Chapter 3 (0.81-15.15 turbine^{-1} year^{-1}). This confirmed that the turbine presence model (Chapter 2, Table 2.3) had a 100% probability (alpha = 0.05) of detecting population losses at the higher fatality rate (15.15) whilst it lacked the power to detect changes at the lower fatality rate (0.81) (probability = 4.9%, alpha = 0.05). Similarly the turbine density model (Chapter 2, Table 2.4) had a relatively high (though lower than 80%) probability of detecting the higher fatality rate (68.6%, alpha = 0.05) and lacked the power to detect losses at the lower fatality rate (33.9%, alpha = 0.05). Given that the results from Chapter 2 indicate a lack of significant impact from turbines at a regional population scale, it is therefore considered likely that the actual fatality rate at small and medium turbine sites may be lower than the maximum estimated (15.15 turbine^{-1} year^{-1}) in Chapter 3. However spatially variable rates of turbine planning were highlighted in Chapter 2, therefore a moderately higher relative cumulative risk to populations may exist in some areas. Moreover, without further rigorous fatality monitoring this hypothesis cannot be confirmed.

The definition of cumulative impact is not currently clear (Strickland et al. 2011) and the separation of impact from turbines upon bat populations from that of other sources of conflict (e.g. roads or agricultural intensification (Berthinussen and Altringham, 2012; Wickramasinghe et al. 2003)) is a complicated matter. For example one bird population decline observed at a wind energy facility was later found to have been a probable artefact of wider reductions in the concerned population, as a result of vegetation burning and heavy cattle stocking rates (Strickland et al. 2011). Recent reviews of bird monitoring offer encouragement concerning wider population impacts from turbines. The rates of bird fatalities observed for many species were considered unlikely to represent a risk of population decline (American Wind Wildlife Institute, 2015; Schuster et al. 2015).

Some bat genera may furthermore pose a larger challenge with regard to defining cumulative impacts from wind turbines upon them. For example whilst Chapter 3 of this thesis showed that a high proportion of non-*Pipistrellus* bat activity in the immediate turbine vicinity at sites was from bats of the *Nyctalus* and *Eptesicus* genera, Chapter 2 illustrated that identification and recording of roosts for these genera is lower on a relative basis. The latter pattern is likely partially due to the difficulty in locating these genera's roosts as they typically are tree-roosting species, utilising smaller and more temporary roosts. Attempts to monitor the roosts of these genera in order to define cumulative population impacts from wind turbines may consequently suffer from lower availability of roost data.

The results from both Chapter 2 and 3 concerning bat fatality levels and the wider research context indicate some potential that renewable energy development and bat conservation could be mutually achieved. This is supported by the observation of stability and significant increases in UK bat populations between 1997 and 2013 (Bat Conservation Trust, 2014; Barlow et al. 2015) – a period during which wind turbine installations have expanded widely, as observed in Chapter 2.

6.2.3 Non-fatal impacts

Few studies have investigated the non-fatal impacts of wind turbines upon bats. Those that have, identified localised disturbance of bat activity during high wind speed conditions (Minderman et al 2012), micro-avoidance of turbine blades (Horn et al. 2008; Bach and Rahmel, 2004), displacement of bat activity from the interior of a wind farm and alteration of spatial activity patterns (Bach and Rahmel, 2004). Examples of a lack of impact have also been recorded, for example a study in Iowa, USA found no significant difference in activity levels between turbines and nearby control sites (Jain et al. 2011). The investigation of bat activity levels in three habitat types (linear hedgerow / woodland, open ground and next to the turbine) in Chapter 3 also identified a disturbance of activity in proximity to turbines during high wind speeds, concurring with previous observations of this effect (Minderman et al. 2012). This analysis furthermore identified higher levels of bat activity near linear habitat features than in open habitat. The latter pattern was explained by SNA-derived observations of bats' heavy reliance upon linear habitat features for navigation across wind turbine sites (Chapter 4). These studies' findings regarding habitat associations contribute new knowledge of bats' spatial use of small and medium wind turbine sites. The proposed associations are also consistent with existing expectations regarding bats' more general use of habitat (Verboom and Huitema, 1997; Russ and Montgomery, 2002; Downs and Racey, 2006). Whilst some disturbance is apparent at a micro-scale in the turbine proximity (Chapter 3 and 4), local roosts do not appear to have suffered any population impact from this localised disturbance (Chapter 2).

The wider spatial networks of bat movements and extended flights across sites as detailed in Chapter 4 did not show frequent avoidance of the turbine vicinity. In fact activity at some sites indicated that turbines may be a feature of interest and a navigational hub for bats. It is interesting to consider these findings in conjunction with the observed avoidance during high wind speeds (Chapter 3; Minderman et al. 2012), reports of micro avoidance of turning blades (Horn et al. 2008), approaches by bats to turbines on their leeward/downwind side (Cryan et al. 2014) and higher levels of investigation of blades by bats during low wind speeds (Cryan et al. 2014). The previously proposed hypothesis and evidence that bats are attracted to trees (Lumsden and Bennet, 2005; Verboom and Spoelstra, 1999) and thereby potentially also to turbines as tree-like features (Cryan and Barclay, 2009) (be that for roosting (Cryan and Barclay, 2009; Cryan et al. 2014) or for foraging purposes (Lumsden and Bennet, 2005; Verboom and Spoelstra, 1999; Cryan et al. 2014)) could be given weight by these combined patterns. Bats may try to investigate or fly near to turbines under the impression that they are trees, before unexpectedly having to avoid moving blades. Bats appear to use trees and linear features for wind shelter during foraging (Verboom and Spoelstra, 1999). Observations of bats' approaches to the leeward/downwind side of turbines, hypothesised to be the result of changing air currents caused by turbines as an obstacle to wind (Cryan et al. 2014), may indicate a similar use. Bats' approaches to slow moving blades (Cryan et al. 2014) may indicate a similarity to tree branches being blown by the wind. Permanent recognition of turbines by bats as unsuitable, moving features does not however appear to occur. If this were the case, a small number of exposures of the bats to moving turbines would result in near-complete avoidance of the turbine.

However none of these patterns rule out the hypothesis that insect prey in the vicinity of turbines may explain the presence of bats at turbines (Cryan and Barclay, 2009; Rydell et al. 2010b). Recent evidence has shown that insects are present at turbines, even on turbine surfaces (Rydell et al. 2016). It was suggested that foraging is the main bat behaviour displayed at small and medium wind turbine sites in Chapter 4, supporting the hypothesis of attraction due to insect prey. The latter evidence contributes the first definition of bat behaviour types at small turbine sites.

Chapter 5 of this thesis provides the first structured research evidence that small turbine noise does not disturb or attract UK bat species. This aligns with previous anecdotal evidence recorded by Ahlen (2003) and addresses for the first time the turbine noise attraction hypothesis (Ahlen, 2003; Cryan and Barclay, 2009), suggesting a lack of support for this hypothesis. This result further indicates that technological aspects of turbines are not linked to levels of risk to bats, following previous research finding no effect of turbine lighting on bat fatality totals (Arnett et al. 2008; Bennet and Hale, 2014).

Nightly bat movement networks at turbine sites were typically found to be weakly connected and vulnerable to disruption (Chapter 4), such as that represented by the avoidance of a turbine during high wind speeds (Chapter 3). Noise from a nearby turbine would however be unlikely to cause such disruption (Chapter 5). The vulnerability of movement networks has important implications for turbine placement and for associated habitat management within a site. The latter is particularly a concern if construction works involve modifying linear habitat features, due to their importance for bat movement (Chapter 4). Movement bottlenecks were also identified using SNA methods in Chapter 4;

the impact of habitat changes will be further exacerbated at these locations. Conversely, the suggestion of likely disruption of bat activity as a result of removing habitat features does offer some potential for mitigation of fatalities. Habitat management may theoretically be able to restrict bat movement towards turbines and encourage movement away (using management methods such as those proposed by Millon et al. (2015) and Peste et al. (2015)). These findings contribute some of the first detailed investigations into bat movement and habitat associations within turbine sites.

Considering all of the above findings as a whole, in addition to previous disturbance evidence (Minderman et al. 2012; Bach and Rahmel, 2004), suggests that small and medium turbines have a small non-fatal disturbance and displacement impact upon bats during high wind speeds, but that this is limited to the immediate turbine vicinity. The presence of turbines may also alter bats’ movement behaviours, encouraging investigation of and foraging around turbines, potentially in preference to open habitats.

6.2.4 Environmental factors and turbine noise

Existing research has shown strong associations between weather conditions and bat activity levels at wind energy sites. These include positive associations with warmer temperatures (Arnett et al. 2011; Amorim et al. 2012; Georgiakakis et al 2013; Baerwald and Barclay, 2011; Weller and Baldwin, 2012; Gorresen et al. 2015), lower wind speeds (Arnett et al. 2008; Brinkmann et al. 2006; Kerns et al. 2005; Rydell et al. 2010a; Amorim et al. 2012) and higher levels of prey availability (Horn et al. 2008). This thesis supports these temperature and wind speed conclusions, observing the same direction of effects during multiple analyses in Chapters 3 and 5. Furthermore rainfall occurrence was found to have a negative impact upon activity levels. The results show that bats react to the same conditions at small and medium turbines as they do at large turbines (at which the majority of the above weather associations were recorded). These findings represent some of the first considerations of the effect of weather upon bats at small and medium turbines, following the only other study to include such analyses (Minderman et al. 2012).

Conclusions regarding the moderating effects of habitat type on bat activity levels are more variable across existing studies. Higher risk habitats have been proposed to include wooded hilltops and locations within 100m of woodland (in Europe) as well as forested ridges and heads of ravines (in North America). Other studies have found no clear effects of habitat upon bat activity or fatality (Dubourg-Savage et al. 2011; Johnson et al. 2004).

Higher activity levels were found to be associated with proximity to linear hedgerow and woodland edge / treeline habitat features at small and medium turbine sites (Chapter 3) (furthermore validating the choice of this habitat type for the turbine-noise investigation carried out in Chapter 5). The proportion of built environment landcover in the surrounding environment (in this case within a 5km radii) was also found to feature a negative association with bat activity (Chapter 3). These findings again represent some of the first considerations of the effect of habitat upon bats at small and medium turbines, following the only other study to include such analyses (Minderman et al. 2012). Considered together, these habitat associations suggest turbine development in open habitat closer to urban environments may reduce overall risk to bats. The use of GIS in this context, to derive habitat variables and assess related bat activity, highlights the value of this technology in assisting bat conservation research and activities. The ability of GIS to spatially relate environmental issues is also exemplified in Chapter 2, analysing the interaction of turbines across wide areas with roost populations. Recent advances have been made in the use of species data (e.g. from local biological records centres) at variable spatial resolutions to derive multi-scale habitat use models for bats (Bellamy et al. 2013; Ducci et al. 2015; Bellamy and Altringham, 2015). This opens a wide range of possibilities for future research to consider landscape and local-scale bat movements in relation to wind turbines, to improve our understanding of bat interactions with wind energy infrastructure.

No turbine-related variables were found to have any significant association with bat activity during the development of models, including height to blade tip, number of blades, turbine noise or number of years since turbine planning approval (a measure of relative approximate length of installation time) (Chapters 3 and 5).

6.2.5 Implications for ongoing research

This thesis has presented results largely showing low levels of impacts from small to medium scale turbines upon bats, though with uncertainty still present in the levels of risk estimated. The principle of proportionality of effort suggests this thesis' indications of low impact support use of research effort for other, larger sources of bat mortality, with justification for further research only in focused aspects (e.g. fatality monitoring to narrow fatality rate estimates) at small to medium scale turbines.

The current range of fatality rate possibilities calculated in Chapter 3 and the legally-protected status of bats leave small-medium turbine planning open to strict regulation, regardless of the small number of carcasses found in reality. Planning guidance and policy for bats at small to medium turbines is also still urgently required for the efficiency of both bat conservation and turbine planning (Park et al. 2013), whilst very few studies or evidence sources are available regarding this topic. The level of emphasis placed upon detailed aspects of fatality rates within the wind farms research and policy environment suggests the same will be relied upon for small to medium turbines. As a result, focused monitoring research purely concerning the tighter definition of fatality rates is supported.

Knowledge of national and local bat population sizes also remains limited and therefore no clear definitions exist of the situations in which bat fatalities of given levels are unacceptable. Without such knowledge, the precautionary principle may be adopted by conservation bodies and regulators, particularly due to cumulative impact estimates from the thousands of turbines installed across the UK (which are further exacerbated by high fatality rate estimates when large uncertainty levels are accounted for, as discussed above). This supports focused research into bat population sizes, for the benefit and efficiency of all bat conservation efforts and topics (including large wind farms, roads and agricultural intensification).

The volume of future research regarding non-fatal impacts of turbines (of all sizes) upon bats may depend on the priorities of the wider bat conservation research and strategy environment. Further understanding is first required regarding the biological importance of non-fatal impacts upon bats from any source.

This thesis does not appear to justify a further large scale research programme into bats and small-medium turbines. Instead it may justify carrying out a small number of studies in a more intense manner within the topics shown to have potential for impacts upon bats. Those areas recommended for further monitoring efforts are: (1) bat fatality monitoring using a short survey interval over a long time period (e.g. months) at a small sample of sites, to determine accurate actual fatality rates; (2) consideration of species-specific risk using monitoring at sites with diverse bat species, perhaps within the same monitoring setup as ‘1’ above; (3) improved estimations of bat population sizes so that cumulative fatality estimates at turbines can be placed in context and assessed for their risk level as appropriate. If a low-cost acoustic bat deterrent can be commercially produced for small-medium turbines, research to test and confirm its effectiveness for mitigation may be justified. A targeted list of possible future research questions is provided in section 6.4.

6.3 Practical implications and recommendations

6.3.1 Mitigation

The current national statutory guidance in England (Natural England, 2014) suggests a minimum separation distance of 50m between turbines and habitat features of value to bats. For small to medium turbines, within the context of small agricultural holdings and domestic settings, it is often impossible or impractical to achieve this separation distance due to the size of the land parcel. Turbines installed at larger farms, however, may be more able to meet this criterion.

The recommendation of Minderman et al. (2012) that guidance includes the use of a separation distance of 20m between small and medium turbines and linear habitat features or other important bat habitats is supported. The analysis within Chapter 3 of this thesis, finding that non-fatal disturbance impacts upon bats during high wind speeds dissipate within a short distance from the turbine, corroborates the evidence recorded by Minderman et al. (2012).

It is recommended more generally that mitigation strategy guidance focuses on siting of turbines as a first priority. In addition to achieving a reduction in disturbance of bat activity (Chapter 3) appropriate siting of turbines may avoid disruption to vulnerable movement networks (Chapter 4). Additionally, where the introduction of a turbine is thought to represent a high risk to bats at a site, SNA methods may help determine appropriate mitigating actions. The application of SNA would both enable identification of bat movement networks and highlight those locations most vulnerable to disruption. Further research is required to evaluate the effectiveness of habitat management as a mitigation strategy (Millon et al. 2015; Peste et al. 2015), however this thesis has provided indications that habitat modifications could offer value for this purpose (Chapter 4).

Use of increased turbine cut-in speeds is recommended only as a last resort for small turbines. Low wind speeds will comprise a higher proportion of available wind resource at the lower heights of small turbines, relative to large turbines (Mathew, 2006). The proportional reduction in generation of renewable energy would therefore be higher at small turbines, having a negative impact upon wider efforts to mitigate climate change. However it is important that protected species are given appropriate shelter and sites considered to pose a high-risk to bats may present a reasonable case to use increased cut-in speeds. Similarly the use of advanced curtailment algorithms incorporating weather variables is unlikely to be possible at small turbines due to a lack of relevant control technologies at this scale (personal communication with a small turbine manufacturing company).

It should be noted that the use of set turbine cut-in speeds should not assume equal impact upon the generation of identical turbine models that are installed at different sites. The wind speed distribution will differ at each site and therefore wind speeds below the cut-in speed will comprise differing proportions of potential energy generation at different sites. The same principle also applies at a national level. Wind speeds are generally higher, for example, in Scotland than in England and therefore the energy generation impact of identically increased cut-in speeds will tend to be greater in England. Turbine shut-down mitigation where timings are defined in relation to sunrise and sunset will similarly have a disproportionate effect upon energy generation between sites located at different latitudes, due to differing night lengths. Finally a cubic relationship exists between wind speed and power, hence small increases in cut-in speeds will have increasingly large impacts upon power generation. For example, a doubling of wind speed increases the available power from the wind by 8 times, up to a set wind speed for each turbine model before energy generation will plateau due to mechanical limitations (Mathew, 2006).

Wider questions also exist regarding approaches to active mitigation (e.g. use of cut-in speeds), including whether mitigation should be applied from the point of turbine installation, or whether monitoring results should be used to trigger the application of mitigation.

6.3.2 Fatality monitoring

It is emphasised that monitoring of bat fatalities in the UK (e.g. in research programmes) should be carried out using professionally trained search dogs and should account for length of carcass persistence and searcher efficiency, in order to produce reliable estimates of total possible fatalities (Chapter 3). Assessing and monitoring fatality risk at small turbines is a challenging subject, as the development of a small turbine at a private property or small farm holding is unlikely to include the financial scope for professional fatality monitoring. However statutory authorities still have a responsibility to prevent and regulate fatalities of protected species, including bats. The scope of this study does not include defining methods for regulation of fatalities and this subject is the responsibility of statutory authorities.

Whilst the use of search dogs is recommended for fatality monitoring, this method carries inherent logistical and practical demands. Financial costs may be high, incorporating welfare, health and everyday care expenses for the dog. In addition professional training is required for both the dog and the human handler and the costs of the handler’s time and expenses must be considered. If the dog search handling is carried out on an internal basis by a research institute or developer, rather than via a professional service provider, this places a significant personal demand upon researchers or staff to house and care for the dog on a full-time, long-term basis.

Furthermore access to bat carcasses for carcass removal and search efficiency trials may be a limiting factor. Wildlife rehabilitators may be able to supply a limited numbers of carcasses; however the use of small mammal carcasses (e.g. mice) may need to be considered as an appropriate alternative.

6.3.3 Acoustic monitoring methods

Acoustic bat monitoring rapidly generates a very large volume of sound recording data, particularly when using multiple detectors. Subsequent sound analysis and bat identification processes place a large time demand upon the monitoring organisation and will require many hours of staff/researcher time. Associated with this issue is a requirement for significant levels of data storage. These challenges may lessen over time with improvements in automated species identification technology and reductions in the cost and availability of large-format storage devices.

Powering of equipment in the field can be logistically challenging. High-capacity batteries that are able to provide power over a scale of weeks tend to feature a trade-off between cost and both performance and weight. Cheaper batteries such as the lead-acid format often feature poorer performance and length of powering-time. Furthermore the weight of these batteries can make transport and installation very difficult. The cost of higher-performance batteries such as the lithium-ion format can be prohibitive, though the improvement in length of powering-time, their lighter weight and generally higher reliability may justify this cost. Batteries also suffer performance issues during cold weather periods. Solar-panel battery charging systems may be installed for extended monitoring lengths, though again at increased cost.

6.3.4 Wind monitoring

Researchers should take into account the moderating effect of measurement height on wind speed analyses. Wind speeds generally increase with height as a result of the wind shear principle (Mathew, 2006). Consequently, when reporting the influence of wind speed on bat (or other wildlife) activity, it is useful to also report the wind measurement height. In this way, reported relationships of bat activity with wind speeds e.g. at ground height, are clearly understood to be related to ground and not hub height wind conditions.

6.3.5 Access to turbine sites

Research at wind turbine sites relies upon the granting of access permission by turbine and land owners. This can present a challenge to researchers, particularly those investigating impacts upon protected wildlife species. Turbine owners can be reluctant to accept a perceived risk of exposure regarding their turbine's impact upon wildlife. The use of guarantees regarding anonymity of published data and protection from Freedom of Information (FoI) requests may mitigate such fears. It is recommended that research in this area allows an extended period of time to agree access to sites.

Access to monitor at turbine hub heights may be particularly problematic, largely due to practical access and space limitations at small and medium turbines and more widely health and safety and technical concerns at all sizes of turbine. Not all small or medium turbine models will feature space to safely install bat detectors within / on a nacelle, whilst the nacelle of some small turbines can only be accessed by the winching of the whole turbine structure down to the ground by professional maintenance staff. This is unlikely to be feasible for many small turbine owners.

Access to the nacelle of taller turbines that can be climbed using internal/external ladders is likely to be restricted to turbine engineers, on health and safety grounds. Turbine owners may also have technical concerns regarding the installation of detector and battery equipment alongside the nacelle's internal machinery. Furthermore some turbine models will require the drilling of a small hole in the turbine's nacelle, through which the detector's microphone may be deployed. This may understandably cause concern from turbine operators and restrict installation. If installation is achieved, it is possible that access to maintain detectors and batteries will rely upon the turbine operators' timetabling and as such loss of monitoring time may occur. Detector setups that have powering options providing long-term/permanent power and storage options for long-term data storage or remote data access are therefore preferable.

Identifying the presence and locations of small and medium wind turbine sites can be difficult, as observed in Chapter 2 of this thesis. The publication of a version of the Microgeneration Certification Scheme database that includes location data, but removes personal information and energy generation data, would eliminate this barrier whilst protecting the personal information of turbine owners.

6.3.6 Strategic conservation efforts

Statutory authorities at all geographic and political levels have a responsibility for the conservation of bats and other wildlife. Furthermore wildlife movements do not respect administrative or political boundaries between planning authorities or countries. As a result, joined-up conservation strategies and monitoring guidelines are required across these areas and levels of government (Van der Meij et al. 2015; Rodrigues et al. 2015). A unified classification of turbine sizes would also aid application of appropriate planning guidance and research to individual sites, as no consistent definition is currently available (Rodrigues et al. 2015). Such a classification scheme would need to be flexible with regard to future turbine developments as their proposed sizes increase.

The impact of the recent 2016 UK referendum vote to leave the EU, upon the link between European-level (Rodrigues et al. 2015) and UK-level guidelines (Natural England, 2014), is not yet known.

As uneven spatial distributions of wind turbines have been observed within regions of the UK (Chapter 2), conservation efforts and local-population-level impact assessments could be focused within areas of high turbine density.

Further clarification may also be required regarding the legal standing of individual turbine owners and wind farm developers in the context of recorded bat fatalities and the legal protection of bats as a protected species.

6.3.7 Vertical axis turbines

Vertical axis turbines were not included in the scope of this research project and no dedicated studies of the impact of this turbine-format upon bats have been completed to date, as far as the author is aware. Whilst numbers of vertical axis turbines in the UK appear to be far lower than those of the horizontal-axis format, future studies may wish to investigate whether they present any risk to bats.

6.3.8 Medium scale wind turbines and small numbers of turbines

Medium scale wind turbines are typically planned in similar environments to small turbines and are a format frequently used for farm-scale energy generation, with most sites usually comprising a single turbine. This size of turbine presents a challenge for defining the required level of acoustic monitoring during bat impact assessments. The nacelle heights of medium scale turbines often reach approximately 20-35m. Bat activity at this height is therefore close to the upper limit of detection distance by most bat detectors and out of the detection range of other models. Consequently, monitoring equipment may need to be installed in or next to the nacelle (depending on the format of the turbine model – some feature access platforms adjacent to the nacelle). Not all turbine models will however feature space to safely install bat detectors within / on a nacelle.

The majority of research regarding bats or other wildlife may be most likely to focus upon either large or small-scale turbines, leaving some areas of knowledge deficit at medium turbines. Planning guidelines designed for large turbines, or indeed small turbines, may as a result be wrongly applied to medium turbines. Further research to confirm any differences in bat activity levels at the hub height of medium turbines, relative to monitoring at ground level and at large turbines’ hub heights, may reduce uncertainty in this area.

Similar issues may exist around sites with small numbers of installed/proposed turbines e.g. 2-4. The majority of existing research focuses upon either large wind farms or single turbines.

6.3.9 Small and medium wind turbines

A large deficit remains in research effort regarding small and medium wind turbines, as discussed throughout this thesis and as highlighted by previous research (Minderman et al. 2012; Park et al. 2013; Minderman et al. 2015; Rodrigues et al. 2015). These sizes of wind turbine represent a large proportion of the planned turbines in the UK (Chapter 2). Consequently this issue requires attention if we are to appropriately address concerns regarding bat conservation at wind energy sites. Whilst initial investigations have begun to clarify fatality rates (Minderman et al. 2015; Chapter 3; Chapter 2), bat activity levels (Minderman et al. 2012; Chapter 3) and disturbance (Minderman et al. 2012; Chapters 3, 4 and 5), wider monitoring is required to further strengthen our understanding. Furthermore little information is available regarding bats behavioural patterns at small and medium wind turbines, the reason(s) for their presence at these turbines, cumulative impacts at a population level or the potential for mitigation of impacts.

6.4 Future research questions

This thesis has discussed a number of existing and newly-highlighted research gaps concerning the assessment of impacts upon bats at wind energy sites. Topics with particularly limited volumes of research include the population-level impact of wind turbines upon bats (Arnett et al. 2013), non-fatal impacts upon bats and assessment of impacts from small and medium turbines (Rodrigues et al. 2015). Bats' interaction with turbines during wider movement around sites/landscapes and the assessment and testing of habitat management methods for mitigation of impacts upon bats are also areas requiring further investigation (Peste et al. 2015).

A range of research questions and directions for future investigation are provided below, in order to address some of these deficiencies in knowledge, to improve our understanding of this topic and to increase our ability to reduce the impact of wind turbines upon bats. The questions are categorised into 'Urgent priorities', 'Medium term priorities', 'Long term research needs' and

‘Supplementary areas of interest’, in order to provide a prioritised strategy for future research.

Urgent priorities

1. Reduce the level of uncertainty in current estimates of fatality rates at small to medium turbines, by applying a rigorous monitoring protocol using trained search dogs at a sample of small and medium turbine sites. Carcass removal and search efficiency trials must be applied.

2. Carry out long-term monitoring at a small number of high-risk small and medium wind turbine sites, in areas supporting a diverse range of bat species, in order to quantify the species composition of fatalities at small and medium turbines.

3. Improve and update estimates of the size of the UK bat population, or regional / local population sizes, in order to increase the feasibility of estimating population-level impacts from wind turbines.

4. Further define the habitat associations of bats at wind turbine sites to enable improved prediction of fatality risk at a pre-construction stage.

5. To identify variation in fatality rates between habitat/landscape types at small to medium turbines, in the UK.

Medium term priorities

6. Provide clearer definitions of cumulative impact, addressing choice of geographical and temporal scales, assessments at a total population or species population level and threshold levels of concern.

7. Investigate spatial patterns of bat activity where roosts are found to be in very close proximity (e.g. less than 500m) to wind turbines. The restriction of development in proximity to roosts during planning stages may however reduce numbers of available turbines for monitoring.

8. Further explore and clarify the behavioural cause(s) of bat’s presence at wind turbines.

9. Investigate bat movements across wider landscapes incorporating multiple wind turbines, to investigate any cumulative impacts upon bats

or use of turbines by bats within wider movements. If GPS technology is not restricted by size and weight, consider using GPS tagging to monitor bat movements.

10. Investigate the use of modelling approaches to estimate population impacts upon bats, with associated field validation.

Long term research needs

11. Identify any geographic variation in fatality rates by region within the UK, to allow improved estimation of population level impacts from small and medium wind turbines.

12. Further explore non-fatal impacts upon bats at wind energy sites. This may include consideration of barrier effects, time-lagged disturbance effects or alteration of flight patterns within the wider landscape.

13. Explore and experimentally test in the field the use of habitat management (e.g. hedgerow repositioning) for mitigation of impacts upon bats and small and medium wind turbine sites. Social Network Analysis methods may aid the interpretation of resulting activity patterns

14. Investigate the effect of increasing numbers of turbines within wind energy sites i.e. comparing single turbine sites to double turbine sites or small wind clusters. Additionally consider the impact of spatial layout configurations for multiple turbines.

15. Assess the differences in bat activity from monitoring at both ground level and the hub height of medium scale wind turbines. Furthermore confirm whether bat activity at medium turbines’ hub heights can be predicted from ground-level monitoring.

Supplementary areas of interest

16. Expand the testing of acoustic deterrents to small and medium wind turbine sites and test the efficiency of such devices in these environments, relative to large turbines.

17. Automating the identification of bat movements within thermal infrared imaging (TIR) and producing software to enable repeatability of such analyses.

18. Investigate methods to quantify and automatically record volumes of insects present at wind turbine sites, in order to better understand associations with bat presence.

19. Investigate any variation in the effect of turbine noise across differing habitat types e.g. in open habitat away from linear habitat features

20. Identify whether vertical axis wind turbines pose any fatality or disturbance risk to bats

6.5 Final remarks

Climate change poses one of the greatest global risks to the environment that humanity has ever experienced. The impacts of climate change are of equal concern for this planet’s biodiversity and compound the existing pressures of anthropogenic development, habitat loss and pollution. We are faced with a significant challenge to reduce global emissions of greenhouse gases, in order to avoid increased levels of global warming. To do so we must explore and develop clean, renewable sources of energy generation, including from the wind, sun and sea. However no single source of energy generation offers a perfect solution.

This thesis has explored a well-publicised negative aspect of wind energy generation: the fatality and disturbance of bats resulting from the operation of wind turbines. Research around the world has now confirmed fatalities and other negative impacts upon bats caused by wind turbines. Consequently there is no longer any doubt that this is a global conservation concern. Whilst fatality reporting has increased rapidly across numerous continents in the last decade, we still have much to learn about this issue. Knowledge is still limited concerning the non-fatal impacts of wind turbines upon bats, their risk to bat populations and methods to mitigate any such impacts. In particular we are yet to fully understand the level of risk posed by small and medium scale wind turbines.

This thesis has explored the interaction between bats and small to medium size wind turbines. In doing so it has contributed new knowledge to this area of research and may equally provide a catalyst for further research investigation. Impacts upon bats were identified during this study and yet these are by no means an unassailable barrier to both bat conservation and renewable wind energy generation. Nonetheless it is important to retain a wide perspective of cumulative impacts from small to medium wind turbines, alongside large scale wind farms and other key sources of risk to bats. Parties from both sides of this debate should work together to minimise impacts upon these equally important aspects of global concern. This planet’s wildlife and climate are intrinsically linked and neither should be considered in isolation or taken for granted.

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Appendices

Table A.1: Reported bat fatalities in Europe (2003-2014) – State 17/09/2014. Annex 2 Eurobats 2015 (Guidelines for consideration of bats in wind farm projects – Revision 2014)

Species	**AT**	**BE**	**CH**	**CR**	**CZ**	**DE**	**ES**	**EE**	**FI**	**FR**	**GR**	**IT**	**LV**	**NL**	**NO**	**PT**	**PL**	**RO**	**SE**	**UK**	**Total**
Nyctalus noctula	24				3	716	1			12	10					1	5	5	1		**778**
Nyctalus lasiopterus							21			6	1					8					**36**
Nyctalus leisleri			1		1	108	15			39	58	2				206					**430**
Nyctalus spec.							2									16					**18**
Eptesicus serotinus					7	43	2			14	1			1		0	3				**71**
Eptesicus isabellinus							117									1					**118**
Eptesicus serotinus / isabellinus							11									16					**27**
Eptesicus nilssonii						3		2	6				13		1		1		8		**34**

Species	AT	BE	CH	CR	CZ	DE	ES	EE	FI	FR	GR	IT	LV	NL	NO	PT	PL	RO	SE	UK	Total
Vespertilio murinus				7	2	89				6	1		1				3	7	1		**117**
Myotis myotis						2	2			2											**6**
Myotis blythii							4														**4**
Myotis dasycneme						3															**3**
Myotis daubentonii						5										2					**7**
Myotis bechsteinii										1											**1**
Myotis emarginatus							1			1											**2**
Myotis brandtii						1															**1**
Myotis mystacinus						2					2										**4**
Myotis spec.						1	3														**4**
Pipistrellus pipistrellus		10		2	3	431	73			277		1		14		243	1	3	1		**1059**

Species	**AT**	**BE**	**CH**	**CR**	**CZ**	**DE**	**ES**	**EE**	**FI**	**FR**	**GR**	**IT**	**LV**	**NL**	**NO**	**PT**	**PL**	**RO**	**SE**	**UK**	**Total**
Pipistrellus nathusii	2	3		3	2	565				87	34	2	23	7			12	12	5		**757**
Pipistrellus pygmaeus						46				121			1			31	1	2	1	1	**204**
Pipistrellus pipistrellus / pygmaeus			1				483			44	54					35	1	2			**620**
Pipistrellus kuhlii				62			44			81						37		4			**228**
Pipistrellus pipistrellus / kuhlii																19					**19**
Pipistrellus spec.				37	2	36	20			85	2		2			85		4		3	**276**
Hypsugo savii				53		1	44			30	28	10				43					**209**
Barbastella barbastellus						1	1			2											**4**
Plecotus austriacus	1					6															**7**
Plecotus auritus						5															**5**
Tadarida teniotis				2			23			1						22					**48**

Species	**AT**	**BE**	**CH**	**CR**	**CZ**	**DE**	**ES**	**EE**	**FI**	**FR**	**GR**	**IT**	**LV**	**NL**	**NO**	**PT**	**PL**	**RO**	**SE**	**UK**	**Total**
Miniopterus schreibersii							2			4						3					**9**
Rhinolophus ferrumequinum							1														**1**
Rhinolophus mehelyi							1														**1**
Chiroptera spec		1		14		46	320	1		175	8	1				102	2		30	7	**707**
Total	**27**	**14**	**2**	**180**	**20**	**2110**	**1191**	**3**	**6**	**988**	**199**	**16**	**40**	**22**	**1**	**870**	**29**	**39**	**47**	**11**	**5815**

AT = Austria, BE = Belgium, CH = Switzerland, CR = Croatia, CZ = Czech Rep, DE = Germany, ES = Spain, EE = Estonia, FI = Finland, FR = France, GR = Greece, IT = Italy, LV = Latvia, NL = Netherlands, NO = Norway, PT = Portugal, PL = Poland, RO = Romania, SE = Sweden, UK = United Kingdom

Table A.2: Maximum foraging distances of species and height of flight. Annex 3 Rodrigues et al. (2015)((Guidelines for consideration of bats in wind farm projects – Revision 2014)) *note 'references' column removed from re-production, refer to Rodrigues et al. (2015) Annex 3 for further information*

Species	**Max foraging distance (km)**	**Height of flight (m)**	**Radio-tracking studies**
Nyctalus noctula	26	10 to a few hundred	Yes, no
Nyctalus leisleri	17	above canopy, >25, >40-50 (foraging & direct flight)	Yes, no
Nyctalus lasiopterus	90	1300 (telescope & radar)	Yes
Pipistrellus nathusii	12	1-20 (foraging); 30-50 (migration), >25, foraging above canopy & >40-50 in direct flight	Yes, no
Pipistrellus pygmaeus	1,7 (mean radius)	up to the rotor, occasionally >25, >40-50 in direct flight	Yes, no
Pipistrellus pipistrellus	5,1	up to the rotor, >25, >40-50 in direct flight	No; chemiluminescent tags, no
Pipistrellus kuhlii	no information	1-10; up to a few hundred, >25	Yes, no
Hypsugo savii	?	>100	No, no
Eptesicus serotinus	5-7, 12	50 (up to the rotor), >25, forages above canopy, >40-50 in direct flight	Yes, no
Eptesicus isabellinus	?	?	?
Eptesicus nilssonii	4-5 (breeding period); >30 afterwards	>50 (foraging & direct flight)	Yes
Vespertilio murinus	6,2 (female) 20,5 (male)	20-40, above canopy (foraging) & >40-50 (direct flight)	Yes, no

Species	**Max foraging distance (km)**	**Height of flight (m)**	**Radio-tracking studies**
Myotis myotis	25	1-15 (direct flight in open sky in transit); >25; up to 40 (50) in direct flight	Yes, no
Myotis blythii	26	1-15	Yes
Myotis punicus	mean 6, up to 16,5	<2 (foraging). Probably 100 commuting from ridge to ridge	Yes
Myotis emarginatus	12,5; 3	no information ?	Yes
Myotis bechsteinii	2,5	1-5 and in the canopy, sometimes above canopy (direct flight)	Yes, no
Myotis dasycneme	34; 15 from nursery, >25 (spring and autumn)	2-5 (up to the rotor)	Yes
Myotis daubentonii	10 (female) >15 (male)	1-5, forages up to the canopy & sometimes above in direct flight	Yes, no
Myotis brandtii	10	Up to the canopy (foraging) & sometimes above in direct flight	?, no
Myotis mystacinus	2,8	Up to 15 in the canopy, up to canopy (foraging) & sometimes above in direct flight	Yes, no
Plecotus auritus	2,2-3,3	Up to the canopy and above (foraging and direct flight)	Yes, no
Plecotus austriacus	regularly up to 7, usually 1,5	Exceptionally >25, up to the canopy and above (foraging and direct flight)	Yes, no
Barbastella barbastellus	25	Above canopy, >25, canopy and above (foraging and direct flight)	Yes, no
Miniopterus schreibersii	30 to 40	2-5 (foraging) and open sky (transit), >25	Yes, no

Species	**Max foraging distance (km)**	**Height of flight (m)**	**Radio-tracking studies**
Tadarida teniotis	>30 (Portugal), 100 (Switzerland)	10-300	Yes

Table A.3: Research findings compiled by Strickland et al. 2011 concerning the disturbance of birds by wind energy installations, with overarching categories of disturbance. All text from the first 2 columns quoted from or based upon Strickland et al. 2011 unless otherwise referenced; the final column 'Potentially transferable outcomes for bat research at turbines' provides interpreted principles for disturbance impacts upon bats

Original research reference	Key findings and outcomes	Potentially transferable outcomes for bat research at turbines
Category of disturbance: Displacement by turbines		
Leddy et al. 1999	Fields with turbines installed were found to have lower breeding bird densities than those without in an area of Minnesota (USA), with partial displacement measured to occur in areas within 80m of turbines	Suggests that the impact of displacement may vary depending on the sensitivity of taxa to habitat alterations. If bats are able to withstand small shifts in foraging routes, impacts may not be particularly harmful. Impacts may vary between bat species. Displacement can be measured by monitoring species presence both in proximity to turbines and in adjacent, turbine-free areas.
Johnson et al. 2000a; Erickson et al. 2004	Estimated displacement distances of grassland birds of 100m from turbines, however found no general density reduction in the overall wind farm area. Erickson et al.'s research indicated that grassland bird impacts were lower at another monitored wind energy installation, with the primary displacement observed occurring as a result of habitat removal during turbine infrastructure construction. Displacement impacts were also found to vary between bird species	
Shaffer and Johnson, 2008; Winkelman, 1990; Pedersen and Poulsen, 1991; Spaans et al. 1998; Fernley et al. 2006	Displacement of songbirds, waterfowl and shorebirds. Studies took place in Europe	
Devereux et al. 2008	Whilst studying wintering farmland birds in England, the common (ring-necked) pheasant was found to be displaced by turbines. The remaining species studied however did not show displacement by the wind turbines. Eurasian skylarks and corvids even increased their occurrence near turbines, interpreted as a possible response to raised food resources in the disturbed construction areas	Bat species adapted to disturbed, open and cutblock areas may increase their activity near turbines rather than being displaced.

Original research reference	Key findings and outcomes	Potentially transferable outcomes for bat research at turbines
Johnson et al. 2010; Beck et al. 2011	The only study to have examined response of greater sage-grouse to wind energy development was conducted at a wind energy facility in Carbon County, Wyoming (Johnson et al. 2010, Beck et al. 2011). Results of the telemetry study indicate that female sage-grouse used areas near wind turbines as late as two years after construction. Notwithstanding, Johnson et al. (2010) and Beck et al. (2011) indicated that data from this study are preliminary and are not meant to form the basis for any conclusions regarding impacts of wind energy development on sage-grouse.	Increased activity may be best investigated before and after construction of new turbines.
Naugle et al. 2009	Although the data collected on response of prairie grouse to wind-energy development indicate that prairie grouse may continue to use habitats near wind energy facilities, Naugle et al. (2009) found population declines in greater sage-grouse populations attributed to oil and gas production occurred four years post-construction	Long-term monitoring research schedules (e.g. up to 5 or 10 years) may be required for key research on disruptive effects upon bats, particularly for investigations considering population-level effects
Desholm and Kahlert, 2005	Identified a large decrease (by a factor of 4.5) in use of an offshore wind farm area by common eider (*Somateria mollissima*) and geese between pre-construction and early operation. The birds actively flew around the wind farm to avoid it and the few that flew through it avoided individual turbines (Desholm and Kahlert, 2005)	Monitoring around the edges of wind farms may be required to understand if bats are avoiding them. Also consideration of pre- and post-construction activity and individual turbine avoidance is important
Plonczkier and Simms, 2012	Showed avoidance of two offshore wind farms by comparing pre- construction flight paths of pink-footed geese (*Anser brachyrhynchus*). Avoidance was very consistent, estimated as occurring for 94% of flights. The tendency to avoid the wind farms was observed to increase slightly over time (Plonczkier and Simms, 2012)	Monitoring around the edges of wind farms may be required to understand if bats are avoiding them. Also consideration of pre- and post-construction activity is important. Bats may show adjustment of their activity to turbines/wind farms over time
Villegas-Patraca et al. 2014	Identified avoidance of an operational onshore wind farm by soaring migratory birds (Turkey Vultures (*Cathartes aura*) and Swainson's Hawks (*Buteo swainsoni*)). A nearby ridgeline was thought to influence the birds flight lines in avoiding the wind farm (Villegas-Patraca et al. 2014)	Monitoring around the edges of wind farms may be required to understand if bats are avoiding them. Local topography should be considered in estimating levels of risk regarding bats' flight paths towards turbines

Original research reference	Key findings and outcomes	Potentially transferable outcomes for bat research at turbines
Everaert, 2014	Found gulls displayed micro-avoidance of turbines to avoid their rotor swept area when flying through a wind farm, during up to 96% of flights (Everaert, 2014)	Bats may be able to commonly avoid turbines when flying through wind farms
Category of disturbance: Displacement by non-turbine wind energy infrastructure		
Braun et al. 2002; Holloran, 2005; Pitman et al. 2005; Pruett et al. 2009; Robel et al. 2004	Several studies have demonstrated that prairie grouse strongly avoid certain anthropogenic features such as roads, buildings, powerlines, and oil and gas wells, resulting in sizable areas of habitat rendered less suitable (Braun et al. 2002, Holloran, 2005, Pitman et al. 2005, Pruett et al. 2009, Robel et al. 2004). Much of the infrastructure associated with wind energy facilities, such as power lines and roads, are common to most forms of energy development and it is reasonable to assume that impacts would be similar. Nevertheless, there are substantial differences between wind energy facilities and most other forms of energy development, particularly related to human activity. While results of studies of other anthropogenic features suggest the potential exists for wind turbines to displace prairie grouse from occupied habitat, well-designed studies examining impacts of wind turbines themselves on prairie grouse are currently lacking.	Bat research should consider associated infrastructure features (e.g. access tracks, substation buildings) as well as turbines
McNew et al. 2009; Johnson et al. 2009a	Ongoing telemetry research being conducted by Kansas State University to examine response of greater prairie-chickens to wind energy development in Kansas (McNew et al. 2009) and a similar study being conducted on greater sage-grouse response to wind energy development in Wyoming (Johnson et al. 2009a) will help to address the lack of knowledge of turbine impacts on prairie grouse	
Category of disturbance: Disruption / destruction of specific habitat (species-specific and behaviour-specific)		
Giesen, 1998; Fuhlendorf et al. 2002; Arnett et al. 2007b	Prairie grouse and big game are likely candidates for displacement effects. Prairie grouse, which exhibit high site fidelity and require extensive grasslands, sagebrush, and open horizons (Giesen, 1998, Fuhlendorf et al. 2002), may be especially vulnerable to wind energy development (Arnett et al. 2007b)	Specific turbine site habitats and habitat alterations should be considered in order to identify focus-species in terms of impact, if habitat alterations are likely to have a preferential disruptive impact upon species linked to that habitat

Original research reference	Key findings and outcomes	Potentially transferable outcomes for bat research at turbines
Flock, 2002	Leks, the traditional courtship display grounds of greater sage-grouse (*Centrocercus urophasianus*), Gunnison's sage-grouse (*C. minimus*), sharp-tailed grouse (*Tympanuchus phasianellus*), lesser prairie-chicken (*T. pallidicinctus*), and greater prairie-chicken (*T. cupido*), are consistently located on elevated or flat grassland sites with few vertical obstructions, terrain very often attractive to wind energy developers	Turbine sites with habitats related to specific bat behaviours (e.g. swarming, mating) should be identified to consider disruption to these behaviours
Vodenhal, 2009; Toepfer and Vodehnal, 2009	Studies of lesser prairie chicken and sharp-tailed grouse response to wind turbines in Nebraska (Vodenhal, 2009) and studies of greater prairie chicken response to wind turbines in Minnesota (Toepfer and Vodehnal, 2009) have found that some prairie grouse on leks as well as nesting hens do not appear to avoid turbines on the sites studied	It is possible that turbines have no behavioural impacts upon bats
Johnson et al. 2009a; Johnson et al. 2009b; Kansas Department of Wildlife and Parks, unpublished data (in Strickland et al. 2011); Robbins et al. 2002	Greater prairie chicken lek surveys were conducted three years before and five years after construction of a wind energy facility at a site in the southern Flint Hills of Kansas (Johnson et al. 2009b). During the year immediately preceding construction of the project (2005), 10 leks were present on the project area, with 103 birds on all leks combined. By 2009, four years after construction, only one of these 10 leks remained active, with three birds on the lek. The 10 leks were located between 88m to 1,470m from the nearest turbine, with a mean distance of 587m; eight of the ten leks were located within 0.8 km (0.5 mi) of the nearest turbine. Although this decline may be attributable to development of the wind energy facility, greater prairie chicken populations have declined significantly in the Flint Hills due to the practice of annual spring burning. During the same time frame that leks were monitored at the Elk River facility, the estimated average number of greater prairie chickens in the southern Flint Hills declined by 65 percent from 2003 to 2009. In Butler County, the estimated number of birds declined by 67 percent from 2003 to 2009 (Kansas Department of Wildlife and Parks, unpublished data). This regional decline is attributed primarily to the practice of annual spring burning and heavy cattle stocking rates, which remove nesting and brood-rearing cover for prairie chickens (Robbins et al. 2002). While not a true reference for this study area, this suggests that it is unlikely that the decline of prairie chickens on the Elk River site was due entirely to the presence of wind turbines (Johnson et al. 2009a).	Specific bat behaviours may be disrupted at turbine sites, even if bat presence is not. However general local, regional and national bat population change estimates should be used to make objective assessments of levels of bat activity and behaviour observations

Original research reference	**Key findings and outcomes**	**Potentially transferable outcomes for bat research at turbines**
Johnson et al. 2010; Beck et al. 2011	The only study to have examined response of greater sage-grouse to wind energy development is being conducted at a wind energy facility in Carbon County, Wyoming (Johnson et al. 2010, Beck et al. 2011). Based on surveys at three leks, the mean number of males decreased from 43 in 2008, the year prior to construction, to 23 in 2010, two years post construction. Similar declines occurred on leks within a nearby reference area, where mean lek size decreased from 37 to 23 over this same time period, but the rate of decline appears to be slightly greater on the three leks in close proximity to wind turbines. Notwithstanding, Johnson et al. (2010) and Beck et al. (2011) indicated that data from this study are preliminary and are not meant to form the basis for any conclusions regarding impacts of wind energy development on sage-grouse.	
Zeiler and Grünschachner-Berger, 2009	Outside of North America, the black grouse (*Lyrurus tetrix*), another grouse with a lek mating system, was found to be negatively affected by wind power development in Austria. The number of displaying males in the wind power development area increased from 23 to 41 during the 3-year period immediately prior to construction, but then declined to nine males four years after construction. While no reference data were reported, in addition to the decline in displaying males the remaining birds shifted their distribution away from the turbines. One lek located within 200m of the nearest turbine declined from 12 birds one year prior to construction to no birds four years after construction	
Harju et al. 2010	This study of oil and gas development suggested that there is a delay of 2–10 years before measurable effects on leks manifest themselves (Harju et al. 2010). Therefore, data spanning several grouse generations may be required to adequately assess impacts of wind energy development on prairie grouse	Long-term monitoring research schedules (e.g. up to 5 or 10 years) may be required for key research on disruptive effects upon bat behaviour, particularly for investigations considering population-level effects
Howell and Noone 1992; Johnson et al. 2000b, 2003b	Most studies suggest that wind facilities have little impact on the nesting of birds	It is possible that bat roosting may not be affected by local turbine installations

Original research reference	Key findings and outcomes	Potentially transferable outcomes for bat research at turbines
Usgaard et al. 1997	The only report of avoidance of wind facilities by raptors occurred at Buffalo Ridge wind facility, Minnesota, where raptor nest density on 261 km^2 of land surrounding the facility was 5.94/100 km^2, yet no nests were present in the 32 km^2 facility, even though habitat was similar	Roost impacts may have to be considered across wide areas with multiple turbine sites and/or multiple roost sites considered, not just those that are in close proximity
Johnson et al. 2010; Beck et al. 2011	The only study to have examined response of greater sage-grouse to wind energy development is being conducted at a wind energy facility in Carbon County, Wyoming (Johnson et al. 2010, Beck et al. 2011). Whilst monitoring at turbines and a nearby reference area, no statistically significant differences were found in nest success for 2009 and 2010 between the two sites. Notwithstanding, Johnson et al. (2010) and Beck et al. (2011) indicated that data from this study are preliminary and are not meant to form the basis for any conclusions regarding impacts of wind energy development on sage-grouse.	
Pearce-Higgins et al. 2009	After monitoring at 12 UK wind farms, suggested breeding bird densities may be reduced by 15-53% within 500m of turbines. Particular species were highlighted as most affected (buzzard (*Buteo buteo*), hen harrier (*Circus cyaneus*), golden plover (*Pluvialis apricaria*), snipe (*Gallinago gallinago*), curlew (*Numenius arquata*) and wheatear (*Oenanthe oenanthe*)) (Pearce-Higgins et al. 2009).	Roost densities of bats may be affected if in moderate proximity to turbines. Vulnerability may vary by species
Johnson et al. 2010; Beck et al. 2011	The only study to have examined response of greater sage-grouse to wind energy development is being conducted at a wind energy facility in Carbon County, Wyoming (Johnson et al. 2010, Beck et al. 2011). Whilst monitoring at turbines and a nearby reference area, no statistically significant differences were found in brood-rearing success for 2009 and 2010 between the two sites. Notwithstanding, Johnson et al. (2010) and Beck et al. (2011) indicated that data from this study are preliminary and are not meant to form the basis for any conclusions regarding impacts of wind energy development on sage-grouse.	It is possible that bats' breeding success may not be affected by local turbine installations

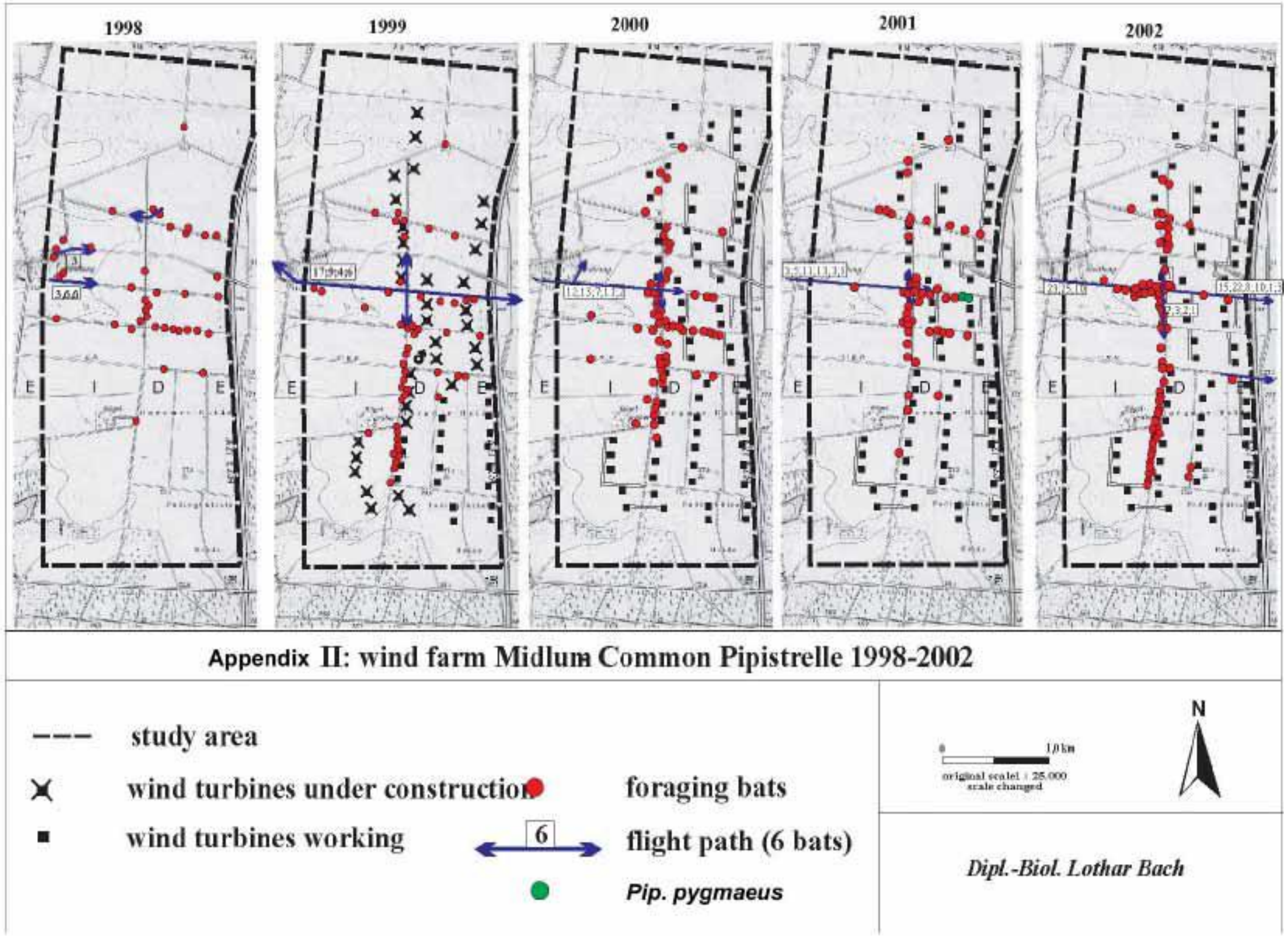

Figure A.1: Changing Common pipistrelle foraging activity and flight routes over time, during construction of a wind farm in Germany (from Bach and Rahmel, 2004)

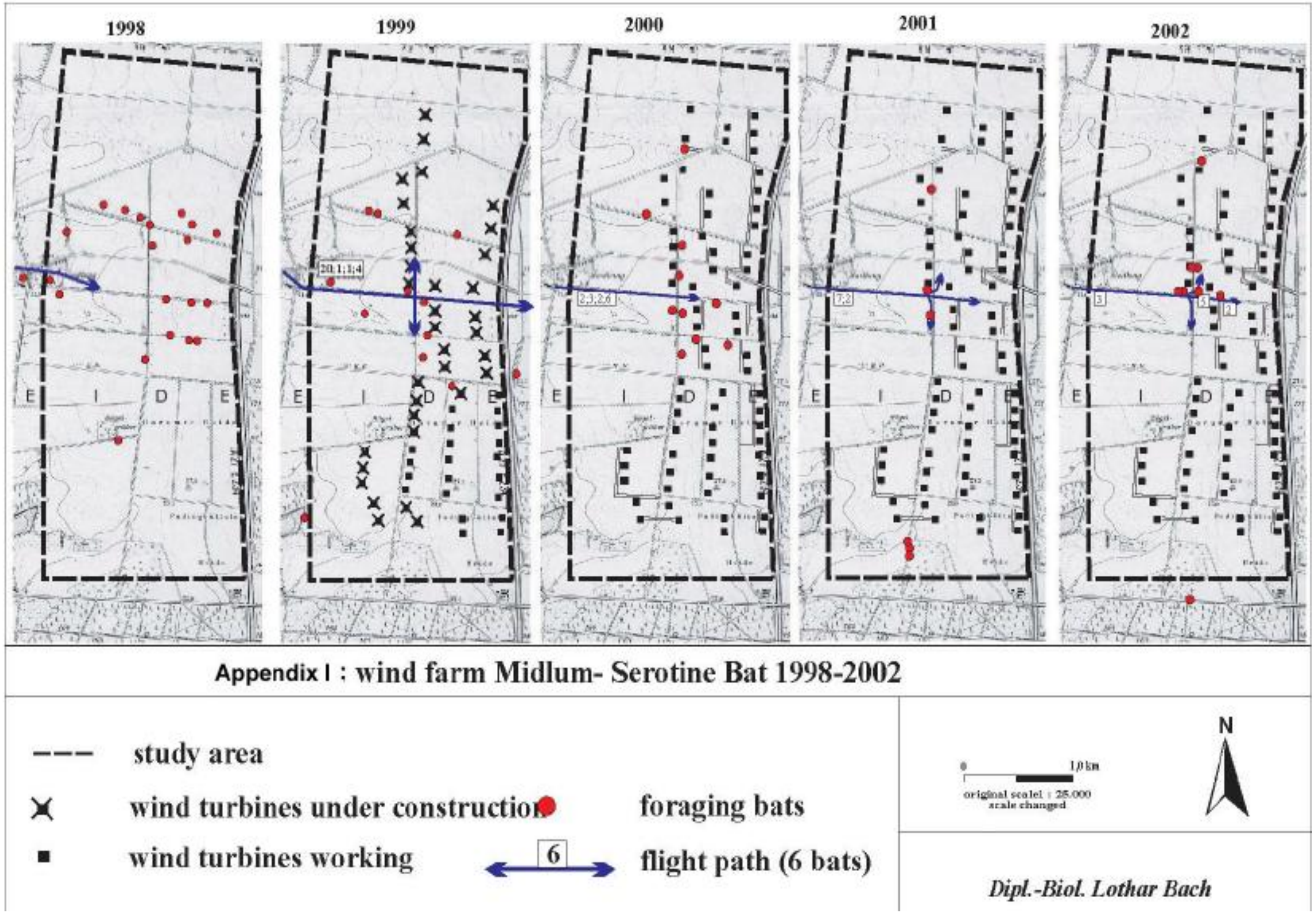

Figure A.2: Changing Serotine bat foraging activity and flight routes over time, during construction of a wind farm in Germany (from Bach and Rahmel, 2004)

Table A.4: UK long-term bat population trends to 2013 and average annual percentage change. Underlined figures are statistically significant trends (from Bat Conservation Trust (2014))

Species	**Status**	**Survey**	**Trend time period**	**Sample size 2013**	**Long-term trend %**	**Average annual change %**
Greater horseshoe bat	Very rare, largely confined to southwest England and south Wales	Hibernation	1997-2013	148	79.6	4.3
		Roost	1997-2013	29	108.9	5.4
Lesser horseshoe bat	Rare, largely confined to southwest England and Wales	Hibernation	1997-2013	227	109.4	5.4
		Roost	1997-2013	256	60.7	3.5
Whiskered/Brandt's bat	Both species are relatively uncommon but widespread in England and Wales	Hibernation	1997-2013	189	31.4	2.0
Natterer's bat	Common	Hibernation	1997-2013	415	93.6	4.8
		Roost	2000-2013	76	-14.3	-1.4
Daubenton's bat	Common	Hibernation	1997-2013	325	22.7	1.5
		Waterway	1997-2013	821	4.5	0.3
Serotine	Uncommon, largely restricted to south	Field	1998-2013	417	35.2	2.2
		Roost	1997-2013	91	-29.1	-2.4
Noctule	Uncommon, absent from Northern Ireland	Field	1998-2013	559	11.7	0.8
Common pipistrelle	Common	Field	1998-2013	561	66.0	3.7
		Roost	1997-2013	459	-54.0	-5.4
Soprano pipistrelle	Common	Field	1998-2013	563	19.2	1.3
		Roost	1997-2013	357	-49.4	-4.7

Species	Status	Survey	Trend time period	Sample size 2013	Long-term trend %	Average annual change %
Brown long-eared bat	Common	Hibernation	1997-2013	365	9.9	0.7
		Roost	2001-2013	143	12.4	1.0
Bechstein's bat	Very rare	No trend data available; Bechstein's bat Survey provides baseline distribution data				
Leisler's bat	Uncommon in GB although may be under recorded, common in Ireland	Recorded by iBats but more data needed to detect trends				
Nathusius' pipistrelle	Uncommon but widespread, may be under recorded	Recorded by iBats but more data needed to detect trends; Nathusius' pipistrelle survey provides baseline distribution data				
Barbastelle	Rare	Woodland Survey monitors presence at designated sites				
Grey long-eared bat	Very rare	No trend data available				
Alcathoe bat	Status unconfirmed	Presence in UK confirmed in 2010, distribution unknown				
(Greater mouse-eared bat)	Status unconfirmed	Only one individual known in the UK at present				

Glossary of definitions

Term	**Definition**
Acoustic jamming	Bats' confusion with similar sound frequencies to their own echolocation
Barotrauma	Rapid decompression of air in the lungs and pulmonary system
Bayes' formula	A mathematical method to calculate conditional and posterior probabilities
Blade-tip vortices	Turbulent low pressure areas near turbine blades where air curls to form a vortex
Cluttered habitat	Area a with dense vegetation structure due to hedges, foliage, trees etc.
Edges	Connections or associations between nodes in a network
Nodes	A member of a network, to which 'edges' connect
Loops	Self-association of a node within a network
Etiology	Concerning the cause of a disease
Fatality estimator algorithms	Methods to calculate adjusted fatality rates that account for imperfect fatality search protocols
Fixed covariate	A continuous predictor variable
Fixed factor	A categorical predictor variable
Genera	Taxonomic rank grouping together species (below a 'family' in taxonomy)
Histopathology	The study of diseased tissue
Nacelle	The 'hub' of a wind turbine holding the gearbox and other turbine mechanisms
Necropsy	Surgical examination of a carcass
Lek	A gathering of male birds for competitive display to attract a mate
Tympana	The cavity of the middle ear
Horizontal axis wind turbine	A turbine with the main rotor shaft pointing into the wind (often perceived as the 'traditional' wind turbine format)
Vertical axis wind turbine	A turbine with the main rotor shaft aligned vertically
Sub-micro turbine	Wind turbine with an upper blade tip height of <10m
Micro turbine	Wind turbine with an upper blade tip height of 10-15m
Small turbine	Wind turbine with an upper blade tip height of 15-30m
Medium turbine	Wind turbine with an upper blade tip height of 30-55m
Large turbine	Wind turbine with an upper blade tip height of >55m

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