

**Understanding Bat Activity Patterns and Influencing  
Factors in Urban Environment: A Study Based on  
Queen Elizabeth Olympic Park, London**

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## **Abstract**

As the only mammal capable of sustained flight, bats serve pivotal roles in ecological balance and economic systems. The rapid pace of urbanization is steadily encroaching on bat habitats, escalating concerns over their conservation. Fortunately, recent evidence suggests that some bat species are gradually adapting to urban environments. Therefore, how to optimally protect bats within cities and achieve harmonious coexistence with humans has become a widely discussed topic. However, long-term investigations on urban bat activity patterns and influencing factors are limited, the absence of inventory data constrains strategic conservation initiatives.

This paper delves into activity patterns and influencing factors in Queen Elizabeth Olympic Park, London, with the goal of offering a comprehensive insight into urban bats. Building upon the initiative of “Nature-Smart Cities” project, this study acts as a continuation of the research enabled by the deployment of 15 acoustic sensors in 2017. With five years of continuous bat monitoring, this study is grounded on a rich dataset, promising profound findings.

## **Declaration**

I, Wendi Li, hereby declare that this dissertation is all my own original work and that all sources have been acknowledged. It is 11900 words in length.

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## List of Acronyms and Abbreviations

**P. pygmaeus**      *Pipistrellus pygmaeus*

**P. pipistrellus**      *Pipistrellus pipistrellus*

**P. nathusii**      *Pipistrellus nathusii*

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# **Chapter 1 Introduction**

As the most geographically widespread and diverse non-human mammals, bats play an important role in ecosystem. Bats are always considered as good bioindicators, given their taxonomic stability and sensitivity to human activities (Kalcounis-Rueppell et al., 2007; Park, 2015; Jones et al., 2009). They are also significant pollinators and seed dispersers for maintaining urban biodiversity (Hodgkison et al., 2003). Economic importance is another benefit that bats provide. In United States, insectivorous bats save agricultural sector about 22.9 billion USD per year, thanks to their ability to control pests (Boyles et al., 2011). However, urbanisation and logging are reducing bat species (Lane et al., 2006; Mickleburgh et al., 2002; Browning et al., 2021).

Social development trends indicate that urbanisation is an inevitable process (Zhang, 2016). Government of the United Kingdom has predicted that the urban population will increase in all size categories by 2030 (GOV.UK, 2021). Therefore, studies and conservation measures for bats are gradually shifting to a more anthropocentric perspective: how bats can better survive in cities, and how cities can maximize the retention of bat populations (Scanlon et al., 2008; Lewanzik et al., 2022). Some studies have proven that opportunistic bats could adapt to urban habitats and adjust their foraging strategies accordingly, making urban-bat coexistence a possibility (Egert-Berg et al., 2021; Ancillotto et al., 2015). Based on this fact, countries worldwide are striving to enable coexistence between cities and bats. For example, bat populations in Europe have shown signs of recovering after the proposal of the Convention on Biological Diversity (CBD) (UN, 1992; Browning et al., 2021). However, the 2010 target mentioned in CBD was missed, and some evidence suggested that subsequent targets may also be difficult to achieve (Mace et al., 2018). Browning stated that more investigation and practical actions are required for

bat conservation, including understanding city-specific activity patterns and their influencing factors, rather than just monitoring and planning (Browning *et al.*, 2021a).

As a bio-friendly country, UK is an early proponent of policies related to urban bat conservation, including Biodiversity Action Plan (BAP) and legal regulations (BAP, 1994; legislation.gov.uk, 2017). However, there is limited detailed research on bat activity patterns in the UK, with most studies from the last century, and even fewer specifically addressing London (Swift, 1980; Maier, 1992). This fact hinders bat conservation in UK cities. In order to fill the gap, this paper focuses on London city. Queen Elizabeth Olympic Park is selected as the study area, which is a large urban park in east London. In May 2017, a research about embedded machine learning in ecological field started here, with 15 bat sensors — “Echo Boxes” being deployed (Gallacher *et al.*, 2021). This previous study demonstrated the possibility of combining artificial intelligence sensor technology and ecology to create valuable insight for conservation decisions, and the success of experiments prompted stakeholders to keep the sensors operational until today, providing data basis for this study.

This study analyses bat call sequence data obtained from five consecutive years of monitoring to explore the activity patterns in London, and further combining data on habitat types, weather, and event to analyses the influencing factors. This study hopes to provide empirical insight on bats and lay a solid foundation for conservation decision-making in London. The central research question is addressed here:

What are the activity patterns of bats in London? How do factors such as habitat type, weather, and human activity influence these patterns?

To address the central research question, this study will pursue the following objectives based on analytical logic:

- Q1: What are the annual variations, seasonal trends, and nightly activity patterns of bats, and how do these patterns differ among species?
- Q2: How do habitat variations influence bat activity levels, and what preferences distinguish different species?
- Q3: Considering location as a random effect, how do various weather factors influence bat activity?
- Q4: Does human activity (events and weekends) affect nocturnal animals?

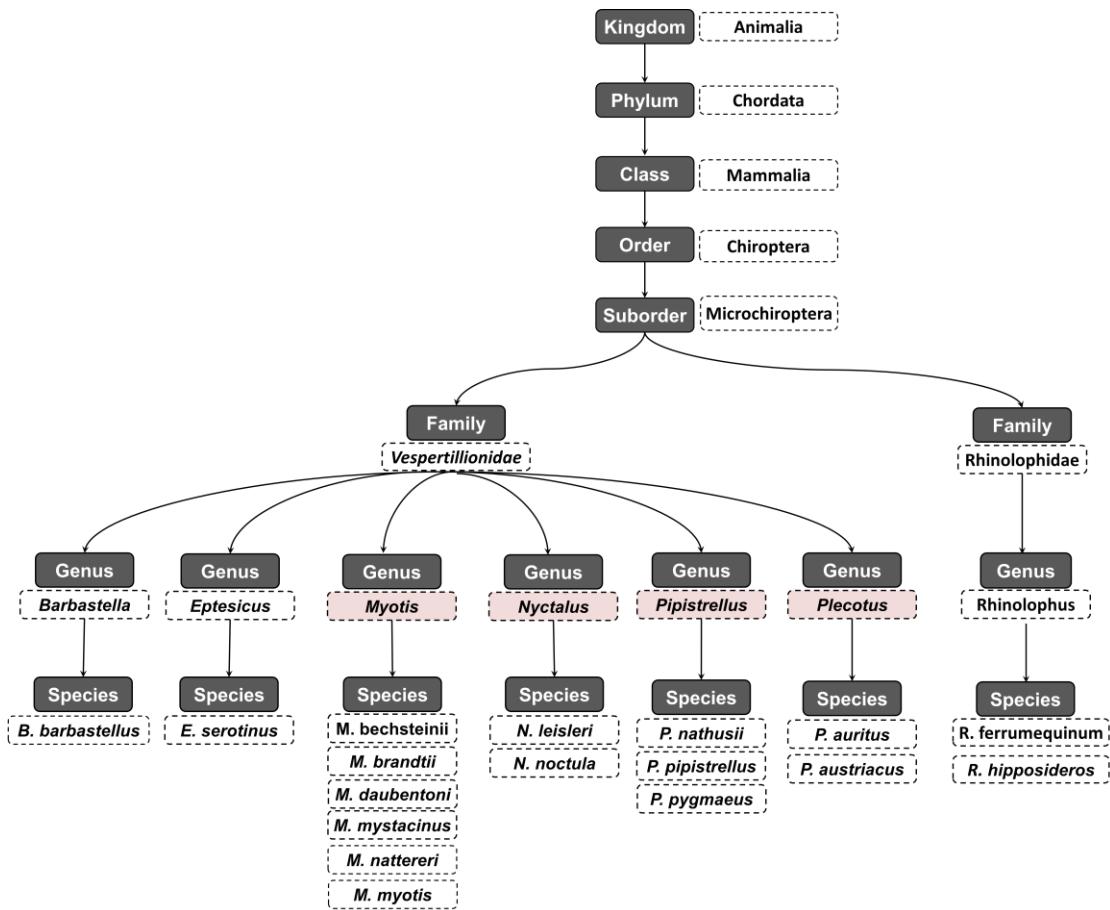
There is an aspiration that people no longer misunderstand bats as a kind of “awkward creatures” or the sinister, humans can embrace the co-existence of bats and cities (Ginn, Beisel and Barua, 2014). As Wright (2014) says, “becoming-with nonhumans, and appreciating their capacity for meaning-making and worlding, may enhance our ability to respond to the disturbing and amorphous becoming-withs of the Anthropocene”. Understanding and appreciating the interdependence of organisms would shape a better society, and the intricate dynamics in the world. Ultimately, this study expects to start from a small perspective, to provide an attempt and reference for exploring urban bat conservation through empirical data analysis, making some contributions to harmonious coexistence of human and nature

## **Chapter 2 Literature Review**

This chapter contextualizes the relevant literature on bats. Initially, providing an overview of characteristic and current status of bats, and the threats they are facing. Then the temporal activity patterns are summarised. Subsequently, factors that might influence bat activity are reviewed, encompassing critical habitat elements and the widely studied factors of weather and human activities. Lastly, it contrasts the various methods used for monitoring bats.

### **2.1 Characteristic, Benefits and Threat of Bats**

Bats are the most widely distributed and diverse mammals in the world, forming the second largest colony in existence after humans (Adams, 2004; O'Shea TJ and Bogan MA, 2003). As the only mammals capable of sustained flight, powered flight not only makes possible for bats to spread across the world, but also contributes to their distinctive feeding and survival habits (Smith, 1977; Sivasekaran et al., 2021; Adams, 2004;.Patterson et al., 2003). Bats are also diverse eaters, including various types of insects, fruits, leaves, etc., which makes them highly adaptable to different environment (Kunz, 2013). Of the over 1,400 bat species globally, 17 are currently breeding in the UK (Simmons N.B. and Cirranello A.L., 2020; Bat Conservation Trust, n.d.). Taxonomy helps clarify the classification of these bats (Figure 2.1.1), where the genera marked pink are those that have occurred in this study area (Gallacher et al., 2021).



**Figure 2.1.1 Taxonomy of Bats in UK. Source: Adapted from Warwickshire Bat Group (n.d.)**

Many studies suggest the potential of bats as biodiversity indicators, especially biodiversity indicator, for their stable taxonomy, easy catchability, broad geographic range and environmental sensitivity (Cunto and Bernard, 2012; Spector and A.B. Forsyth, 1998; Wickramasinghe et al., 2003; Jones et al., 2013). Although structure modification and activity level variation of bats perpetually prevail across various area, the species composition are always similar (Wickramasinghe et al., 2003; Pineda et al., 2005). Bats are also crucial pollinators and seed dispersers for over 300 species of plants (Shilton et al., 1999; Hodgkison et al., 2003; Ramírez-Fráncel et al., 2022). In addition to their ecological value, the pest control capabilities of bats make a significant socio-economic contribution. Benefited from this, Boyles et al. (2011) predicted that the “ecosystem services” bats providing will rich \$3.7 billion to \$53 billion per

year.

However, bats are under threat in the world. According to the International Union for the Conservation of Nature (IUCN), nearly 40% of species are listed for protection, and nearly a quarter of bats are threatened worldwide (Mickleburgh et al., 2002; Mathews, 2020). There are many causes for the current predicament, including invasive species, climate change, anthropogenic expansion etc. (Welch and Leppanen, 2017; Festa et al., 2023; Greenfeld et al., 2018). Among all the causes, urbanisation is considered the greatest causes latterly, accompanied by misconceptions about bats due to the COVID-19 and the insufficient experience in urban conservation (Nanni et al., 2022; Gallo et al., 2018; Vlaschenko et al., 2019). Most importantly, the issue of lacking basic inventory data on bats in cities, raised 30 years ago, still exists today (PIERSON, 1998). Urban decision-makers struggle to understand local activity patterns, making it challenging to create effective protective measures. This results in inefficient bat conservation and failures to meet global commitments (Browning *et al.*, 2021b).

## **2.2 Temporal Pattern of Insectivorous Bats**

All bats breeding in UK are insectivorous bats (Bat Conservation Trust, no date a). As a typical nocturnal animal, the vast majority of insectivorous bats are active during night (Speakman J R, 1995; Rydell et al., 1996). Hibernation behaviour in insectivorous bats is also prevalent in temperate regions (Kim, Choi and Yoo, 2019). Owing to these active nature, habitats of bats are diverse, including hibernacula, summer day roosts, summer night roosts, maternity roosts and foraging area (Kunz, 1982). Radar tracking and capture techniques are commonly used for habitat observation (Mackie and Racey, 2007; Newman et al., 2021), whereas acoustic identification, capitalizing on bats' echolocation abilities (Hayes, 1997; Barclay, 1999; Bogdanowicz et al., 1999), serves as a

prevalent method for studying foraging behaviours. Yet one study by Davidson-Watts and Jones (2005) suggested that foraging area of two species of pipistrelle are likely close to night roosts, thus to some extent foraging sites can provide insights into roost selection.

The endogenous circadian rhythm and reproductive habits make activity of bats vary significantly in different seasons and time (Decoursey and Decoursey, 1964; Agosta et al., 2005). Bats typically exhibit their minimal level of activity during winter months, witnessing a rise starting around April, peaking in summer and then tail off (Russ et al., 2003; Kuenzi and Morrison, 2003; Agosta et al., 2005; Maier, 1992). Such patterns are mainly related to the hibernation habits and special reproductive patterns. Although many studies suggest that a significant number of bats still engage in foraging activities during winter rather than fully hibernate, it is indisputable that bats exhibit a significantly lower level of activity in winter compared to other seasons (Zahn and Kriner, 2016; Wermundsen and Siivonen, 2010; Hope and Jones, 2012). The special reproductive patterns of bats could further explain seasonal variation: After mating in autumn, the sperm is stored in female for several months until after hibernation, then oviposition and fertilisation occurs within 1-3 days and young bats are eventually born in summer, which is known as “delayed fertilisation” (Pfeiffer and Mayer, 2013; Bradley, 2006; Zukalova et al., 2022). This kind of fertilization causes the low demand of energy during winter but high in other seasons, which cause the various activity level. However, there is one point that little studies focus on or explore the underlying cause: The month in which peak occurs and birth starts varies across study area, for example, peak occurs in July in Russ et al. (2003)'s observation but in late August in Agosta et al. (2005)'s study.

Nightly patterns of bats have received a lot of scholarly attention rather than

seasonal patterns. Many studies suggest that nightly activity of bats is linked to sunrise and sunset rather than fixed clock hours, and there are always two foraging periods during night (Erkert, 1978; Erkert, 1982; Anthony et al., 1981; Barclay, 1982). The first period is the primary foraging that occurs a few hours after dusk, when insects are at their most abundant, and the second period is during pre-dawn (Maier, 1992). Swift (1980)'s research in Scotland explored in more depth the nightly patterns that vary with different reproductive phases, the results show that the bimodal mode is most noticeable after parturition in June, but weakens during pregnancy (May and early June) and weaning (August). This support for the argument that bats adjust nocturnal duration according to energy requirements and foraging needs (Barclay, 1991; Agosta et al., 2005). Although many studies have elaborated on individual nightly pattern, few have compared them across seasons and analysed variation between species, which is a research gap.

## **2.3 Factors Affecting Bat Activity**

Bat activity are influenced by many factors, including habitat features, weather, human activity, artificial lighting, etc. Among these factors, habitat stands out as the most fundamental. Without suitable habitats, bats simply cannot exist. In this section, a literature review will be conducted firstly on habitat, followed by weather and human activity.

### **2.3.1 Habitat**

Habitat, as the most basic need of bats, plays a decisive role in their population, activity level, spatial distribution, and even influences their survival (Niebuhr et al., 2015; Thomas et al., 2021). Water area and deciduous forests are the most common foraging habitats for bats, including riparian woodland, deciduous woodland, broadleaved woodland, lake etc. (Walsh and Harris, 1996; Razgour

et al., 2011; de Jong and Ahlén, 1991). These areas provide an abundance of aquatic insects (e.g. chironomids and caddis flies) and available drinking water, supporting their energy replenishment and substantial need for water (Seibold et al., 2013; Webb et al., 2009; Hagen and Sabo, 2011; Salsamendi et al., 2012). Some studies also further suggest that bats prefer calm waters surfaces over fast-flowing rivers due to less interference with echolocation (Warren et al., 2000; Mackey and Barclay, 1989). Grassland is another potential habitat for bats, however, their preference for these areas varies. In general, bats prefer water bodies and woodlands over grasslands, though they can still be found in some unimproved grasslands. (Glendell and Vaughan, 2002; Vaughan et al., 1997; Seibold et al., 2013). Very few bats occur in open improved grasslands and arable land, which can be attributed to the impact of agricultural intensification on insect pollination dynamics, leading to habitat loss and reduced biodiversity (Holloway and Barclay, 2000; Power et al., 2012). This is along with Yoshikura et al. (2011)'s findings that bat activity in old-growth forests is much higher than in artificial conifer plantations, suggesting human modification of nature is much responsible for habitat loss. Linear and edge structures, like hedgerows and tree lines, are favoured by bats. They attract a diverse range of insects from both types of vegetation and also serve as effective commuting routes (Verboom and Huitema, 1997; Kalcounis-Ruepell et al., 2013; Boughey et al., 2011; Lentini et al., 2012; Morris et al., 2010).

Although bats exhibit overarching congruencies in habitat selection, the magnitude of their preference may vary due to echolocation capabilities, morphological distinctions, and other pertinent factors (Entwhistle et al., 2001). For example, *noctules* prefers to fly in open spaces due to their elongated and slender wings, while *P. nathusii* has a unique fondness for wetlands (Wainwright and Reilly, 1994; Flaquer et al., 2009; Entwhistle et al., 2001). Some studies focus on sibling species that are morphologically similar, such as *P. pipistrellus*

and *P. pygmaeus* or *M. myotis* and *M. blythii* (Hulva et al., 2004; Berthier et al., 2006). Results show that habitat spatial segregation and inter-specific competition always present in these species, suggesting even homogeneous species can show highly variable habitat selection due to resource partitioning (Nicholls and A. Racey, 2006; Arlettaz, 1999; Arlettaz et al., 1997). Two studies conducted by Davidson-Watts et al. further conclude that *P. pygmaeus* prefers riparian habitats while *P. pipistrellus* is more like a generalist (Davidson-Watts and Jones, 2005; Davidson-Watts et al., 2006).

Although bats have a wide range of habitat preferences, as urbanisation accelerates, urban environment is of increasing interest as a potential roosting site. Compared to residential areas, small parks, streets, etc., large urban parks always have the most bat activity due to their rich vegetation and water resources, and low-density old towns are always more popular with bats than new communities (Avila-Flores and Fenton, 2005; Oprea et al., 2009; Gaisler et al., 1998). Many literature illustrate the high correlation between habitats and location of water, again demonstrating the importance of water for bat survival (Lehrer et al., 2021; Ancillotto et al., 2019). With the progression of urbanisation, man-made structures are increasingly becoming common refuges for urban bats, including bridges, green roofs, and bridges (Parkins and Clark, 2015; Soper and Fenton, 2007). Artificial roosts — bat boxes, have also been demonstrated to be a good alternative for urban bats, with rocket box style being mostly favoured (Hoeh et al., 2018; Cruz et al., 2018; Gallacher et al., 2021; (Czenze, Noakes and Wojciechowski, 2022). Large artificial nature reserve is also a valuable conservation measure (Mayfield et al., 2017). However, not all species can adapt well to urban habitats or artificial structure. A comprehensive study conducted by Gili et al. (2020) shows that the genus *Pipistrellus*, *Nyctalus* and the species *E. serotinus* are more resilient to urbanization, while the genus *Barbastellus*, *Myotis* and *Plecotus* are most

vulnerable. Bat abundance is generally lower in artificial habitats than in forests, suggesting that the effects of urbanisation on some species are still unavoidable (Kelm, Toelch and Jones, 2021).

### **2.3.2 Weather and Human Activity**

Atmospheric factors such as temperature, wind speed, precipitation, humidity etc. may positively or negatively affect bats. Bats prefer warmer environments, almost all studies demonstrate a significant positive correlation between temperature and bat activity level (Wolbert et al., 2014; Bender and Hartman, 2015; Ruczyński and Bartoń, 2020; O'Farrell and Bradley, 1970). The effects of wind on bats are inconsistent, it is widely accepted that there is a negative correlation between wind speed and bat activity (Weller and Baldwin, 2012; Wolcott and Vuliniec, 2012; Reynolds, 2006). However, a growing number of studies are surprised to find no significant relationship between wind speed and activity level (Mukherjee Wilske and Korine, 2002; Vaughan et al., 1997; Smith and McWilliams, 2016), with a few even indicating a positive correlation (Ciechanowski et al., 2007; Russ et al., 2003). Numerous studies have examined the influence of precipitation on reproductive patterns of survival, most of them indicating the declining or deferred impact (Stapelfeldt et al., 2022; Davy et al., 2022; Grindal et al., 1992). But the research focusing on capture or activity rates finds mixed results, with some showing a negative impact, while others report no significant effect of precipitation (Geluso and Geluso, 2012; Erickson and West, 2002; Kunz, 1973). An impact of precipitation on bats distribution and diversity is also suggested (Michaelsen, 2016; Patten, 2004). In addition to temperature, rainfall, and wind speed mentioned above, weather factors such as humidity, atmospheric pressure, barometric pressure trends, and thermal indices also affect bats in different ways (Bender and Hartman, 2015; Kotila et al., 2022; Griffin, 1971; Fidiam and Iudica, 2011). However, it is worth noting that research on weather effects may vary by region, season,

environment, etc., and more importantly, different species may react dissimilarly (Culina et al., 2017; Smeraldo et al., 2021; Festa et al., 2023). This echoes Jung and Threlfall (2018)'s point about the necessity for examining trait-based responses among regions and species, which Wolf et al. (2022) tested and extended the same theme four years later. Urban bats are also likely to be affected by a variety of human behaviours. However, while current studies primarily focus on the effects of artificial light, there is less emphasis on human mobility or events (Barré et al., 2021; Stone et al., 2015). Since diurnal animals interact more with human activities, fewer studies focus on nocturnal animal activity (Nix et al., 2018). But Li et al.'s (2020) study on bats and weekend effect suggests that the impact of human activity on nocturnal bats warrants investigation.

## 2.4 Methods for Exploring Bat Activity

Various sampling methods are used to monitor the high-complexity bat populations, which traditionally fall into physical sampling such as trap capture, mist nets, habitat survey etc., and monitor sampling represented by acoustic monitoring. Physical sampling provides a comprehensive insight into bat characteristics, including reproductive status, gender, age, DNA, etc., which is suitable for investigating reproductive patterns and genetic mechanisms (Franci et al., 2012; Sztencel-Jablonka and Bogdanowicz, 2012; Puechmaille et al., 2007; Speakman and Racey, 1986). However, although physical sampling has been improved several times from ordinary mist nets (e.g., canopy nets, harp traps), the limited sampling coverage results in the captured quantity and diversity being unrepresentative of entire bat population (Kunz and Brock, 1975; MacSwiney G. et al., 2008). Stress on bats and propensity to capture certain species may introduce sample bias, moreover, any kind of physical experiment is typically labor-intensive (Barnett et al., 2006; Murray et al., 1999; Flaquer et al., 2007). Acoustic monitoring addresses the above limitations well and provide

a good means to understand activity level. As a non-invasive means, acoustic detector allows for broader surveillance, capturing a richer diversity of species and providing more comprehensive data (Ochoa G. et al., 2000; Parker, 2021; Ahlén and Baagøe, 1999). And as its cost-effectiveness and reduced labor intensity, acoustic monitoring is well suited for continuous sampling or annual monitoring (Walsh et al., 2001; Skalak et al., 2012). Deep learning tools for bat species identification have broadened the applicability of acoustic methods (Aodha et al., 2018; Skowronski and Harris, 2006; Stowell and Plumley, 2014; Armitage and Ober, 2010). Nevertheless, acoustic monitoring cannot know the subtle changes within the population and the exact number, and differences in call frequencies may affect the results, leading several researchers to question its validity (Hayes, 2000; Barclay, 1999). Ultimately, the choice of method highly depends on the research question. Some scholars even combine approaches for a more comprehensive view (Appel et al., 2021; Williams et al., 2006; MacSwiney G. et al., 2008).

Current bat experiments primarily use spot or intermittent sampling, focusing on specific locations or period. These kinds of sampling is concentrated in certain months or only night time when bats are most active due to resource limitation, e.g. Zortéa (2003) collected data six days per month for a year, Froidevaux et al. (2014) choose to conduct daily collection from June to August. Locations of sampling always employ the Random Stratified Sampling method to choose sites (Froidevaux et al., 2014; Hyzy et al., 2020; Gallacher et al., 2021). These discontinuous sampling methods are often more targeted and cost-effective, but there will be some loss of information. Consequently, many new techniques have been proposed to facilitate maximally continuous monitoring spatially or temporally. Internet of Things (IoT) in conjunction with edge processing is one of the focal points, with its low storage and network capacity requirements, the low-cost and unattended monitoring is facilitated

(Zualkernan et al., 2021; Hudson-Smith et al., 2021; Lin et al., 2020). Gallacher et al. (2021) 's successful monitoring, which lasted for over five years, also proved the feasibility of this approach. Novel tracking technologies such as ultra-low power, GPS, LiDAR, thermal imaging etc. have replaced traditional radio telemetry, making a good attempt to monitor bats in a spatially continuous manner with low labor costs (Dressler et al., 2016; Aghababian, 2023; Hermans et al., 2023; Hurme et al., 2019). These new techniques enhance monitoring comprehensiveness; however, it remains challenging to ensure both spatial and temporal continuity over extended periods. In this regard, Skalak et al. (2012) investigated how to optimize monitoring locations and frequencies under constrained hardware conditions, providing good suggestions for improving validity and accuracy of acoustic surveys.

Statistical tools are also widely used in biology, including linear mixed effects Models (LMMs) (Zuur et al., 2009), generalized additive model (GAM) (Hastie and Tibshirani, 1990), generalized linear models (GLM) (Nelder and Wedderburn, 1972) etc. However, due to the varying degrees of complexity and applicability limitations of these models, generalized linear mixed model (GLMM) has become the most widely used model in ecology in recent years (Stroup, 2012). The advantages of the GLMM model in biology and ecology include the following: (i) GLMM model is well-suited to processing non-normally distributed data and zero-inflated data, which are common in biological count data; (ii) GLMM model can account for random effects and is suitable for data with spatially-stratified characteristics, e.g., multiple observations at different locations; (iii) GLMM models can deal with interactions between predictor variables, which are suitable for variables such as weather (Bolker et al., 2009; Harrison et al., 2018; Ruiz et al., 2023). Hence, many studies examining factors influencing bats employ the GLMM model, e.g. Perks and Goodenough (2020), Müller et al. (2013), Węgiel et al. (2023). Additionally, statistical methods

focusing on variability, such as Kruskal-Wallis test and Chi-square test, are also commonly used to study habitat variations (Scanlon et al., 2008; Langlois et al., 2023; Jackson et al., 2023).

## 2.5 Conclusion

Through literature review, it is evident that research on bats has accumulated significant findings since the last century. Improvements in monitoring methods have also led to more extensive and diverse research. However, research on urban bats is still in its early stage, with limited studies related to specific activity pattern and species-specific in cities. Moreover, few studies have realized continuous observation over a long period of time. In this regard, several research gaps intended to be addressed in this paper are identified:

Gap 1: Lack of continuous observation data analysis.

Gap 2: Nightly patterns are rarely compared seasonally.

Gap 3: Few studies use half-hour intervals for GLMM modelling.

Gap 4: Weekend effect or events receive less attention on bats.

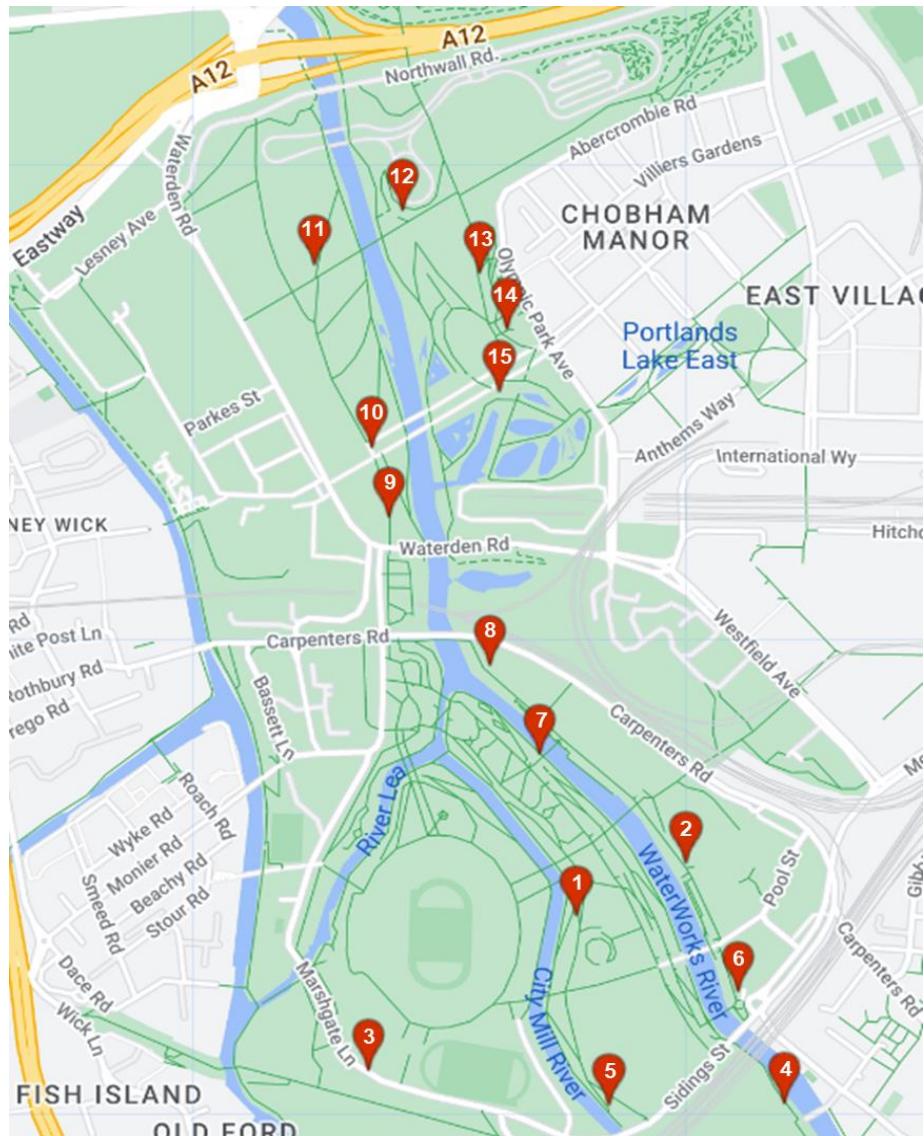
Gap 5: Few studies delve into species-specific urban bat research.

# **Chapter 3 Methodology**

This chapter elaborates on the approach to address missing data caused by sensor breakdowns during the five-year bat monitoring, as well as the specific analysis steps. It starts with an overview of the study area and research framework, delves into data processing and methodology across research stages, and concludes with a discussion on limitations. The dataset and code used for analysis are available here: <https://github.com/ucfnlih/Bats-Elizabeth-park-London>.

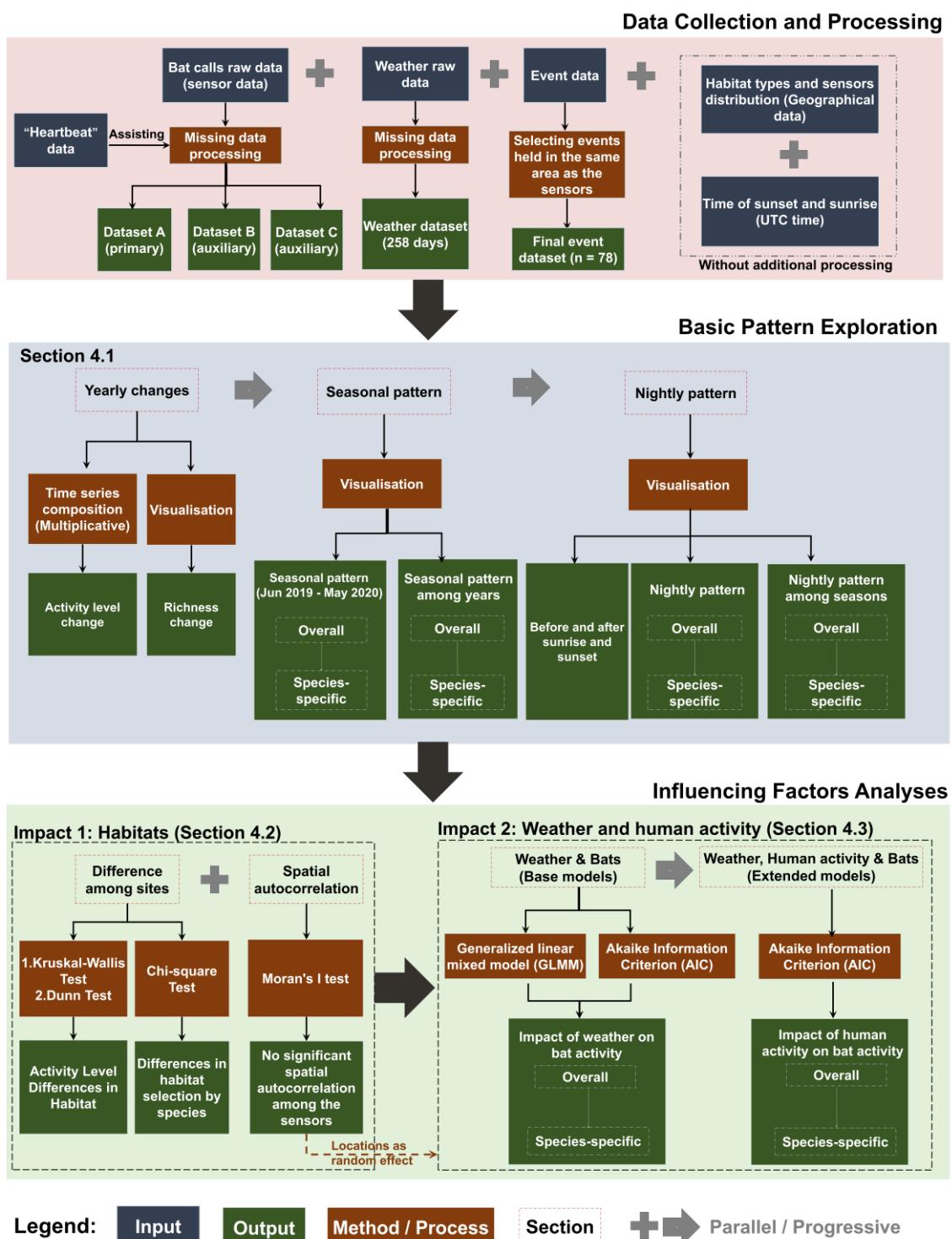
## **3.1 Study Area**

This study is conducted in Queen Elizabeth Olympic Park in East London, the United Kingdom. As a part of River Lea wildlife corridor, Queen Elizabeth Olympic Park connects the Thames and North London across four boroughs. The park strongly focuses on urban-biological harmony, with 78 miles of connected open space providing more than 10 habitats (Queen Elizabeth Olympic Park, 2019). The Biodiversity Action Plan (BAP), proposed in 2008, strongly supporting for conservation of urban biodiversity. Since May 2017, 15 internet connected bat sensors — “Echo Boxes” (Appendix A) have been randomly deployed in the South Park area, achieving five consecutive years of bat observations (Respond to Gap 1) (Gallacher *et al.*, 2021). The rich bat call sequences recorded over five years reflects the healthy urban habitat in the park. This project was jointly founded by UCL and Intel, and in partnership with Arup, the Bat Conservation Trust, and the London Wildlife Trust, more details can be accessed here: <https://naturesmartcities.com/about/>.



**Figure 3.1.1 Study Area and Sensor Distribution. Source: Adapted from Nature-Smart Cities Website <https://naturesmartcities.com/>.**

### 3.2 Research Framework



**Figure 3.2.1 Research Framework. Source: Author**

This study begins with data collection, six datasets obtained from sensors, weather station, project stakeholders, and public data are used as input data.

Bat call data, weather data and event data are then processed to derive cleaned datasets. The basic activity patterns are first visualised in section 4.1, including yearly variation, seasonal patterns, and nightly patterns. This section possesses a strong logic, executing from total to species-specific, from specific instance analysis to lateral comparison (e.g., from single year analysis, to year-to-year comparison). Habitat effect on bats is then explored, including habitat variations selection, which followed by spatial autocorrelation test. In section 4.3, weather data and bat activity are used for modeling, where locations are considered as random variable according to the result of section 4.2. Finally, the base model is extended by adding anthropogenic factors to explore the impact of human activity.

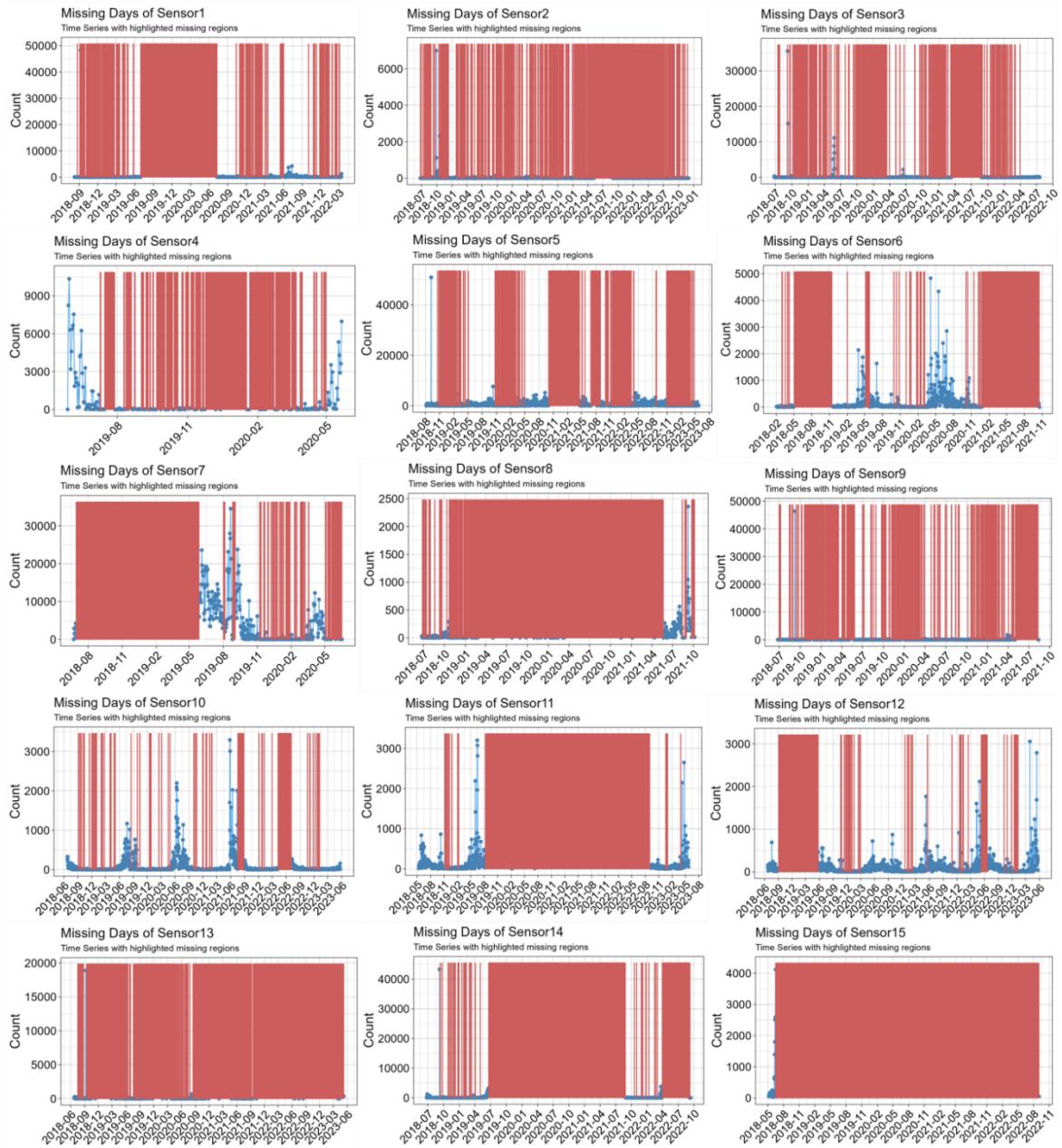
### **3.3 Data Collection, Processing and Exploration**

Sensor experiments frequently encounter machine failures, and the subsequent missing data may impede analysis (Scanlon et al., 2008; Williams et al., 2006; Sharma et al., 2021). Therefore, identifying missing data and selecting available datasets are necessary. Five datasets are used in this study: bat call sequences (primary) and weather, with most of missing data concentrated in these two, followed by sensor and habitat, event data, and sunset/sunrise times. Due to the scattered available data, one primary and two auxiliary datasets are finally used for analysis.

#### **3.3.1 Bat Call Sequences Data**

Bat call sequence data is recorded by acoustic sensors. Data exists only when sensors record at least one call, resulting in incomplete dates in sensor data. Using package “imputeTS” in R to visualise missing days, Figure 3.3.1 displays bat call sequences by days for each sensor, and marking missing days with red bars. It can be observed that each sensor exhibits varying proportions of

missing days, some sporadically and some consecutively.



**Figure 3.3.1 Missing Days of 15 Sensors over Five Years. Red bars indicate missing days, blue points indicate the number of recorded call sequences.**

**Source:** Author

There are two possibilities for data missing: Firstly, there is no bat activity occurring so sensors record no calls; Secondly, mechanical failures or availability limitations, such as Wi-Fi disconnection or sensor damage, in which

bat calls could not be recorded. However, it cannot be directly inferred from the data itself, which becomes the biggest difficulty for the research.

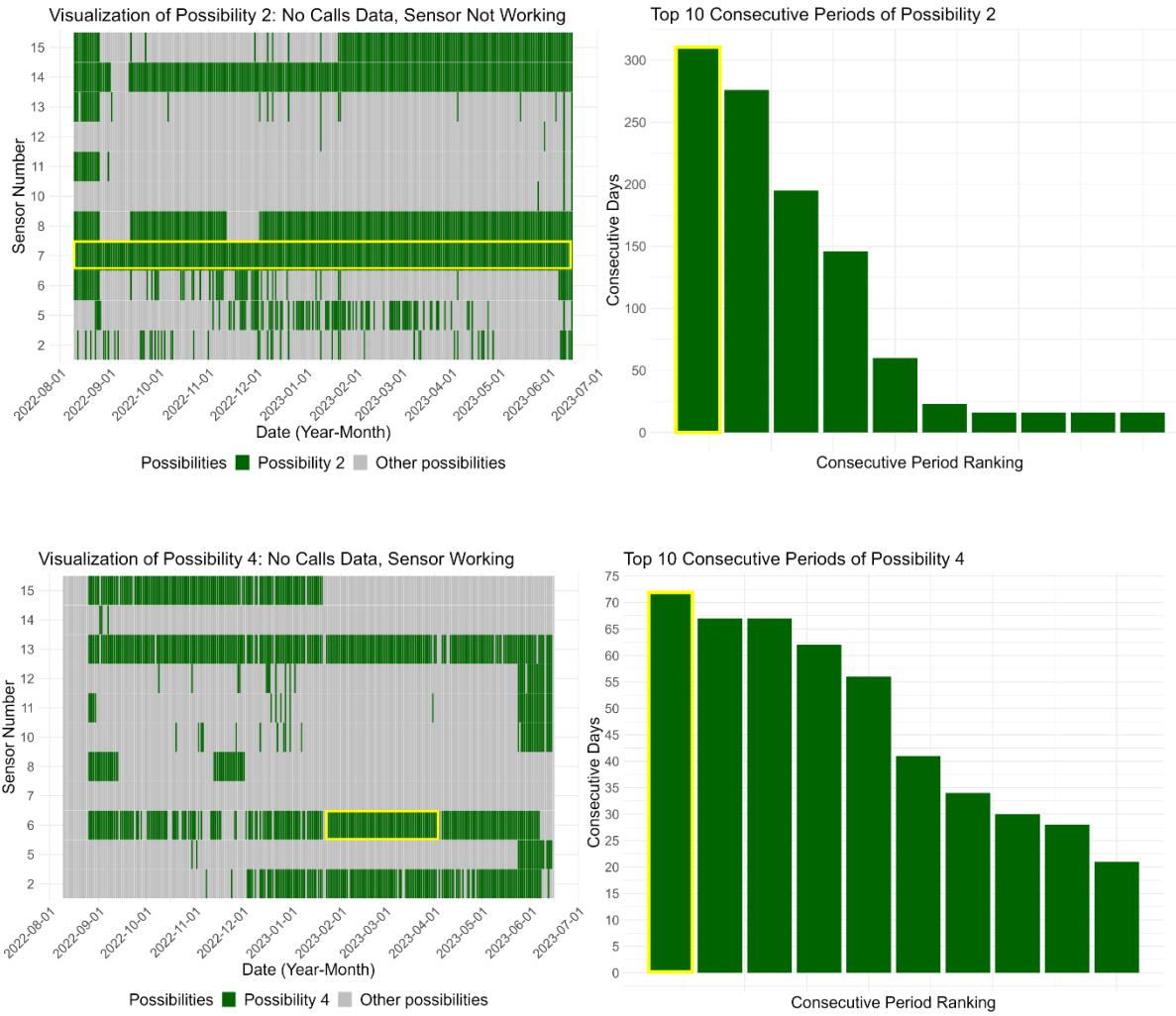
Luckily enough, another small dataset the IoT system providing can help define causes, which is called “heartbeat” dataset. Sensors send heartbeat signals every 6 minutes and up to 240 times a day, which indicates the sensor is working. If the number of heartbeats is close to 240 times one day, it means the sensor operates normally that day; but if not, it indicates a loss of connection, with some bat calls data being lost. Regrettably, this dataset only covers 11 sensors from August 2022 to June 2023, so it cannot be used to determine the cause for all missing data. However, patterns identified in this period are still valuable and will be used to interpret the remaining data.

There are four possible combinations of sensor status and data availability, among which possibility 1 is an unreasonable situation, possibilities 2 and 3 are common, and the case where the sensor is working but there no calls data is most worth exploring (possibility 4). From Figure 3.3.2, two cases when there is no calls data can be compared. Results show that the consecutive periods of possibility 2 are always much longer than possibility 4, which are 300 days and 75 days respectively. This suggests that long consecutive gaps in call data likely stem from machine failure, while intermittent short gaps more likely indicate periods of no bat activity. Therefore, using 75 days as the threshold to deal with missing dates for the remaining periods and sensors.

**Table 3.3.1 Four Possible Combinations of Machine Status and Calls Data**

**Availability.** Source: Author

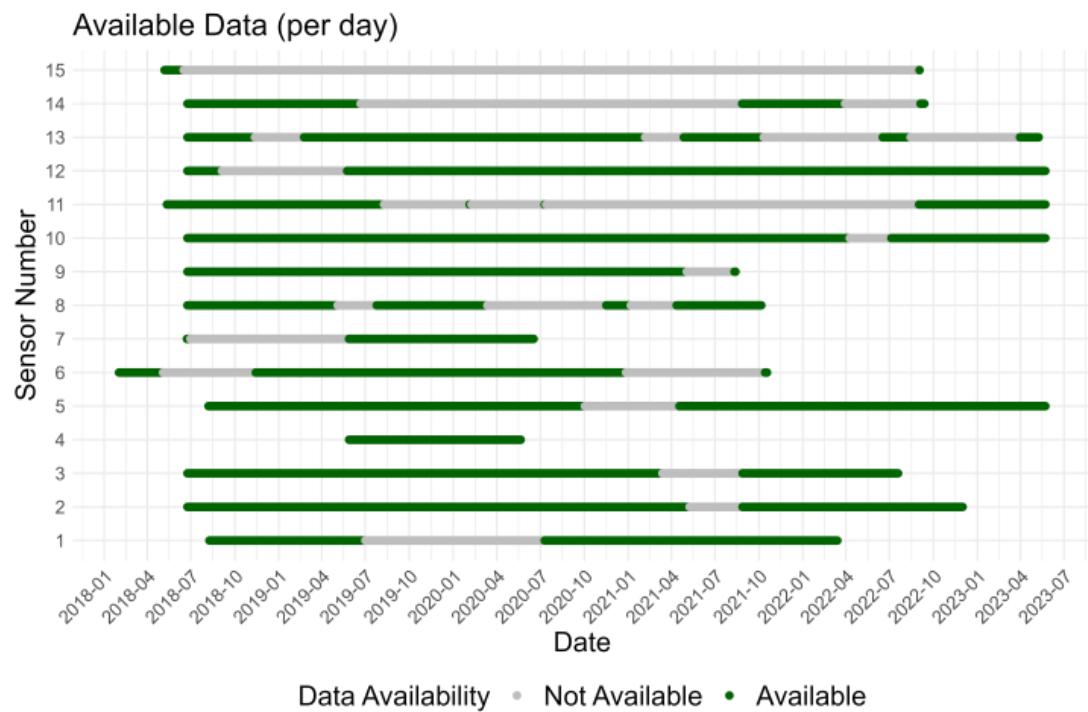
	Possibility 1	Possibility 2	Possibility 3	Possibility 4
Sensor Works?	no	no	yes	yes
Calls Data?	yes	no	yes	no
Impossible/Erroneous		Normal	Normal	Normal (Worth Exploring)



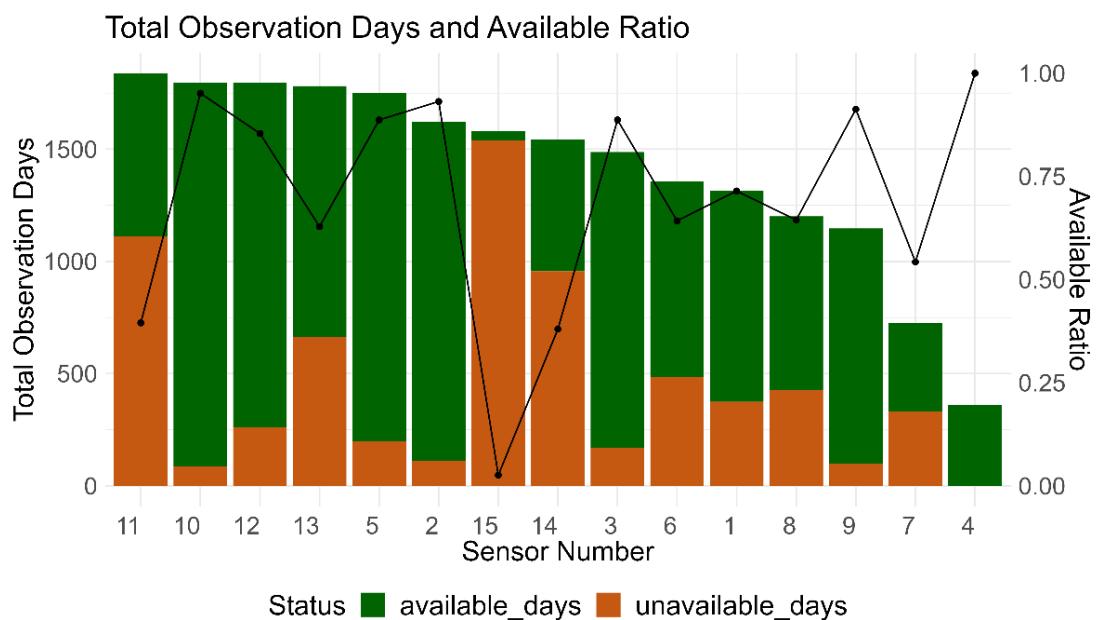
**Figure 3.3.2 Comparison for Possibility 2 and Possibility 4. Source: Author**

Based on the threshold, periods with missing data for fewer than 75 consecutive days are marked as '0' for no bat activity, while periods exceeding 75 days are marked as data unavailable due to mechanical failures. Eventually, available

data is out (Figure 3.3.3). Results show that sensor 11 has the maximum observation time while sensor 5 has the maximum available time (Figure 3.3.4).

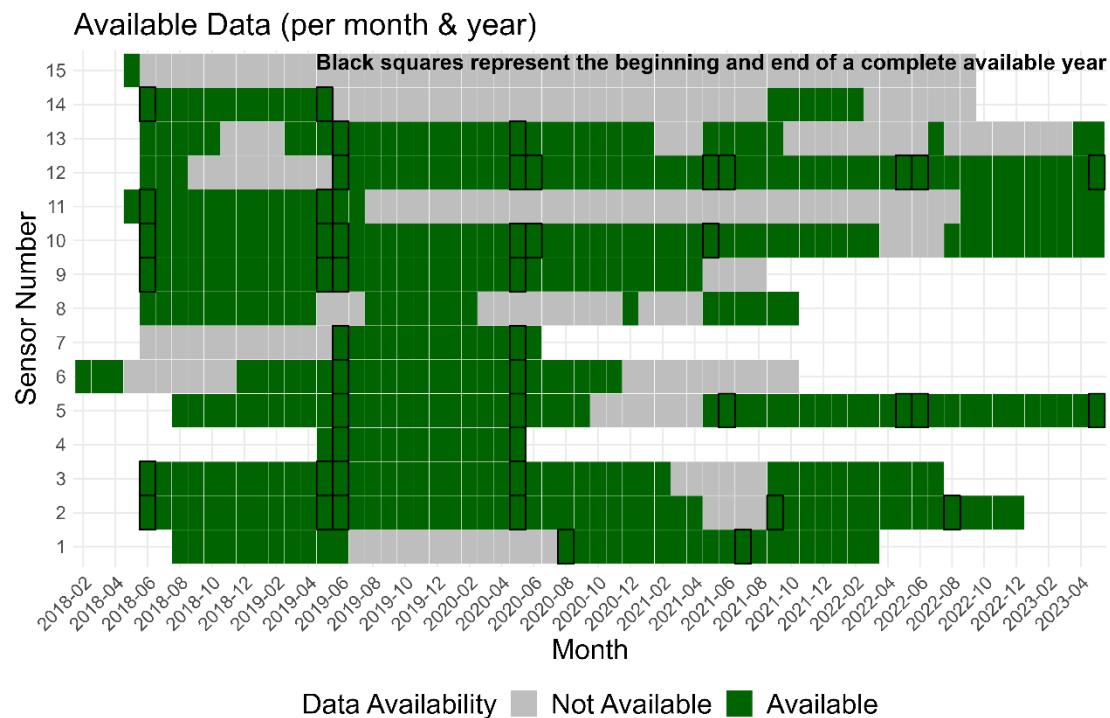


**Figure 3.3.3 Available Data by Days. Source: Author**



**Figure 3.3.4 Total Observation Days and Available Ratio. Source: Author**

If all the days in a month are available, that month is considered an “available month”, and if every month in a year is available, then that year is considered as “available year”. The available data measured in months and years is shown in Figure 3.3.5, where each tile represents a month, and the black boxes indicate the beginning and end of an available year. This kind of data will be useful for the following analysis.

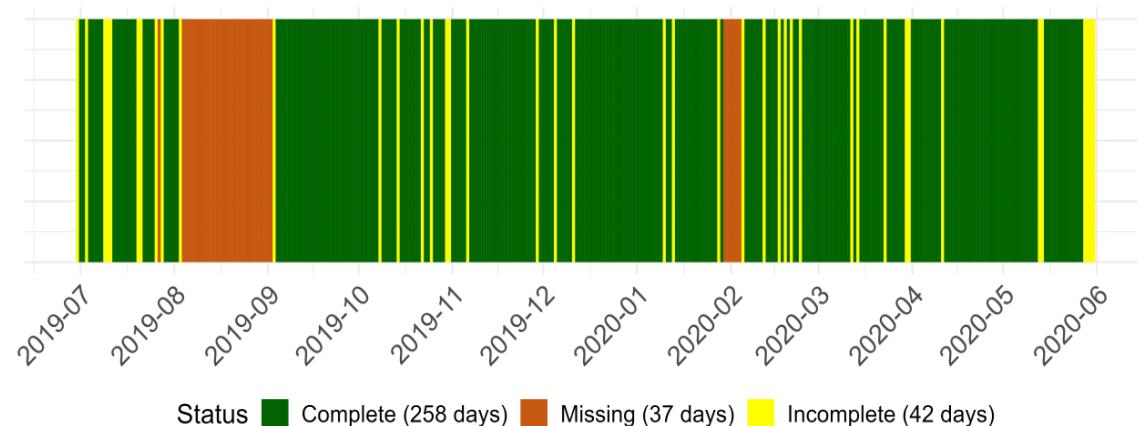


**Figure 3.3.5 Available Data by Months and Years. Source: Author**

### 3.3.2 Weather Data

A weather station (Lat: 51.547607, Lon: -0.014883) is installed in Queen Elizabeth Olympic Park to monitor meteorological data. Recording is in every 5 minutes using UTC (Coordinated Universal Time) rules, data of one single day is stored as one dataset in json format. Due to machine failure, there are large amounts of missing data. The relatively complete period is 1 July 2019 to 1 June 2020, which is chosen for exploration. Recording every five minutes should

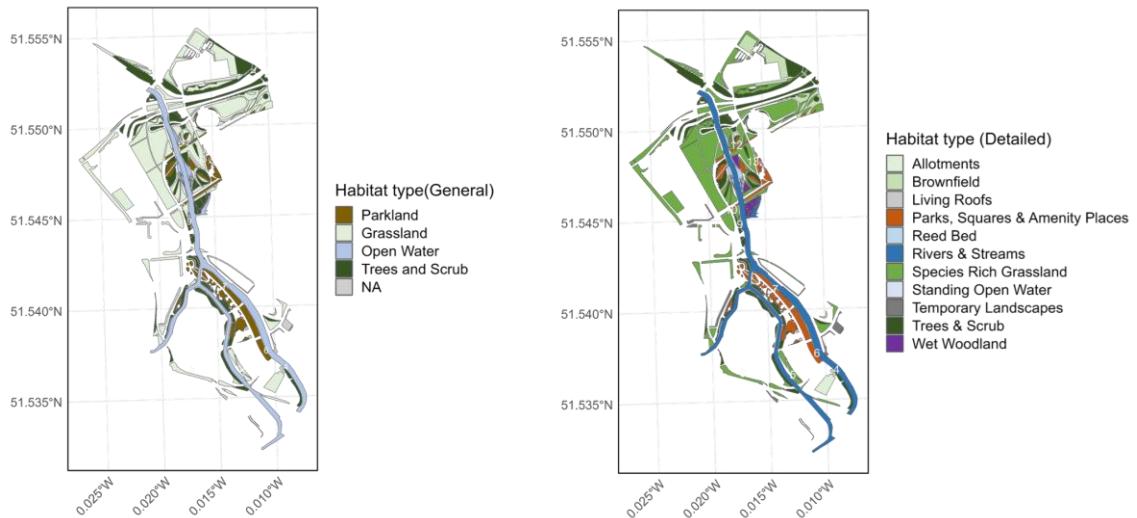
yield 12 records per hour, resulting in 288 data points for a full day. Three states are identified in all data: complete ( $n = 288$ ), incomplete ( $0 < n < 288$ ) and missing (no data recorded due to system error), corresponding to 258, 42 and 37 days, respectively. Therefore, 258 days are selected for GLMM modelling in section 4.3.



**Figure 3.3.6 Status of Weather Data. Source: Author**

### 3.3.3 Geographical Data on Habitats and Sensors

Data of habitats and sensors are provided by project members. There are up to 10 types of habitats within Queen Elizabeth Olympic Park, with a total of 4 types in this study area, which are parkland, grassland, open water area and trees area. More details about habitats are shown in the left figure. Distribution of sensors are shown in section 3.1, all sensors are deployed randomly based on Random Sampling Method, aiming at enabling each sensor to capture the characteristics of different habitat area without interference. In section 4.2, the analysis will focus on differences in activity levels across the four habitats, and the habitat selection by bats. Four general types will be used and the detail will as a supplementary. The specific coordinates of each sensor are obtained from Google Map <https://maps.google.com>.



**Figure 3.3.7 Habitat Types within Study Area.** The habitat classification on the left figure is used in section 4.2, and the details in the right figure is primarily to help understand and interpret the results. Source: Adapted from Gallacher et al. (2021)

### 3.3.4 Data on Events, Sunset, Sunrise

The confidential event data details the timing, description, location, and participant count for events in the park from 2017 to 2020, which is provided by park operators. Given that events too distant from the monitoring site might not impact bats in the study area, 78 out of over 200 events are deemed relevant. Time of sunset and sunrise is collected from a publicly available astronomical calendar website [In-The-Sky.org](https://www.in-the-sky.org), which is also based on UTC time.

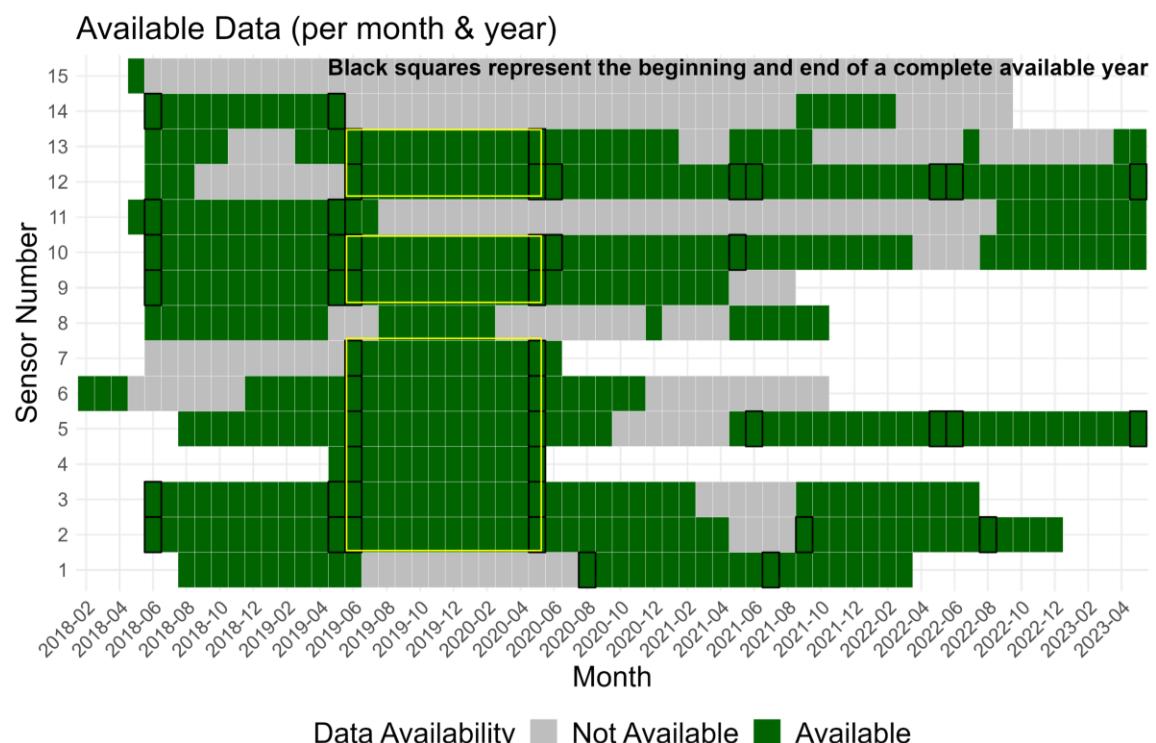
## 3.4 Analytical Stages and Methods

For analysis, datasets with more available sensors and longer continuous periods are preferable. Summarising the available data obtained in section 3.3.1 into Table 3.3.2, it can be observed that period of Jun, 2019 - May, 2020 has the maximum available sensors and sensor 12 has the maximum available years.

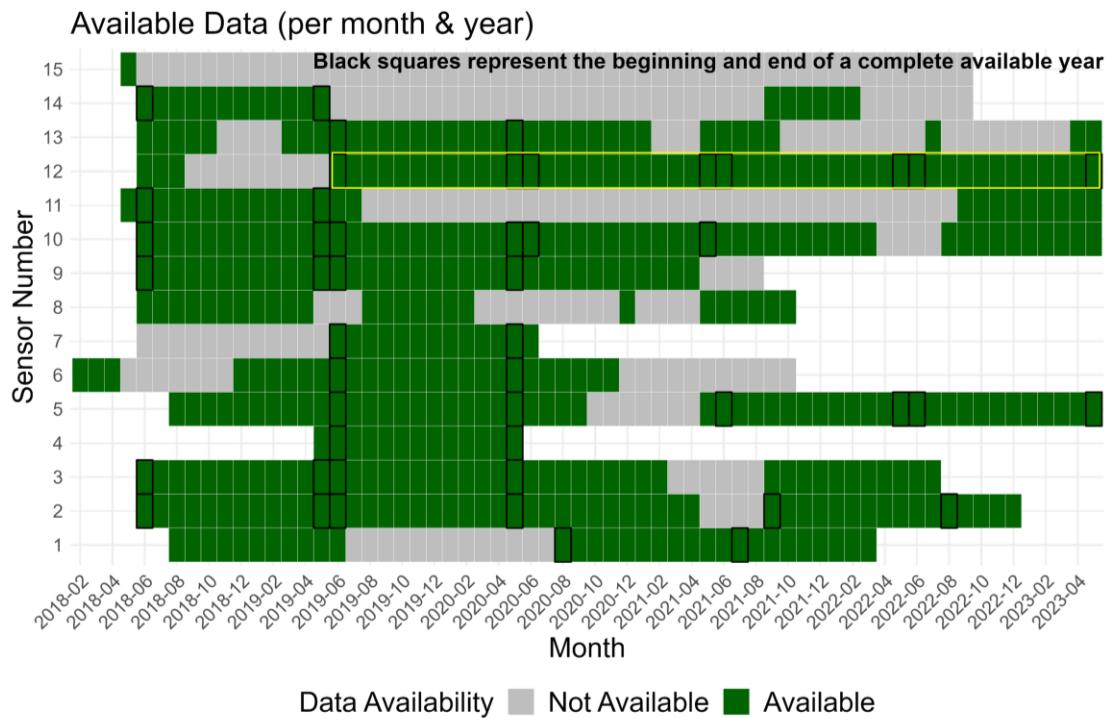
**Table 3.4.1 Summary of Available Data. Source: Author**

	Sensor Number	Total (n)
Jun, 2018 - May, 2019	2 3 9 10 11 14	6
Jun, 2019 - May, 2020	2 3 4 5 6 7 9 10 <u>12</u> 13	10
Jun, 2020 - May, 2021	10 <u>12</u>	2
Jun, 2021 - May, 2022	5 <u>12</u>	2
Jun, 2022 - May, 2023	5 <u>12</u>	2

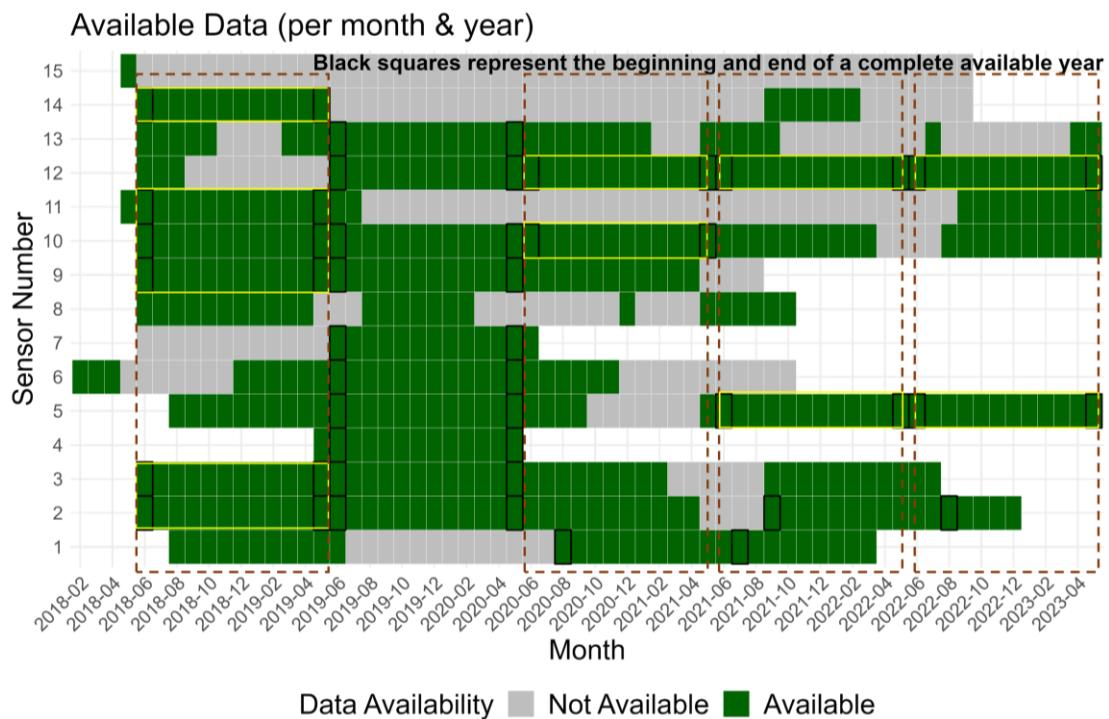
Given the highest availability of both event and weather data between 2019 and 2020, this time frame and its corresponding 10 sensors are chosen as the primary dataset (Dataset A) for this study. Considering the necessity of studying annual variation, sensor 12 with the longest continuous available year is used as the first auxiliary dataset to explore bat trends over a 4-year period (Dataset B). Other fragmented available years are used as another auxiliary dataset to explore yearly comparisons (Dataset C).



**a. Dataset A (primary). Used in all sections.**



**b. Dataset B (auxiliary). Only used in section 4.1.1.**



**c. Dataset C (auxiliary). Only used in section 4.1.2**

**Figure 3.4.1 Three Datasets for Analysis. Source: Author**

### **3.4.1 Temporal Patterns**

As an initial step, this section displays the basic activity patterns of bats, including yearly, monthly, and daily patterns sequentially, aiming to provide a comprehensive insight. Dataset used in this section is various, for which dataset B for section 4.1.1, dataset A and C for section 4.1.2, dataset A for section 4.1.3.

The section begins with an overview of bat activity and bat abundance in the study area, an identifies the primary species to be focused on in subsequent research. Section 4.1.1 firstly exploring yearly changes over 5-year period (Jun, 2019 – May, 2023). Due to the potential for seasonal patterns changing, a multiplicative model is chosen to decompose the bat call data instead of additive model. Then a visualization of species is examined the changes in diversity. Section 4.1.2 starts by utilising Dataset A for a single-year exploration of seasonal pattern, given its extensive data which offers the most representative insights. Datasets A and C are later combined to explore the inter-year differences in seasonal patterns. Due to data volume discrepancies across years, percentages are employed. In section 4.1.3. based on the strong correlation between sunrise/sunset times and bat activity summarised in many studies, nightly pattern before and after sunset/sunrise is firstly focused on, with the temporary omission of the middle of the night. By aligning daily call data with sunrise/sunset time, activity levels in the three-hour time slots before and after sunset/sunrise are charted. Entire nightly pattern is then explored through dividing night time (sunset to sunrise) into 10 equal intervals, including single-day and comparison between seasons (Respond to Gap 2). All analyses in section 4.1 includes total and species-specific of *Pipistrellus nathusii*, *Pipistrellus pygmaeus* and *Pipistrellus pipistrellus* (Respond to Gap 5).

### **3.4.2 Site Variance and Spatial Autocorrelation**

This section focuses on the variations in bat activity and bat species across habitats, and whether there is spatial autocorrelation between the deployment points of sensors, which will be explored through a combination of three methods: visualisation, statistical test and spatial examination. Dataset A is selected for this section.

Section 4.2 begins with three statistical tests assessing variations, with habitat data averaged from corresponding sensors. The non-parametric Kruskal-Wallis test is used to compare three habitat data groups, which are independent and non-normally distributed (Kruskal and Wallis, 1952). If results are significant, the Dunn test, a common post-hoc for the Kruskal-Wallis test, is used to pinpoint differing groups Soetewey, 2022). Dunn test pair comparison is conducted for 5 groups: one whole year group and four seasonal groups, and the results are adjusted by Bonferroni correction to avoid Type I error (Banerjee et al., 2009; Sedgwick, 2012). The Chi-square test evaluates relationships between categorical variables (McHugh, 2013). In this context, it is used to determine if there is a statistically significant association between bat species and habitat type, with a log-transformed bar plot illustrating the differences. All tests are conducted at a significance alpha level of 0.05. In the second part of section 4.2, the Moran's Index will be employed to determine whether there is spatial autocorrelation among the 10 sensor deployment sites, total call sequences will be used as measured values.

In general, this section presents a combination of visual and statistical methods of exploration. Although visualizations appear to show differences, statistical tests provide a more specialised and quantitative way of removing the effects of chance variation. Therefore, adopting the approach of "visual exploration + statistical validation" is meaningful.

### **3.4.3 Impact of Weather and Human Activity on Bats**

Section 4.3 refer to two-step modelling approach conducted by Nix et al. (2018). Considering that weather has the most significant impact on bat activity, the weather-related base model is first developed in section 4.3.1. Generalized linear mixed model (GLMM) is employed for modelling, given their advantages mentioned in literature review (section 2.4). In this case, sensors are treated as random variables (Absence of spatial autocorrelation has been confirmed in section 4.2.2). Bat activity and weather conditions can vary considerably within half an hour, in order to capture the relationship between them more accurately, half-hourly scale is taken for modelling (Respond to Gap 3). The time range is bounded by sunset, taking two hours before sunset and eight hours after sunset, so there are up to 20 intervals in a day. Based on this analytical idea, Dataset A, weather data and sunset data are processed to for modelling. The process of weather variable selection and standardisation is then carried out, the final variables are shown in Table 3.4.2. Before modelling, using Akaike Information Criterion (AIC) to examine and rank the 43 candidate models, including both models that consider interactions and those that do not. The model with smallest AIC value is considered as the top model, which is ultimately modelled at a confidence level of 95% ( $\alpha = 0.05$ ), using negative binomial family.

In section 4.3.2, events and weekends are considered (Respond to Gap 4). Adding activity data and weekend into base model of section 4.3., resulting in three extended models. Using AIC to test the new models and compare AIC value with base model. A decrease in the AIC value signifies an improvement in the quality of the expanded model, thereby providing additional evidence that human activity indeed exerts an influence on bat populations, and vice versa indicates impact is not significant. Both sections modelled the total activity and each of the three species of bats, so basically there are 4 base models and 12

extended models.

**Table 3.4.2 Variables for Generalized Linear Mixed Models. Source: Author**

No.	Variable Types	Data Type	Variable Name	Description
1			All_Calls_Volume	Total Bat Calls Count.
2	Response variable	Continuous	V_Pipistrellus_nathusii	Pipistrellus Nathusii Bat Calls Count.
3			V_Pipistrellus_pipistrellus	Pipistrellus Pipistrellus Bat Calls Count.
4			V_Pipistrellus_pygmaeus	Pipistrellus Pygmaeus Bat Calls Count.
5	Random Variables	Categorical	sensor_number	Sensors in different positions.
6		Categorical	hour_sunset	Time intervals relative to sunset, ranging from two hours prior to sunset to eight hours post-sunset, divided into half-hour increments, resulting in up to 20 units per day (one unit is half hour).
7			Humidity	Highest humidity levels during one unit observation period, expressed as percentages.
8			Temperature	Lowest temperatures during one unit observation period, expressed in degrees Celsius
9			Windspeed	Average wind speeds during one unit observation period, expressed in kilometers per hour.
10			Windgust	Lowest wind gust speeds one unit observation period, expressed in kilometers per hour.
11	Predictor Variables		Dew_point	The average temperature at which air must be cooled to become saturated with water vapor during one unit observation period.
12		Continuous	Wind_chill	The perceived decrease in air temperature felt by the body due to the flow of air.
13			Heat_index	What the temperature feels like to the human body when relative humidity is combined with the air temperature.
14			Pressure	Lowest atmospheric pressures during one unit observation period.
15			Pressure_Trend	The trend in atmosphere pressure changes.
16			Precipitation_rate	The amount of rain falling over one unit observation period, expressed in millimeters per hour.
17			Precipitation_total	Total amount of precipitation during one unite observation period, expressed in millimeters

### 3.5 Limitations

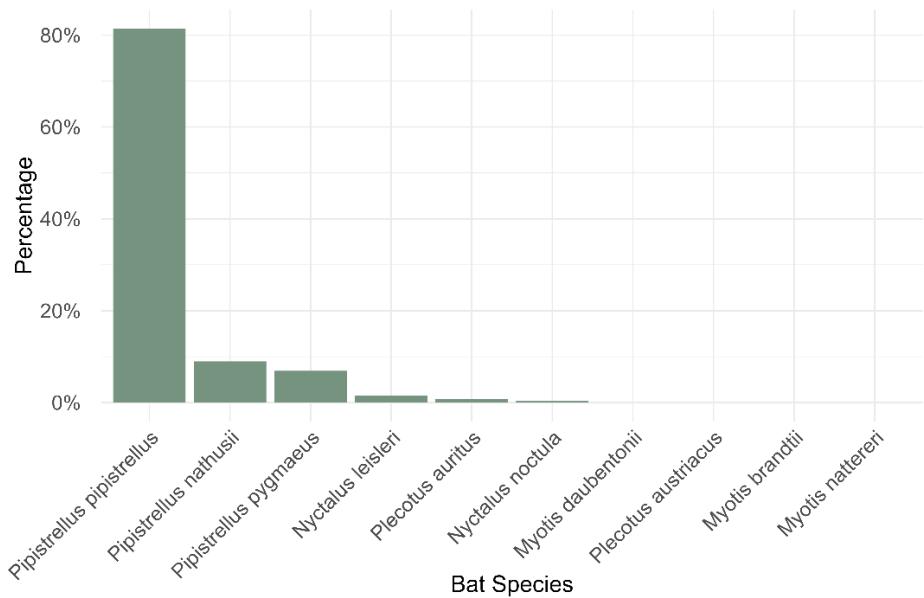
There are two main limitations of this study. Firstly, although a complete exploration is conducted, the large amount of missing monitoring data somewhat affects the accuracy and comprehensiveness. For example, when comparing seasonal patterns between years, proportions are the only method viable for comparison due to the varying available sensors each year. Secondly, using only acoustic monitoring method is unable to explore subtle changes within bat populations, which presents limitations in interpreting monitoring results.

# Chapter 4 Result and Discussion

This chapter presents the analysis results mentioned in Chapter 3 and delves into a detailed discussion. The content covers three main themes: temporal patterns, site variation, and influencing factors. At last, a summary is provided.

## 4.1 Temporal Patterns

From February 2018 to June 2023, 3,144,528 bat call sequences were recorded, revealing the presence of ten distinct bat species. The most prevalent is *Pipistrellus pipistrellus*, followed closely by *Pipistrellus nathusii* and *Pipistrellus pygmaeus*. These three species combined made up over 90% of the total observations, signifying their dominance in the bat population of this area (Figure 4.0.1). In this section, analyses of temporal patterns are systematically conducted across three scales: yearly, monthly, and daily (nightly), species-specific studies will also be conducted on the top three species.

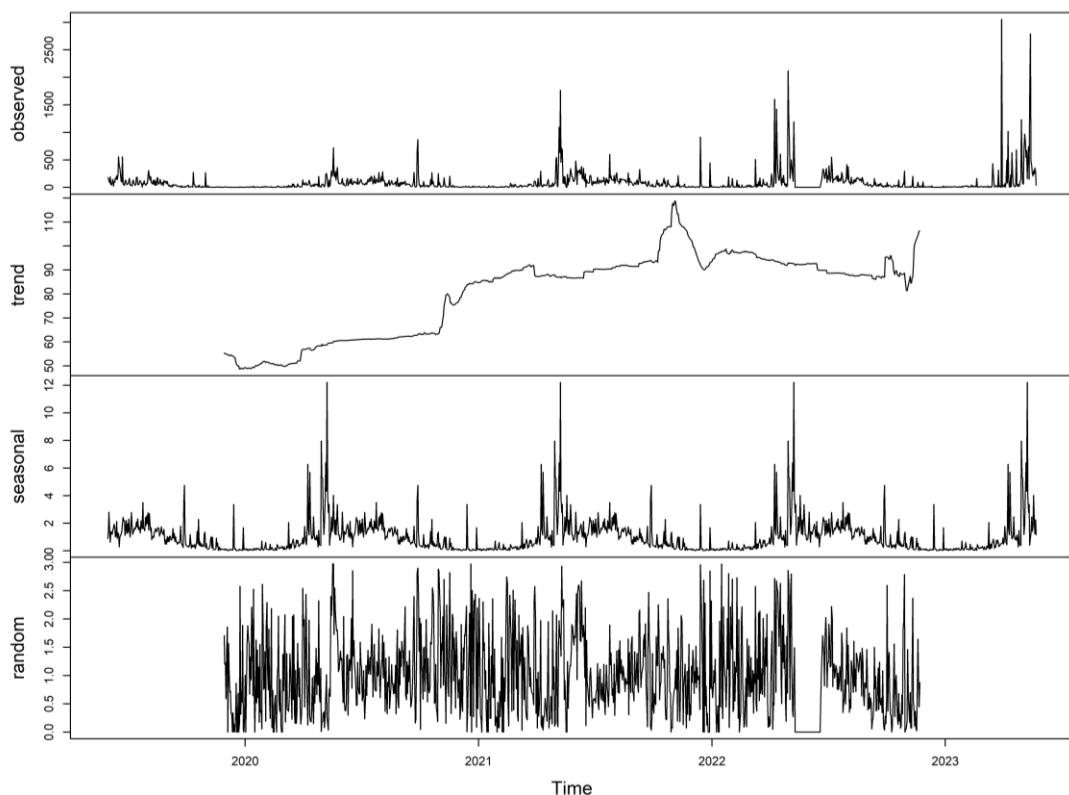


**Figure 4.0.1 Observed Ten Bat Species (Percentage of Total).** Source: Author

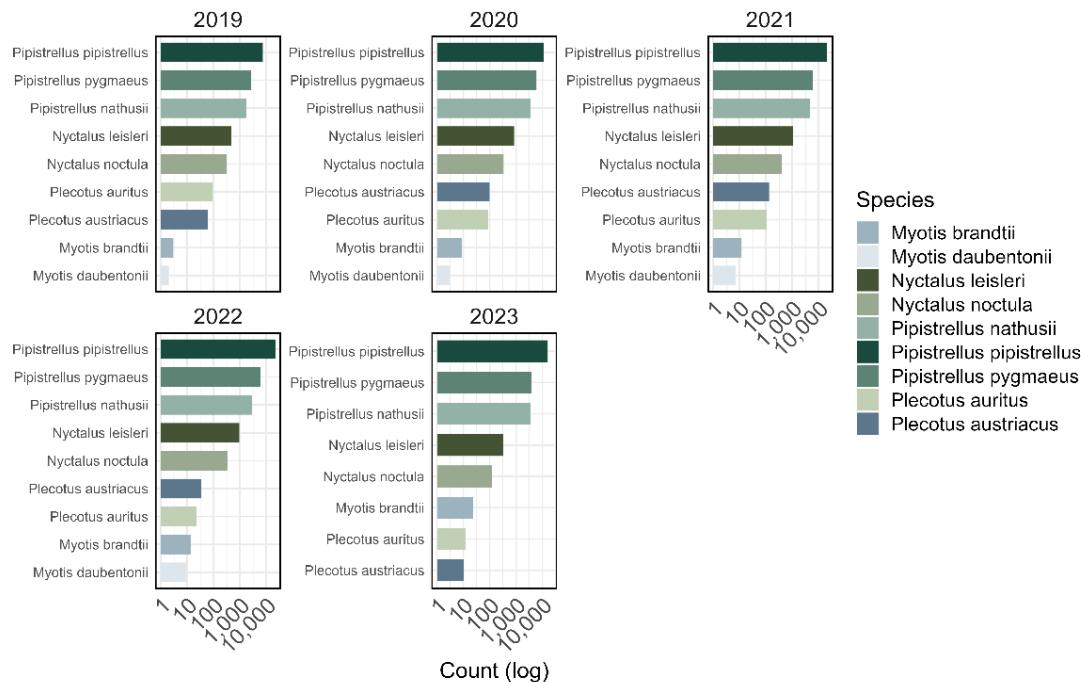
#### **4.1.1 Yearly Change**

Applying time series decomposition to bat call sequences from June 2019 to May 2023. The 'observed' plot in Figure 4.1.1 initially indicates a consistent bat activity level over the five years, accompanied by annual rising peaks. This observation is further supported by 'trend' plot, which reveals a notable increase from 2020 to 2022 and a stable pattern thereafter. The 'seasonal' plot shows a clear annual cycle and the randomness of the 'random' plot (residual plot) indicates a good fit. Overall, bat activity levels in sensor 12 have remained stable over the five-year period with some upward trends, suggesting that this area provides good roosting conditions for bats. Further exploration of richness is conducted (Figure 4.1.2). Sensor 12 recorded 9 out of a total of 10 species, most species maintained a stable population, indicating a positive state of bat diversity. However, *M. daubentoniiid* was not detected in 2023, which might show a sign of negative things.

The consistent activity and biodiversity in Queen Elizabeth Olympic Park suggest it is an ideal urban habitat for bats. Queen Elizabeth Olympic Park published its first Biodiversity Action Plan (BAP) back in 2018, and updates it every five years (Queen Elizabeth Olympic Park, 2019). Under this guidance, the park already has more than 10 types of habitats including rivers, wetlands, grasslands etc., providing a favorable environment for various animals. This empirical result proves the success of targeted ecological interventions, highlighting the potential for strategic measures to reconcile urban development with nature conservation (Berthinussen, Richardson and Altringham, 2014).



**Figure 4.1.1 Decomposition of Multiplicative Time Series (Sensor 12). Stochastic “random plot” indicates a good model fit. Source: Author**



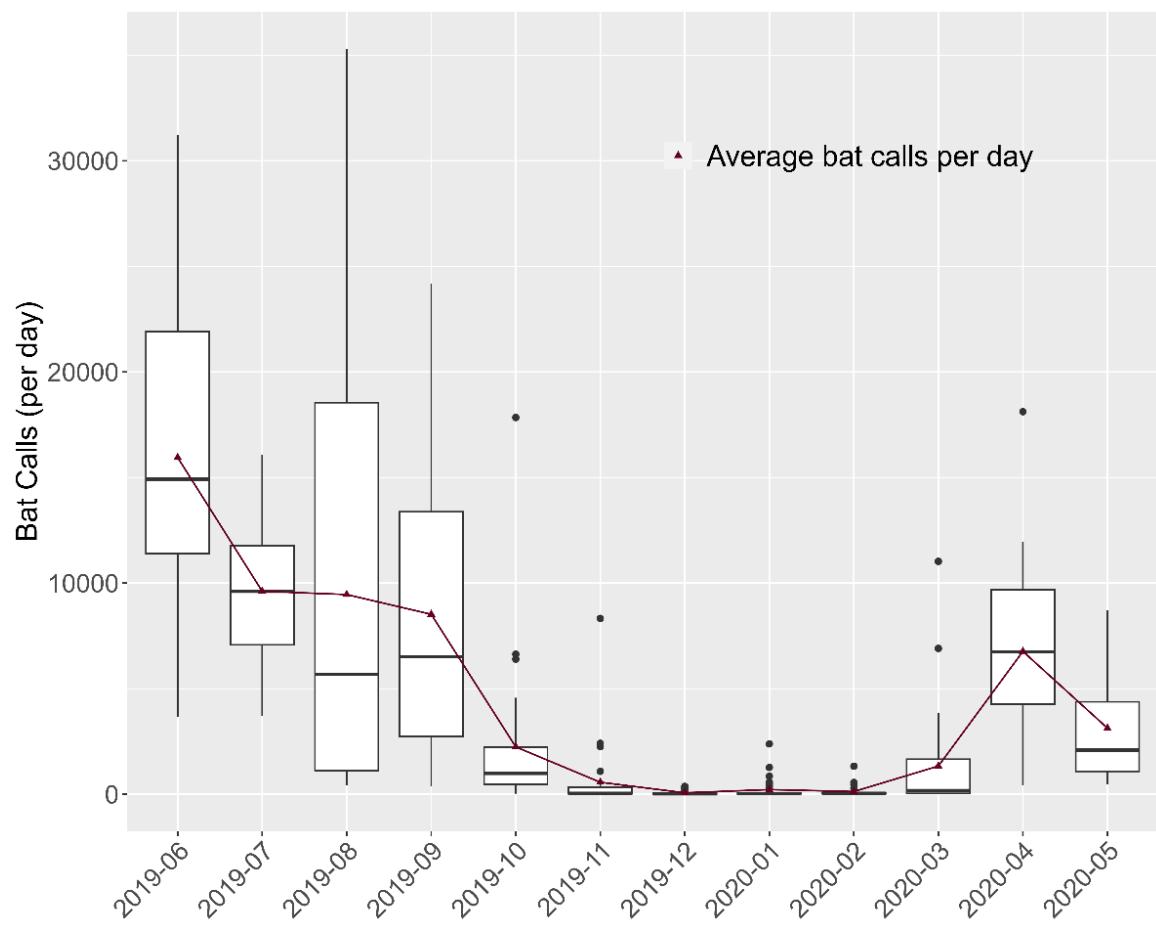
**Figure 4.1.2 Yearly Changes of Bat Richness (Sensor 12). Source: Author**

#### **4.1.2 Seasonal Pattern**

One complete one-year period is first used to in-depth explore, which is June 2019 to May 2020 with the most available sensors (n=10). Figure 4.1.3 depicts the seasonal pattern for all three species. During winter, all insectivorous bats hibernate in hibernacula, total activity levels are very low, but bat calls can still be recorded at some moments, suggesting the presence of winter foraging behaviou. The increase beginning in March marks the end of hibernation and onset of fertilization. Bat activity reaches a first small peak in April and then declines, potentially due to energy recovery from hibernation or increased energy demand because of fertilisation. After pregnancy, female bats give birth in June and the high energy demands of lactation prompt foraging activity, leading to another peak. Bat activity then declines noticeably until winter, but there is a slowdown and even a subtle peak in August and September, which is a sign of mating behaviour in autumn. In general, the seasonal pattern observed in this area coincides with the breeding pattern of bats and most of the literature descriptions. However, the observed peak appears about a month earlier than in most studies, possibly due to the annual climatic differences (Swift, 1980; Maier, 1992; Russ et al., 2003). And only a portion of studies mention an April peak, presumably related to region and bat species (Ciechanowski et al., 2010; Gaisler et al., 1998; Montoya-Aiona et al., 2019).

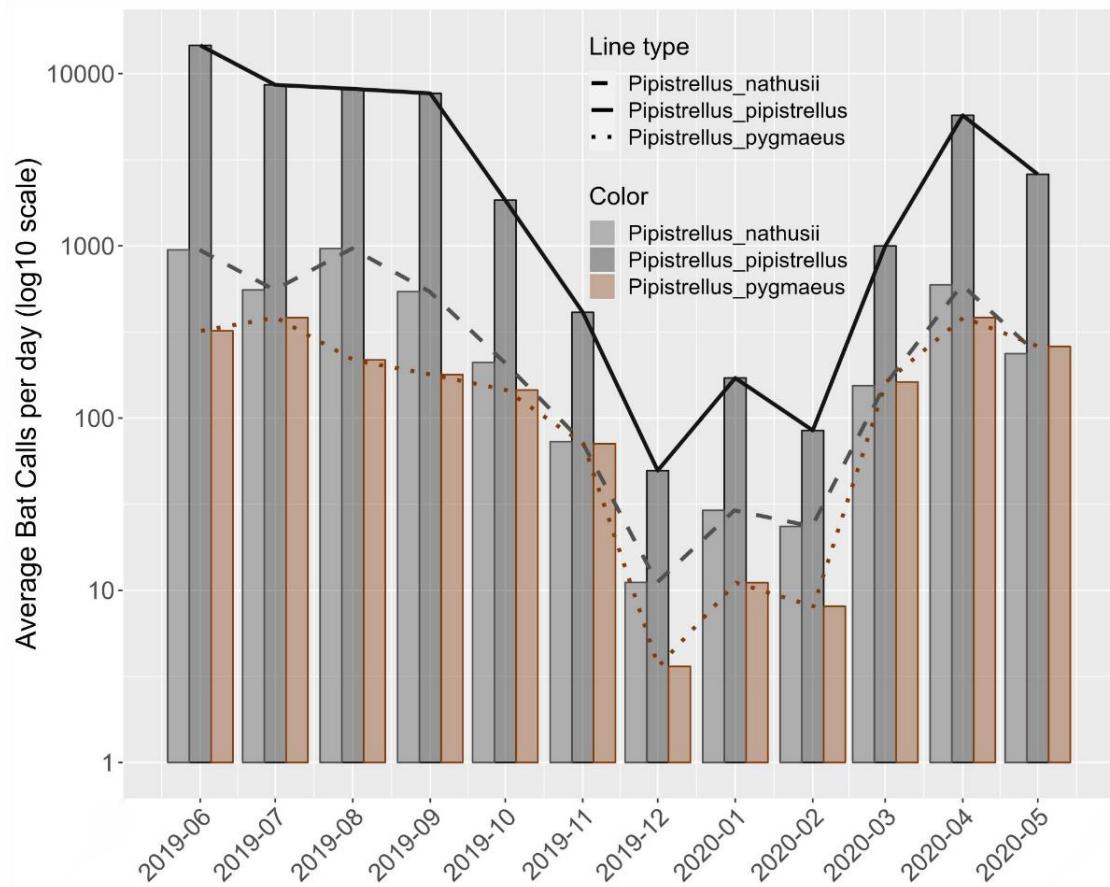
Results depicted in Firgure 4.1.4 presents the seasonal patterns of *P. nathusii*, *P. pipistrellus* and *P. pygmaeus*. Patterns of three species are generally similar, which show the same hibernation recovery time, a small peak in April and the lowest activity level in December. However, differences are observed on peak occurrence during summer, with *P. pipistrellus*, *P. pygmaeus* and *P. nathusii* occurring in June, July, August respectively. This has been reasonably hypothesised to be a difference in gestation period between species, but there is no experimental confirmation of this. Compared to *P. nathusii*, *P. pygmaeus*

and *P. pipistrellus* have a higher degree of similarity in seasonal patterns, which demonstrates that activity patterns are often similar between neighboring species (Barlow, Jones and Barratt, 1997). Winter activity is also seen in all species, and a small peak that occurs around January is surprisingly discovered. This kind of peak has barely been observed, which is most likely related to the hottest winter ever recorded in UK in 2019, with temperatures reaching 21.2 degrees Celsius (Mohdin, 2019).



**Figure 4.1.3 Seasonal Pattern of Total Bat Activities (Jun, 2019 – May, 2020).**

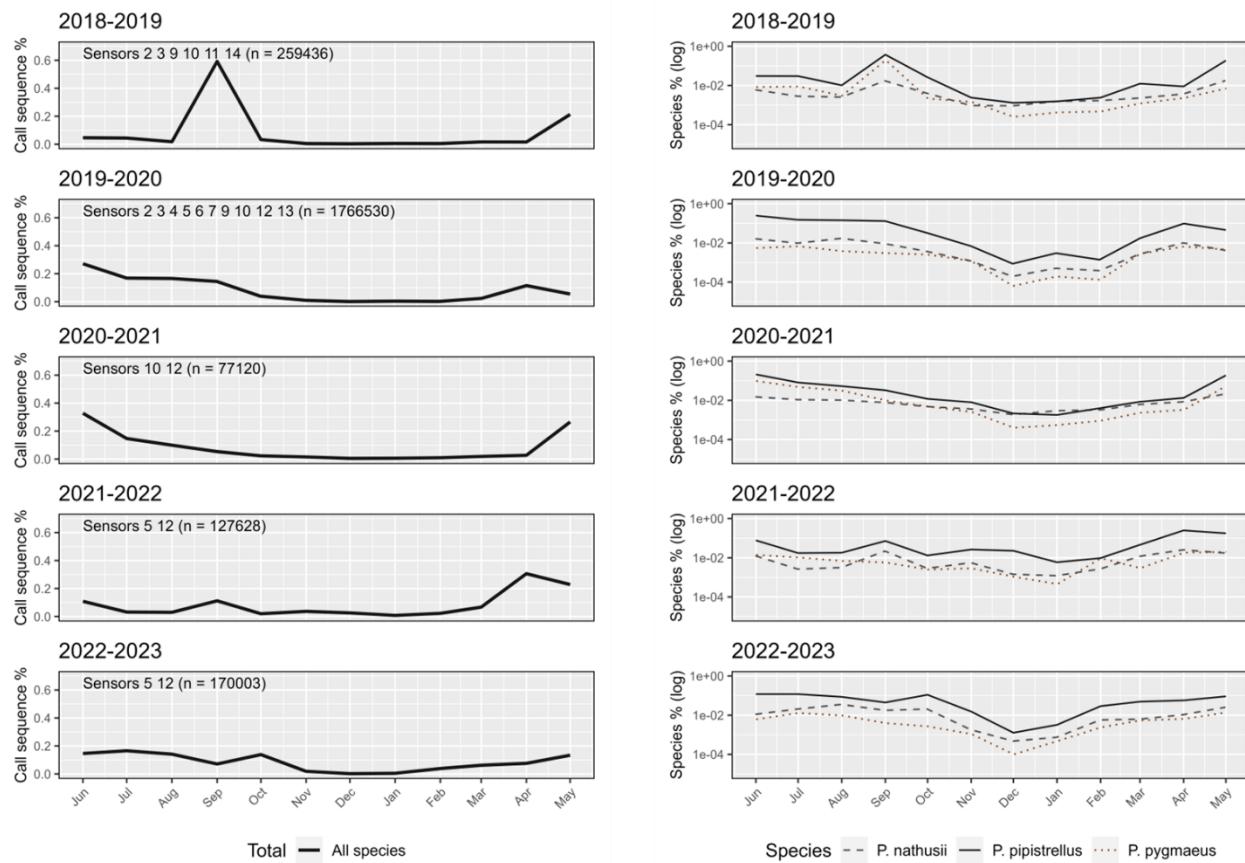
**Source: Author**



**Figure 4.1.4 Seasonal Pattern of Species-specific Bat Activities. Source: Author**

Seasonal patterns among years are further explored. Due to the varying number of sensors available each year, only using the percentage of total call sequences for each year to compare trends, rather than actual values. Overall pattern is explored firstly (Figure 4.1.5.a), there are observable differences in seasonal patterns across years, with 2018-2019 being extremely anomalous. Most of highest peaks occur between June and August, but unexpectedly occur in spring between 2021-2022. Autumn mating patterns are clearly observed in some years (2021-2022, 2022-2023), but some are almost impossible to detect (2019-2020, 2020-2021). Bat activity in April is very irregular, with peaks in some years and "valleys" in others. The reason of extremely high peak between 2018-2019 perhaps due to the continuous abnormally high temperatures during summer months in 2018, which tied as the hottest summer since records began in 1910 (BBC News, 2022; Press Office, 2018). This suggests that extreme

weather may have unanticipated impacts on bats. Figure 4.1.5.b provides insight for three species. The pattern can be summarised as follows: the seasonal patterns of different species are similar in the same years, while in different years even the same species show significant differences. Overall, comparisons of years show that external factors have a much greater influence on bats than interspecific effects. All species are greatly affected when there are extremes in weather or other environmental factors, which evidences the sensitivity of bats to climate change and urbanization (Russo and Ancillotto, 2015).



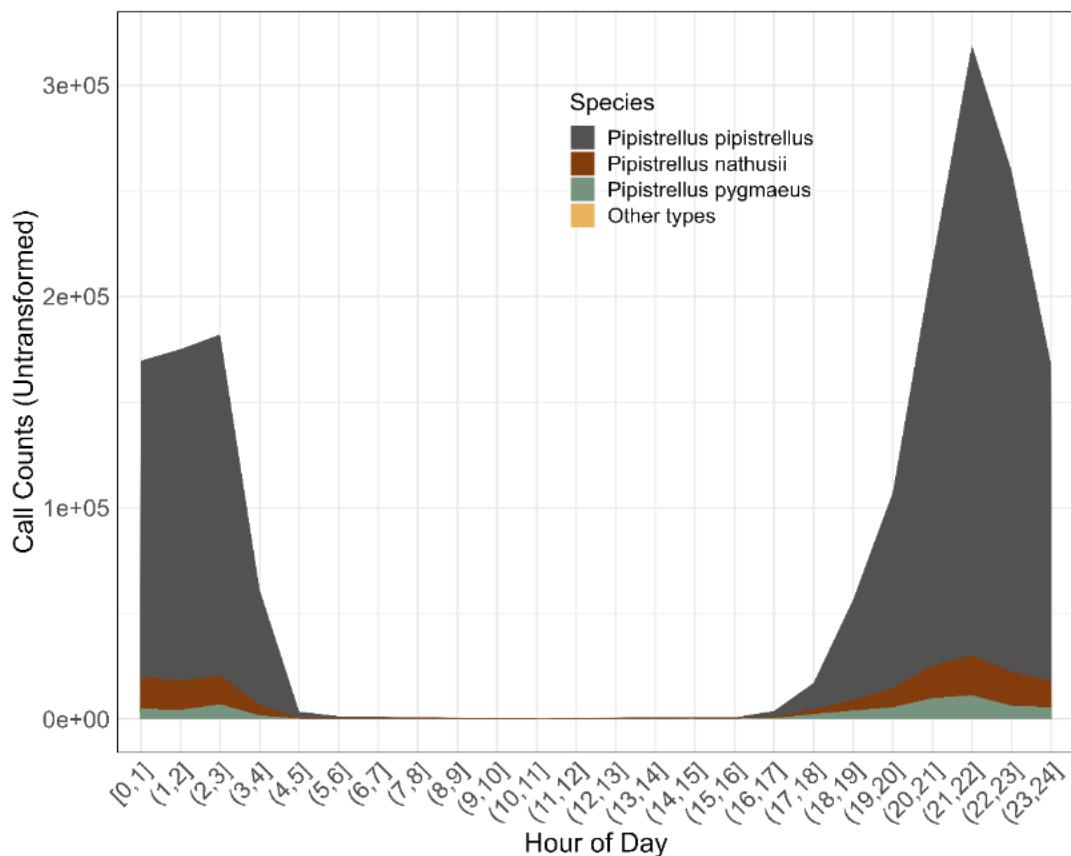
#### 4.1.5.a All Species

#### 4.1.5.b Three Species

**Figure 4.1.5 Seasonal Pattern among Five Years (2018-2023). Source: Author**

#### 4.1.3 Nightly Pattern

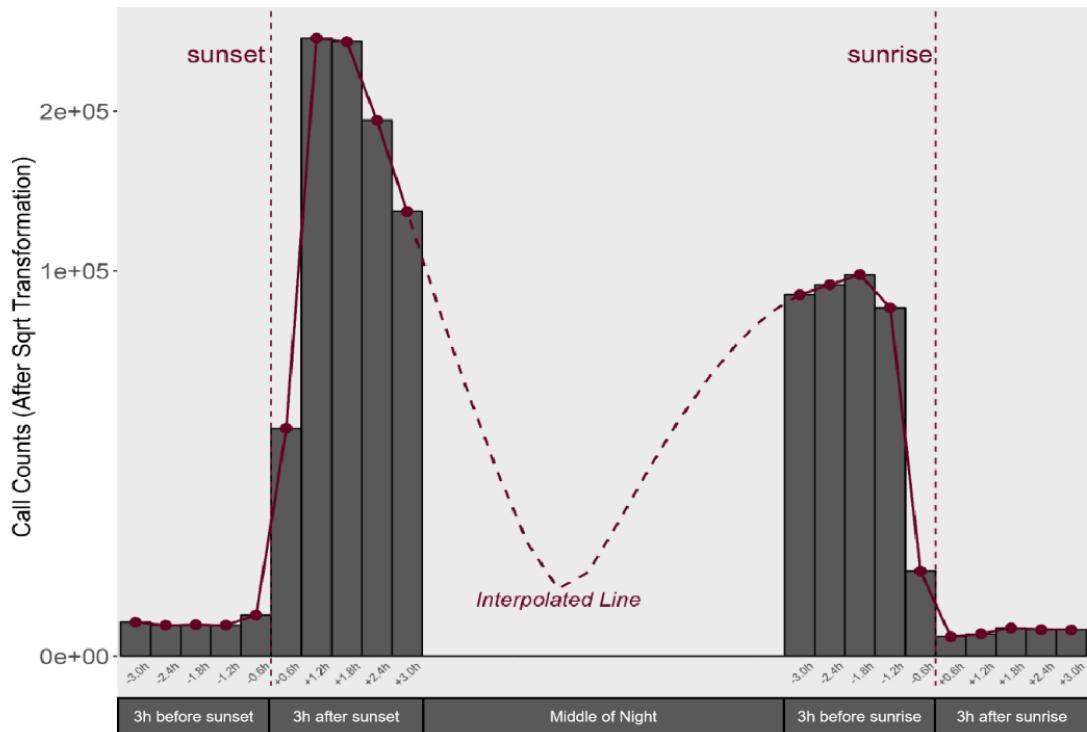
Although the nocturnal nature of insectivorous bats is well-documented in almost all literature, calls distribution throughout the day is undertaken to validate this finding. Figure 4.1.6 shows a significant proportion of bat activity occurs between dusk and 5 a.m., with greater numbers in the first half of the night than in the second. This corroborates the clear nocturnal pattern of bats in this study area. The absence of other types (yellow legend) indicates the small quantity of other species.



**Figure 4.1.6 Distribution of Bat Calls in a Day. Dividing the day in hours into 24 intervals, counting the number of all calls in the corresponding intervals (June 2019 to May 2020). Source: Author**

Many studies have demonstrated the relationship between bat activity and sunset and sunrise (Erkert, 1978; Holland et al., 2011; Hayes, 1997; Bateman

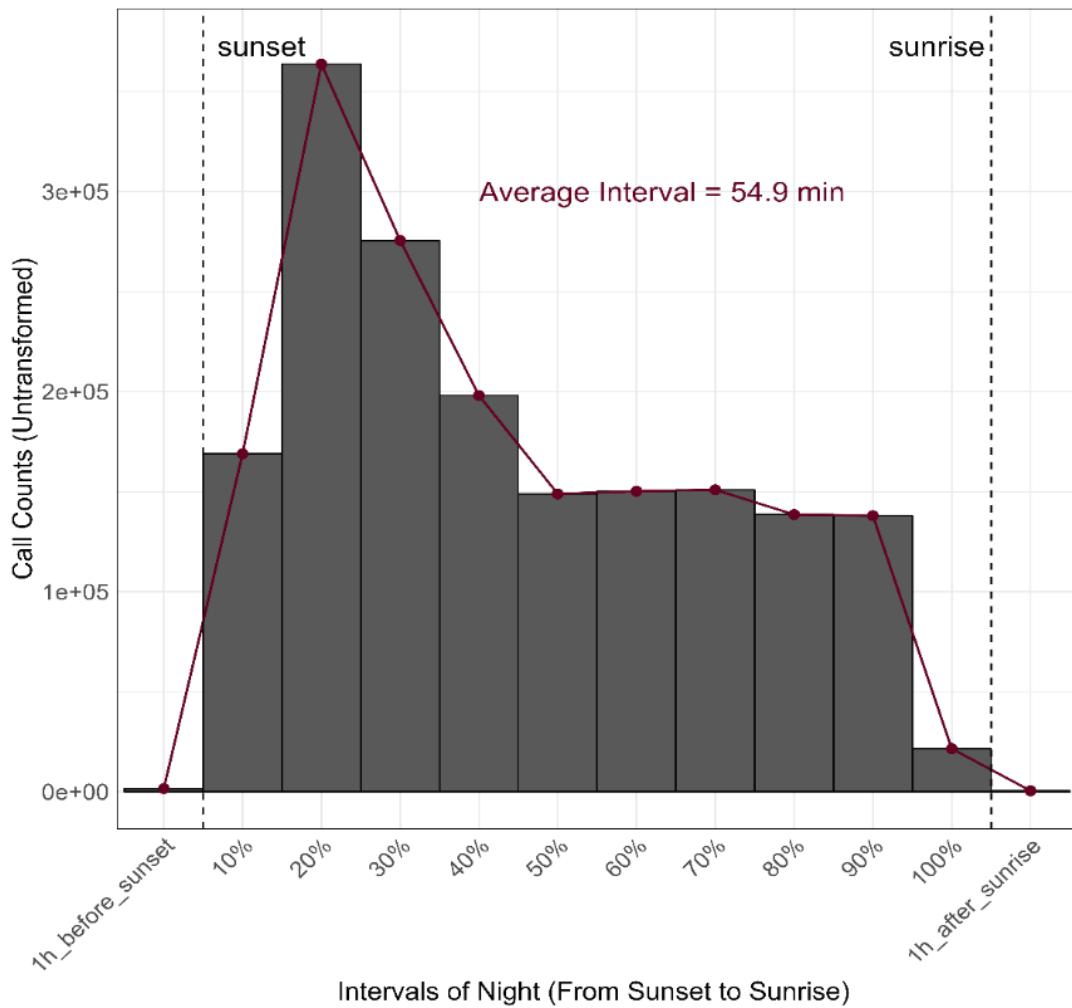
and Vaughan, 1974). Given these findings, the variations in bat activity around sunset and sunrise are initially investigated. Figure 4.1.7 shows a clear relationship with these two timings. Based on the observations, bat activity tends to surge after sunset and wane as sunrise approaches. Patterns around sunrise and sunset exhibit similarities, with both peaking approximately 1.8 hours from the boundary emerging a clear trend 0.6 hours from these times, and stabilizing in a notably low level in the period away from night. Generally, activity around sunset is higher than around sunrise. This trend aligns with the findings of Holland et al. (2011) and Hayes (1997), but the observations here exhibit a more profound and precise correlation with the diurnal transitions, suggesting that bats in this region adhere strictly to the patterns of sunrise and sunset. Peak activity after dusk may indicate predation risk avoidance by small aerial-hawking bats in this area, which the high risk of predation by nocturnal predators prevents them from taking full advantage of the abundance of pre-dusk insects (Jones and Rydell, 1997; Lima and O'Keefe, 2013). Rydell et al. (1996) also suggests that more Canopy cover protection could allow bats to emerge earlier and get more food. The middle of night in Figure 4.1.7 is estimated and populated based on calls of sunrise and sunset using statistical interpolation methods, to verify its veracity, the full nightly pattern is further explored.



**Figure 4.1.7 Bat activity before and after sunrise and sunset. The number of bat call sequences are counted for 3 hours before and after sunrise and sunset, and connected using non-dashed lines. A square root transformation is applied to deal with the significant disparities. (The dashed section in the middle represents a trend estimate obtained by applying spline interpolation, not observed value.) Source: Author**

Figure 4.1.8 refutes the above estimates, with the total nightly activity of bats not showing a strong bimodal pattern, but a gradual decline from sunset to sunrise. Given the finding of extremely low activity levels before sunset and after sunrise in Figure 4.1.7, 1 hour time slots are used. Interval lengths range from 43.8 to 97.2 minutes during the year, with an average of 109.8 minutes, reflecting the temperate climate characteristics in UK. Bat activity is extremely low before sunset and after sunrise, but increases abruptly from the first interval and peaks in the second interval. After 60% of the night time has passed, another small peak occurs, followed by a plateau, and finally rapidly drop before sunrise. This pattern is similar to the two-phase pattern observed in many

studies, but peak in second phase before dawn is less noticeable and more of a leveling off after concentrated foraging (Anthony et al., 1981; Swift, 1980).

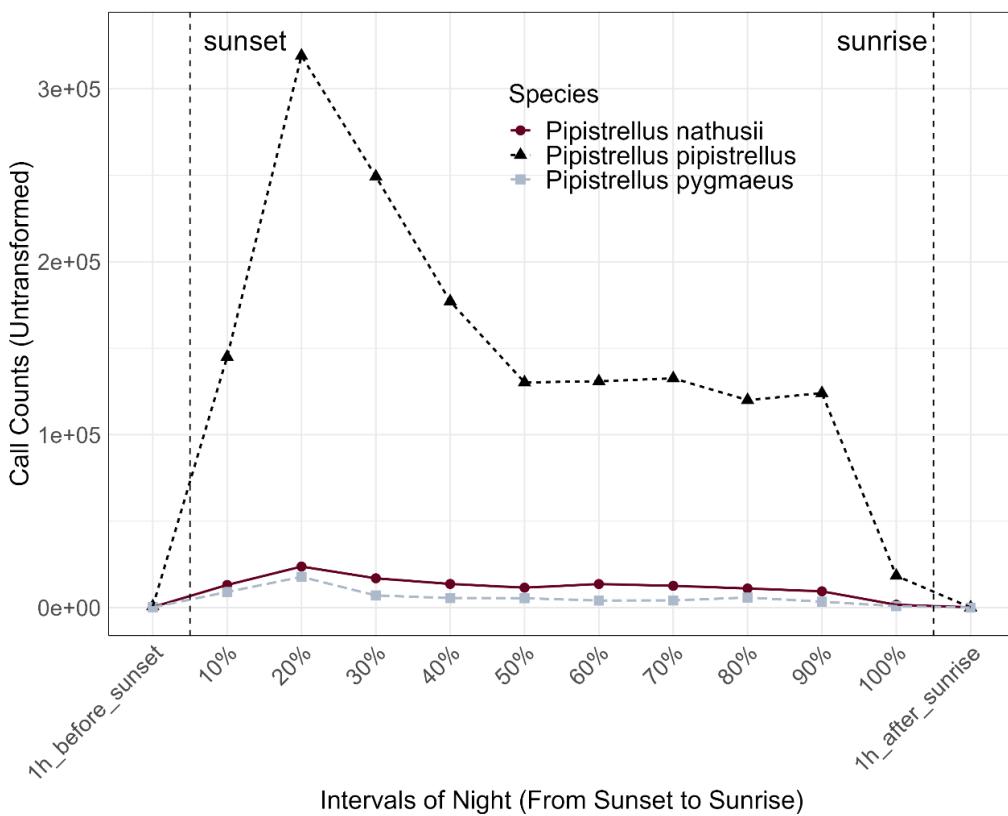


**Figure 4.1.8 Nightly Pattern of Bat Activity.** Nocturnal time is divided into 10 equal intervals to address the issue of circadian lengths varying throughout the year. **Source:** Author

Species exploration shown in Figure 4.1.9 breaks down nightly patterns. Result shows the significant distinction of *P. pipistrellus* from *P. nathusii* and *P. pygmaeus*, which underscores the importance of exploring species separately. The nocturnal pattern of *P. pipistrellus* shows marked fluctuations, with concentrated and rapid emergence and disappearance of populations. In contrast, *P. nathusii* and *P. pygmaeus* tend to stabilise in general. This may indicate that *P. pipistrellus* prefers to forage in groups, with greater interspecific influence and "following behaviour" than the other two species. All three species

reach their peak activity at the point marking 20% of the night, with a less pronounced foraging event near dawn, suggesting that one foraging session a day is sufficient to maintain energy demands for most situations.

However, the strong difference in nightly patterns between *P. pipistrellus* and *P. pygmaeus* is unexpected; two similar species are usually thought to have more similar patterns (as demonstrated in seasonal pattern in section 4.1.2), but the results show that there is even temporally segregated. When *P. pipistrellus* exhibits minor troughs at 50% and 80% time points, *P. pygmaeus* conversely displayed minor peaks. This supports Davidson-Watts and Jones (2005) 's conclusion that *P. pipistrellus* and *P. pygmaeus* often differ in their foraging behaviour, including flight time, frequency and range; and also supports the temporal segregation of these two species in terms of resource allocation, which supposed by Nicholls and A. Racey (2006).

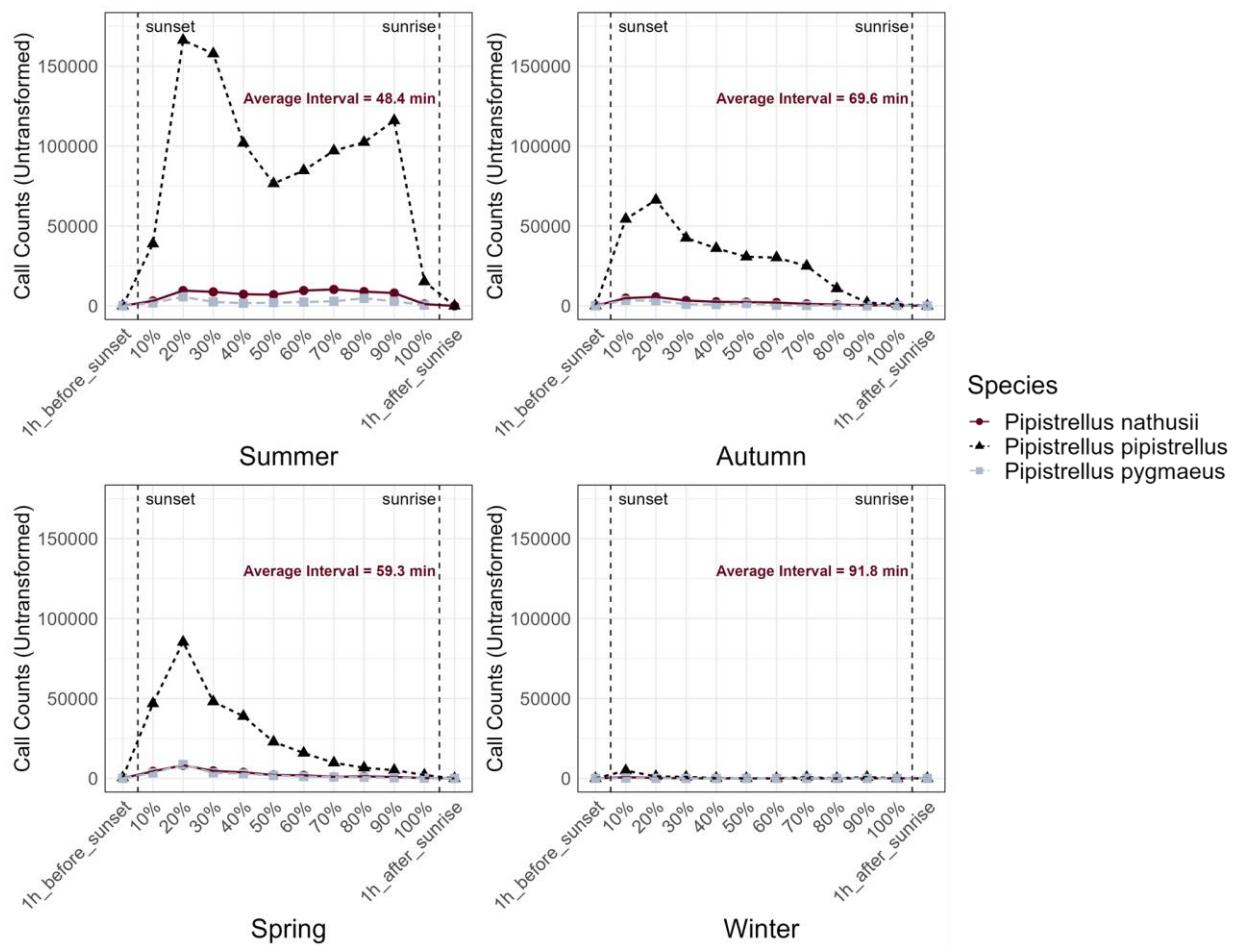


**Figure 4.1.9 Nightly Pattern for Three Species. Using the same method as Figure 4.1.8. Source: Author**

Further exploring variations in nightly patterns between seasons. Average intervals

highlight the UK's seasonal contrasts: over 15 hours of night in winter and about 8 hours in summer. Figure 4.1.10 shows that bats forage at similar times in different seasons, which is still between sunset and sunrise. Nightly patterns of species *P. nathusii* and *P. pygmaeus* remain similar despite in different seasons and almost overlap during autumn and spring, while *P. pygmaeus* and *P. pipistrellus* still show a segregation. Activity level of *P. nathusii* and *P. pygmaeus* is more stable than *P. pipistrellus*, suggesting *P. pipistrellus* is more sensitive to seasonal changes.

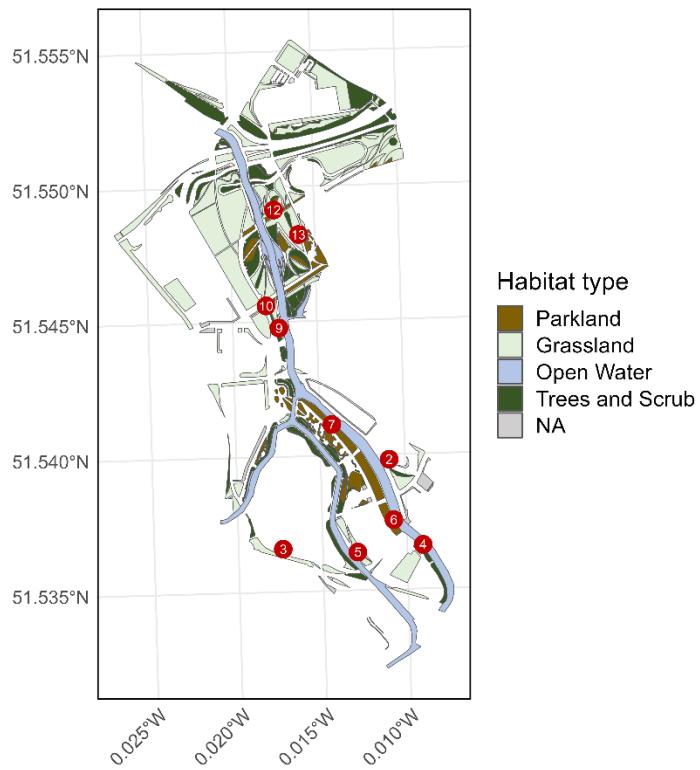
The typical bimodal pattern is observed only in summer and is predominantly found in species *P. pipistrellus* and *P. pygmaeus*, which is similar to findings in other studies (Kunz et al., 1995; Kurta et al., 1989). This observation is a good reflection of reproductive patterns of bats, which bats usually produce and lactate during summer and the enormous energy demands always require female bats to forage twice nightly to sufficiently support their consumption (Anthony and Kunz, 1977; Mclean and Speakman, 1999; Barclay, 1989). Torpor is another potential compensatory mechanism for energy expenditure (Grinevitch et al., 1995; Racey and Speakman, 1987), but the higher activity of three species in spring and summer suggests that this mechanism may not be the first choice for all species during pregnancy, production and lactation. During the non-breeding seasons, the steady activity levels of *P. nathusii* and *P. pygmaeus* suggest they are more likely to use torpor mechanism, but is still not represented on *P. pipistrellus*. These findings related to torpor matches the conclusion of Dzial and Brigham (2013). The small peaks of *P. pipistrellus* in winter indicates foraging activity sometimes occurs during hibernation period.



**Figure 4.1.10 Nightly Pattern among Seasons. Source: Author**

## 4.2 Variance and Spatial Autocorrelation among Sites

Ten sensors are located evenly along the river from north to south in different habitat type. According to the shapefile, photographic record and preceding paper, ten sites are categorised into three habitat types: “Open Water”, “Grassland” and “Trees and Scrub” (Gallacher *et al.*, 2021).

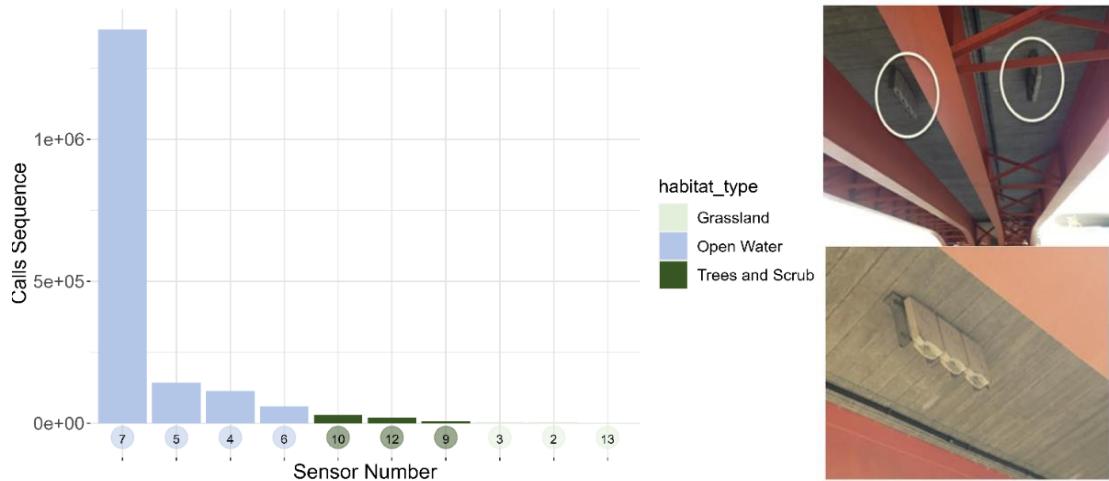


Habitat Type	Open Water	Grassland	Trees and Scrub
Sensor Number	4 5 6 7	2 3 13	9 10 12
Total (n)	4	3	3

**Figure 4.2.1 Locations of Sensors and Corresponding Habitats Types. Source: Author**

#### 4.2.1 Difference of Bats Activity and Species among Sites

Visualization shows a gradient between call sequences and habitat type: sensors near open water had the most bat activity, followed by tree and shrub areas, with grasslands showing the least (Figure 4.2.2 a). Uniquely, sensor 7 recorded 78.5% of the total call sequences. While the abundance of insects near the water plays a part, a significant factor is the artificial roost installed under the bridge by park operators (Figure 4.2.2 b) (Gallacher *et al.*, 2021). The result demonstrates the availability and effectiveness of artificial roost for bats conservation, but unfortunately sensor 7 was no longer operational since June 2020, making it unavailable to explore the long-term role of artificial roosts for bats.



**Figure 4.2.2 Bat Activity among Sites**

To ensure that the observed differences between habitats are statistically significant instead of random variation or chance occurrences, Kruskal-Wallis Test is performed for all five groups. All p-value results are significantly less than given threshold of 0.05, with most results being less than 2.2e-16, except for winter group which has a p-value of 1.221e-08. This indicates that the differences observed are statistically significant. Pair comparison further explore where the differences are. Results in Table 4.2.1 demonstrate that the differences are significant in most of cases, except for comparison of "Open Water" and "Trees and Scrub" in winter, which suggests that there is no significant difference between these two habitats during winter. Comparison results are the same as visualisation (Figure 4.2.2 a) in all five groups, i.e. 'open water' sites exhibit the highest levels of bat activity, while 'grassland' sites is the lowest.

**Table 4.2.1 Pair Comparison (Dunn Test) for Different Habitats in Five Groups. P. adjusted is correlated by Bonferroni test, and the Asterisk (\*) represents the significance between habitat I and J; Z value measures the difference degree, larger Z value means greater difference, in which red font represents the negative difference; chi-square is related to sample size. Source: Author**

Habitat I	Habitat J	Group1: Year		Group2: Spring		Group3: Summer		Group4: Autumn		Group5: Winter	
		chi-squared = 302.85 df =2		chi-squared = 122.90 df =2		chi-squared = 224.44 df =2		chi-squared = 124.62 df =2		chi-squared = 36.44 df =2	
		Z value (I-J)	P.adjusted	Z value (I-J)	P.adjusted						
Open Water	Grassland	17.396	***	11.048	***	14.980	***	11.154	***	4.957	***
	Trees and Scrub	8.273	***	6.318	***	7.293	***	5.978	***	(0.506)	
Grassland	Open Water	(17.396)	***	(11.048)	***	(14.980)	***	(11.154)	***	(4.957)	***
	Trees and Scrub	(9.123)	***	(4.730)	***	(7.687)	***	(5.175)	***	(5.463)	***
Trees and Scrub	Open Water	(8.273)	***	(6.318)	***	(7.293)	***	(5.978)	***	0.506	
	Grassland	9.123	***	4.730	***	7.687	***	5.175	***	5.463	***

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 '' 1

P.adjusted is adjusted by Bonferroni test correlation

This result is in accordance with findings of many studies which suggest bats favour aquatic environments because of the abundant insects (Zeale et al., 2012; de Jong, 1994; Gili et al., 2020). In fact, bats do not really like water itself, Russ and Montgomery (2002) suggested bats generally avoid water bodies that lack of vegetation and most literature refer to open water as encompassing the surrounding plants, the same in this study. Many studies also conclude that the favorite habitat of bats is riparian woodland, but unfortunately, river banks of Queen Elizabeth Olympic Park are fenced due to security and landscape needs (Appendix B), which has led to the loss of this habitat. The observed lowest activity level in grassland is expected and can be attributed to the low insect abundance in improved grassland that has been demonstrated in many studies (Russ and Montgomery, 2002; Fuentes-Montemayor, Goulson and Park, 2011; Razgour et al., 2011). Additionally, bats prefer vertically landscape elements and overgrown grasses, contrasting the shorter grasses in study area (Appendix C) (Coleman and Barclay, 2013).

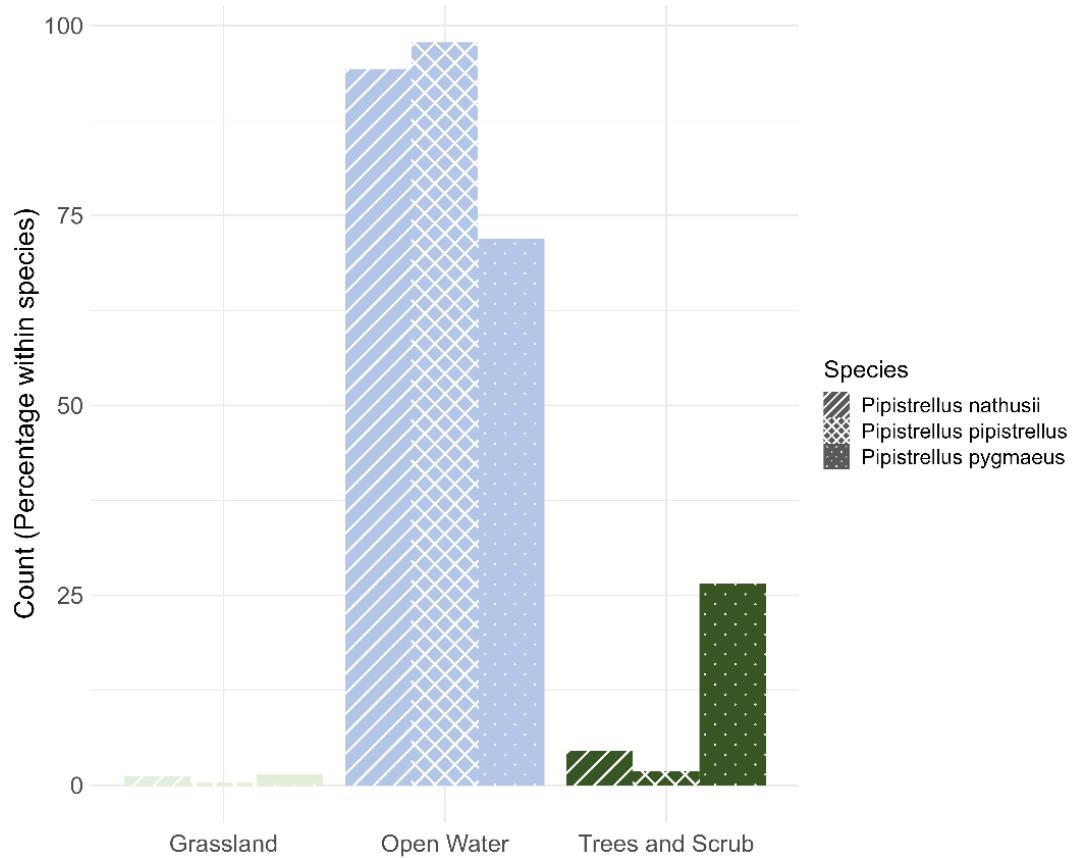
Whether there is a statistical correlation between bat species and habitat type is another question worth exploring. Using chi-square test, the results show that all three species of bats are significant, indicating that they all have preferences for specific habitats. Further visualisation shows the difference more clearly: over 90% of *P. nathusii* and *P. pipistrellus* prefer feeding ground near water, notably more than *P. pygmaeus* with 71%. None of the three species prefer to forage or roost in grassland, while *P. pygmaeus* shows an exclusive preference for trees and scrub. From a comparative perspective, *P. pipistrellus* and *P. nathusii* have the most similar preferences, whereas *P. pipistrellus* and *P. pygmaeus* exhibit the greatest differences. These findings are consistent with previous study conducted by Glendell and Vaughan (2002) which found that *P. pipistrellus* always select habitats near water but *P. pygmaeus* do not, but contrary to Davidson-Watts et al. (2006)'s findings and the point found by Le Comber et al. (2006) suggested that "*P. pipistrellus* has more generalist strategy", this may suggests that the habitat preferences of bat species depend greatly on the specifics of the environment. However, these contradictory findings all reflect a high degree of segregation between *P. pipistrellus* and *P. pygmaeus* in terms of habitat selection, consistent with Nicholls and A. Racey's (2006) findings, but whether this is actually due to interspecific competition has yet to be determined. Wing shape or body size could be another important reason for habitat selection (Entwhistle et al., 2001). As the largest bat in European region, *P. nathusii* cannot easily manoeuvre through trees or scrub, making them prefer open space. Often referred to as cryptic species, both *P. pipistrellus* and *P. pygmaeus* are known for their small size, but some studies found that *P. pipistrellus* is relatively large in terms of skull morphology, wing width and forearm length (Sztencel-Jablonka et al., 2009; ITIS, 2023; Mathews et al., 2020; Jones and Froidevaux, 2020). This feature makes *P. pygmaeus* more favoured and more dominant in occupying trees habitat, which may also

account for the fact that *P.pipistrellus* is least active in this habitat type.

**Table 4.2.2 Result of Chi-square Test. P-value smaller than 0,05 indicates bats vary in their selection of different habitats. Source: Author**

	Pipistrellus nathusii	Pipistrellus pipistrellus	Pipistrellus pygmaeus
X-squared	221433	2896651	50193
p-value	< 2.2e-16 ***	< 2.2e-16 ***	< 2.2e-16 ***

Signif. codes: 0 '\*\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 '' 1



**Figure 4.2.3 Habitat Selection among Species. Source: Author**

#### 4.2.2 Spatial Autocorrelation

Bat detectors are deployed at 15 locations within Queen Elizabeth Olympic Park to record and identify bat calls, with adoption of random stratified sampling method for deployment to ensure that each observation point is independent. To evaluate if there exists spatial autocorrelation among the detectors - the likelihood that neighbouring detectors might register similar bat activity levels -

the Moran's I statistic is calculated. The coordinates of each detector and their respective total counts of bat calls are utilised for this computation. The resulting p-value of the Moran's I test is found to be very low (Moran's I = 0.16528158), signifying that there is no significant spatial autocorrelation among the detectors. It suggests that the bat detectors successfully achieved independent observations, effectively reflecting bat activity across different habitats. The design of this study allows for the acquisition of unbiased samples of bat activity, providing valuable insights for understanding bat habitat preferences.

## **4.3 Impact of Weather and Human Activity on Bats**

### **4.3.1 Weather and Bats (Base Model)**

The quality of 48 models is evaluated through Akaike information criterion (AIC) and the top 10 models are shown in Table 4.3.1 (full version in Appendix D). Nine of these ten models considered interactions, implying the necessity to consider interactions when modelling weather variables. No  $\Delta$ AIC within two units, proving that there is no competing model. Therefore, top model that includes all 15 variables is selected.

**Table 4.3.1 Top 10 Generalized Linear Mixed Models Ranking by AIC (All Species).**  
**The lower the AIC value, the better the quality of model; Models with an AIC difference of less than 2 are considered competing. Source: Author**

No.	Model	No. of Variables	AIC	ΔAIC	Weather Consider Interation	Note
1	All_Calls_Volume ~ hour_sunset + season + Humidity + Temperature + Windspeed*Windgust + Dew_point + Pressure*Pressure_Trend + Precipitation_rate*Precipitation_total + Wind_chill*Heat_index + (1 sensor_number)	15	64935.97	0.00	yes	Top 1 Generalized Linear Mixed Model
2	All_Calls_Volume ~ hour_sunset + season + Temperature + Windspeed*Windgust + Pressure*Pressure_Trend + Wind_chill*Heat_index + (1 sensor_number)	11	65068.24	132.27	yes	Top 2
3	All_Calls_Volume ~ hour_sunset + season + Temperature + Windspeed*Windgust + Dew_point + Wind_chill*Heat_index + (1 sensor_number)	10	65093.03	157.06	yes	Top 3
4	All_Calls_Volume ~ hour_sunset + season + Temperature + Windspeed*Windgust + Wind_chill*Heat_index + (1 sensor_number)	9	65097.88	161.91	yes	Top 4
5	All_Calls_Volume ~ hour_sunset + season + Temperature + Dew_point + Pressure*Pressure_Trend + Wind_chill*Heat_index + (1 sensor_number)	10	65121.23	185.26	yes	Top 5
6	All_Calls_Volume ~ hour_sunset + season + Temperature + Pressure*Pressure_Trend + Wind_chill*Heat_index + (1 sensor_number)	9	65128.51	192.54	yes	Top 6
7	All_Calls_Volume ~ hour_sunset + season + Temperature + Humidity + Wind_chill*Heat_index + (1 sensor_number)	7	65157.13	221.16	yes	Top 7
8	All_Calls_Volume ~ hour_sunset + season + Temperature + Dew_point + Wind_chill*Heat_index + (1 sensor_number)	8	65162.13	226.16	yes	Top 8
9	All_Calls_Volume ~ hour_sunset + season + Temperature + Wind_chill*Heat_index + (1 sensor_number)	7	65171.03	235.06	yes	Top 9
10	All_Calls_Volume ~ hour_sunset + season + Humidity + Temperature + Windspeed + Windgust + Dew_point + Pressure*Pressure_Trend + Precipitation_rate + Precipitation_total + Wind_chill*Heat_index + (1 sensor_number)	15	65200.80	264.83	no	Top 10

Fitting result is described in Table 4.3.2. In terms of total bat activity, the p-values for time of day, season and most of the weather metrics are all less than 0.05, proving that there is indeed a significant relationship between weather and bat activity. Temperature is positively correlated with activity levels, which is the highest positive coefficient of all temperature variables, suggesting the greatest impact of temperature among all weather factors, which also coincides with findings in section 4.1 and in most literature (Gorman et al., 2021; Davis and Reite, 1967). Heat index is an indicator that combines temperature and humidity, reflecting perceived heat. The highest negative correlation implies that when high temperatures and high humidity occur simultaneously, excessively high physical temperatures could make bats feel uncomfortable and reduce activity. Another possible explanation is that bats have very thin and light wings, high humidity may burden them and hinder the flight (Makanya and Mortola, 2007). Geluso and Geluso's (2012) experiments also show that bat capture rates are low in wet areas, suggesting that bats prefer dry environments. The

two measures of precipitation have opposite results, but the significance and coefficients of precipitation rate perform better than total precipitation. Taking into account the findings of most of literature suggest the negative effect of precipitation, precipitation rate metric is considered more representative of this study area (Johnson et al., 2011; Klug-Baerwald et al., 2016; Erickson and West, 2002; Wimsatt, 1969; Stapelfeldt et al., 2022). Wind gust has a significant negative impact on bat activity, while wind speed and activity does not show a correlation, which implies that bats are not affected by variations in wind speed within a normal range for flight, but they opt to remain in roosts if wind speeds exceed this range. Pressure and dew point do not show a significant correlation in this case.

**Table 4.3.2 Result of Top Generalized Linear Mixed Model (All Species). P value smaller than 0.05 indicates a significant effect. Source: Author**

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All Species		Estimate	Std. Error	z value	Pr(> z )
(Intercept)	A11_Calls_Volume ~ hour_sunset + Humidity + Temperature + Windspeed*Windgust + Dew_point + Pressure*Pressure_Trend + Precipitation_rate*Precipitation_total + wind_chill*Heat_index + (1/sensor_number)	3.002426	0.427084	7.030	2.06e-12 ***
hour_sunset		0.172103	0.017795	9.671	< 2e-16 ***
seasonSpring		0.588024	0.042424	13.861	< 2e-16 ***
seasonSummer		0.117009	0.042660	2.743	0.00609 **
seasonWinter		-0.328383	0.070355	-4.668	3.05e-06 ***
Humidity		-0.102157	0.085645	-1.193	0.23295
Temperature		2.166589	0.770587	2.812	0.00493 **
Windspeed		0.060658	0.045114	1.345	0.17877
Windgust		-0.169408	0.041795	-4.053	5.05e-05 ***
Dew_point		0.089668	0.125713	0.713	0.47568
Pressure		0.008063	0.015643	0.515	0.60624
Pressure_Trend		0.035190	0.015418	2.282	0.02246 *
Precipitation_rate		-0.404920	0.045280	-8.943	< 2e-16 ***
Precipitation_total		0.032943	0.013769	2.393	0.01673 *
wind_chill		0.295716	0.123021	2.404	0.01623 *
Heat_index		-2.211792	0.767840	-2.881	0.00397 **
Windspeed:Windgust		-0.009583	0.010415	-0.920	0.35754
Pressure:Pressure_Trend		0.071286	0.012958	5.501	3.77e-08 ***
Precipitation_rate:Precipitation_total		0.057727	0.011109	5.197	2.03e-07 ***
wind_chill:Heat_index		-0.181032	0.011784	-15.363	< 2e-16 ***
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Signif. codes:	0 *** 0.001 ** 0.01 * 0.05 . 0.1 ' ' 1				

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Top generalized linear mixed models for *P. nathusii*, *P. pipistrellus* and *P. pygmaeus* are shown in Table 4.3.3 (AIC rankings in Appendix E-G). Top models for three species are same, but results show marked difference. It is unexpected that only the temperature of *P. pipistrellus* is significant, which suggests that *P. nathusii* and *P. pygmaeus* are insensitive to temperature, the seasonal patterns observed in section 4.1 are mainly caused by sunset time. *P. pygmaeus* shows a unique correlation between indicators humidity and dew point, suggesting it possesses an extremely sensitive perception of humidity. Wind gust and precipitation have a poor effect on all three species, which is a regular pattern for most of insectivorous bats.

**Table 4.3.3 Result of Top Generalized Linear Mixed Models (Three Species). P value smaller than 0.05 indicates a significant effect. Source: Author**

<i>P. nathusii</i>						
(Intercept)V_Pipistrellus_nathusii ~ hour_sunset + Humidity + Temperature + Windspeed*Windgust + Dew_point + Pressure*Pressure_Trend + Precipitation_rate*Precipitation_total + Wind_chill*Heat_index + (1/sensor_number)						
	Estimate	Std. Error	z value	Pr(> z )		
(Intercept)	0.927995	0.399503	2.323	0.20186	*	
hour_sunset	0.079431	0.019689	4.034	5.48e-05	***	
seasonSpring	0.106435	0.046512	2.288	0.022117	*	
seasonSummer	-0.399098	0.045425	-8.786	< 2e-16	***	
seasonwinter	-0.422805	0.083612	-5.057	4.26e-07	***	
Humidity	0.020853	0.093152	0.224	0.822871		
Temperature	0.976581	0.874425	1.117	0.264069		
windspeed	0.060906	0.050142	1.215	0.224491		
Windgust	-0.216975	0.045875	-4.730	2.25e-06	***	
Dew_point	-0.006917	0.135777	-0.051	0.959372		
Pressure	0.071584	0.017783	4.025	5.69e-05	***	
Pressure_Trend	0.048739	0.017554	2.777	0.005494	**	
Precipitation_rate	-0.304604	0.041587	-7.325	2.40e-13	***	
Precipitation_total	0.051453	0.014776	3.482	0.000497	***	
wind_chill	0.160077	0.141026	1.135	0.256337		
Heat_index	-0.905327	0.870376	-1.040	0.298268		
Windspeed:Windgust	0.021046	0.012008	1.753	0.079661	.	
Pressure:Pressure_Trend	0.090443	0.014965	6.044	1.51e-09	***	
Precipitation_rate:Precipitation_total	0.025534	0.009608	2.658	0.007868	**	
wind_chill:Heat_index	-0.142080	0.014588	-9.739	< 2e-16	***	
---						
Signif. codes:	0 '***'	0.001 '**'	0.01 '*'	0.05 '.'	0.1 ' '	1
<i>P. pipistrellus</i>						
(Intercept)V_Pipistrellus_pipistrellus ~ hour_sunset + Humidity + Temperature + Windspeed*Windgust + Dew_point + Pressure*Pressure_Trend + Precipitation_rate*Precipitation_total + Wind_chill*Heat_index + (1/sensor_number)						
	Estimate	Std. Error	z value	Pr(> z )		
(Intercept)	2.51177	0.48050	5.227	1.72e-07	***	
hour_sunset	0.22255	0.01832	12.148	< 2e-16	***	
seasonSpring	0.76566	0.04442	17.239	< 2e-16	***	
seasonSummer	0.08088	0.04340	1.864	0.062359	.	
seasonwinter	-0.31542	0.07448	-4.235	2.29e-05	***	
Humidity	-0.12657	0.08910	-1.420	0.155471		
Temperature	1.78913	0.78507	2.279	0.022670	*	
windspeed	0.04214	0.04672	0.902	0.367059		
Windgust	-0.15763	0.04315	-3.653	0.000259	***	
Dew_point	0.13219	0.13003	1.017	0.309335		
Pressure	-0.01374	0.01628	-0.844	0.398754		
Pressure_Trend	0.02723	0.01570	1.734	0.082931	.	
Precipitation_rate	-0.64991	0.05333	-12.186	< 2e-16	***	
Precipitation_total	0.03407	0.01397	2.438	0.014760	*	
wind_chill	0.29704	0.13148	2.259	0.023874	*	
Heat_index	-1.81658	0.77978	-2.330	0.019827	*	
Windspeed:Windgust	-0.01860	0.01093	-1.701	0.088850	.	
Pressure:Pressure_Trend	0.06911	0.01330	5.197	2.02e-07	***	
Precipitation_rate:Precipitation_total	0.10637	0.01230	8.647	< 2e-16	***	
wind_chill:Heat_index	-0.20299	0.01236	-16.422	< 2e-16	***	
---						
Signif. codes:	0 '***'	0.001 '**'	0.01 '*'	0.05 '.'	0.1 ' '	1
<i>P. pygmaeus</i>						
(Intercept)V_Pipistrellus_pygmaeus ~ hour_sunset + Humidity + Temperature + Windspeed*Windgust + Dew_point + Pressure*Pressure_Trend + Precipitation_rate*Precipitation_total + Wind_chill*Heat_index + (1/sensor_number)						
	Estimate	Std. Error	z value	Pr(> z )		
(Intercept)	0.48952	0.41836	1.170	0.2420		
hour_sunset	-0.16606	0.02055	-8.081	6.42e-16	***	
seasonSpring	0.69657	0.04446	15.667	< 2e-16	***	
seasonSummer	0.46330	0.05281	8.774	< 2e-16	***	
seasonwinter	-1.00571	0.09819	-10.243	< 2e-16	***	
Humidity	0.52434	0.09886	5.304	1.13e-07	***	
Temperature	0.73402	0.99242	0.740	0.4595		
windspeed	0.20577	0.05287	3.892	9.93e-05	***	
Windgust	-0.33648	0.04926	-6.830	8.48e-12	***	
Dew_point	-0.93533	0.14579	-6.416	1.40e-10	***	
Pressure	-0.04009	0.01728	-2.320	0.0203	*	
Pressure_Trend	0.01060	0.01841	0.576	0.5649		
Precipitation_rate	-0.29628	0.05201	-5.697	1.22e-08	***	
Precipitation_total	-0.01406	0.01597	-0.880	0.3787		
wind_chill	0.07830	0.15267	0.513	0.6080		
Heat_index	0.18650	0.99097	0.188	0.8507		
Windspeed:Windgust	-0.02524	0.01310	-1.927	0.0540	.	
Pressure:Pressure_Trend	0.06559	0.01388	4.725	2.31e-06	***	
Precipitation_rate:Precipitation_total	0.02601	0.01294	2.010	0.0444	*	
wind_chill:Heat_index	-0.19070	0.01572	-12.134	< 2e-16	***	
---						
Signif. codes:	0 '***'	0.001 '**'	0.01 '*'	0.05 '.'	0.1 ' '	1

### 4.3.2 Weather, Human Activity and Bats (Extended Model)

Results of three extended models are shown in Table 4.3.4. For model including all species, AIC values all increases compared to base model, indicating that model quality does not become better after adding event and weekend variables. AIC value of *P. nathuii* decreases in extended model 2 and 3, suggesting weekend activity have an impact on it. *P. pipistrellus* also has a small reduction, however, models with a difference in AIC values of less than two units are generally considered competitive models, implying that the variations caused by incorporating 'event' and 'weekend' are not sufficient to mean an impact. The most prominent performing extension model is *P. pygmaeus*, with significant decreasing AIC values for all, which suggests that *P. pygmaeus* is most sensitive to human activities.

**Table 4.3.4 Variance of AIC value for Three Extended Models. A decrease in AIC values indicates an improvement in model quality, with a larger difference signifying a greater enhancement. Source: Author**

Baisc Model	Extended Model 1		Extended Model 2		Extended Model 3		
	Baisc Model + Event	Change of AIC	Baisc Model + Weekend	Change of AIC	Baisc Model + (Weekend + Event)	Change of AIC	
All Species	64935.97	64937.93	Δ = 1.95	64937.96	Δ = 1.99	64939.93	Δ = 3.96
<i>P. nathuii</i>	35598.71	35599.47	Δ = 0.76	35594.54	Δ = - 4.16	35596.51	Δ = - 2.19
<i>P. pipistrellus</i>	60153.47	60155.08	Δ = 1.6	60152.83	Δ = - 0.64	60152.98	Δ = -0.49
<i>P. pygmaeus</i>	32519.03	32503.34	Δ = - 15.69	32493.11	Δ = - 25.92	32489.43	Δ = -29.59

Although most of bats are nocturnal in this study area, these findings suggest that both cyclical (weekend) and non-cyclical (events) human activities may impact them, which support the weekend effect hypothesis of nocturnal organisms proposed by Nix et al. (2018). Events and weekend trips are generally concentrated during the day, suggesting that the impacts of human

activities on bats can be delayed, but the exact reason for this is unknown. The effects of artificial light on bats have been recognized, although *Queen Elizabeth Olympic Park* is open 24 hours a day, the minimal lighting at night may be one of the reasons bats are abundant in this area (Queen Elizabeth Olympic Park, 2023; Luo et al., 2021; Straka et al., 2019; Stone et al., 2015). Perception of and sensitivity to human activities varies considerably among species. Although *P. pygmaeus* and *P. pipistrellus* are generally considered to be two very close species due to the similarity of echolocation calls, they show very different results in environment perception, which may indicate that call similarity cannot be used as a behavioural judgement (Bartonička et al., 2007; Benda et al., 2003). Therefore, developing a deeper understanding of various species' responses to human activities enables a more refined planning for urban and bat habitat management (Nix et al., 2018; Young et al., 2005).

#### **4.4 Summary of Findings**

Chapter 4 conducts a complete analysis of bat activity in Queen Elizabeth Olympic Park, from underlying activity patterns to influencing factors, providing empirical data for bat conservation in London city. Section 4.1 first reveal a five-year plateau in activity levels and abundance, demonstrating the effectiveness of the strategy of park. Seasonal analysis reveals that bats typically hibernate in winter and are active in summer, but the peak month is observed one month earlier than in most cases with another small peak in April, presumably due to differences in climate and species. The seasonal patterns of the three main species are generally similar, but the similarities between the sibling species *P. pygmaeus* and *P. pipistrellus* are relatively higher than that of *P. nathusii*. Yearly seasonal patterns show that different species have similar trends within a year, while the same species varies more between years, suggesting that environmental factor exert a more consistent influence than species-specific characteristics. For bats in this study area, using sunset and sunrise as

boundary is reasonable, with peaks usually occurring around 1.2 hours after sunset, and activity shows a gradual decline instead of a statistical valley pattern. The nightly bimodal pattern is only evident in summer, and torpor is not commonly used during breeding seasons. Unlike seasonal pattern, nightly pattern of *P. pygmaeus* and *P. pipistrellus* shows a segregation in the temporal, while *P. pygmaeus* and *P. nathusii* are highly consistent. This section addresses Q1 posed in the Chapter 1.

Section 4.2 demonstrates significant differences in activity levels between habitats, with the area around open water being the most popular with bat. There are also significant differences in habitat selection by species, with spatial segregation being found between *P. pygmaeus* and *P. nathusii*. Section 4.3 suggests models incorporating weather interactions best capture the relationship between weather and bat activity. Precipitation and wind gust consistently have negative effects on all species while pressure show a positive impact. Unexpectedly, temperature only shows a significant impact on *P. pipistrellus*. Additionally, *P. pygmaeus* shows a particular sensitivity to humidity. Human activities, including weekends and events, have a minor impact on nocturnal bats, but *P. pygmaeus* shows notably greater sensitivity than other species. These two sections address Q2 to Q4 in Chapter 1.

In general, variations among bat species manifest in their activity patterns, habitat choices, and responses to environmental factors, even between two closely related species. Neighboring species may segregate in finer spatial and temporal scales due to resource partitioning, evident in nightly activity and foraging patterns; but due to inherent similarities, they exhibit analogous broader patterns, such as seasonal patterns. Significant environmental shifts show a ubiquitous impact on all bats, for instance, no bat escapes the peculiar peaks brought on by extreme heat, underscoring the importance of

environmental enhancement.

## Chapter 5 Conclusion

In order to contribute to the empirical research on urban bats, providing localized, quantitative data that informs tailored conservation strategies. This paper visualizes the activity patterns of bats in Queen Elizabeth Olympic Park, East London, across yearly, monthly, and daily scales. This study represents a progression from the project begun five years ago (Gallacher *et al.*, 2021), the continuous monitoring data on bats makes this study unique and valuable. Furthermore, this paper delves deeper into understanding how habitat variations, meteorological conditions, and human activities influence these bat activity levels.

Overall, the bat populations in this study area are thriving. Both activity levels and species richness have shown a consistent and slight upward trend over the five years. Additionally, the expected seasonal and nightly activity patterns suggest that bats are successfully and consistently reproducing in this region, indicating a stable and flourishing population. The importance of species-specific research is underscored in this study; even bats that inhabit the same area and have similar physiques can exhibit markedly different activity patterns and sensitivities to environmental factors. This paper also provides some practical insights into urban bat conservation. Large urban parks may serve as optimal places for fostering bat conservation and facilitating harmonious coexistence between humans and nature. As their greater landscape plannability and stability, bats will have a more stable habitat than fragmented sites (e.g. green roof). Additionally, urban parks as a venue for recreation and family gatherings, the intensity and complexity of human activities would be lower, which appears to have minimal disturbance to bats (Results in Section 4.3.1). But it is crucial to note that for urban large parks to truly fulfill their potential, the well-conceived planning strategies for landscape and habitat are

required, and must be diligently implemented. In this regard, Queen Elizabeth Olympic Park serves as an exemplary model.

Although there are some limitations mentioned in section 3.5, this study presents an attempt to maximize insights from limited available data when facing with sensor failure. The value of continuous observation data highlights the benefits of ongoing improvements in bat monitoring methods. Moving forward, it is imperative to continue enhancing monitoring methods in terms of stability, economical and robustness. The path to urban bat conservation is extensive and necessitates a unified societal endeavor. In light of the challenges facing urban bat conservation, the words of Hopkins (2013) 'weaving together the needs of wildlife with those of people', is not just an ideal, but a vital imperative for ensuring a harmonious future

## References

- Adams, R.A. (2004) 'Kunz, T. H., M. B. Fenton (eds.) 2003. Bat Ecology. University of Chicago Press, Chicago, Illinois. 779 pp. ISBN 0-226-46206-4, price (hardbound), \$55.00', *Journal of Mammalogy*, 85(2), pp. 366–367. Available at: [https://doi.org/10.1644/1545-1542\(2004\)085<0366:BE>2.0.CO;2](https://doi.org/10.1644/1545-1542(2004)085<0366:BE>2.0.CO;2).
- Aghababian, S.C. (2023) *Bat Behavior at Commercial Wind Turbines as Revealed by 3-D Thermal Videography*. M.Sc. University of Colorado Colorado Springs. Available at:<https://www.proquest.com/docview/2845430602/abstract/2D198018CBE94079PQ/1> (Accessed: 18 August 2023).
- Agosta, S.J. et al. (2005) 'Nightly, Seasonal, and Yearly Patterns of Bat Activity at Night Roosts in the Central Appalachians', *Journal of Mammalogy*, 86(6), pp. 1210–1219. Available at: <https://doi.org/10.1644/05-MAMM-A-012R1.1>.
- Ahlén, I. and Baagøe, H.J. (1999) 'Use of ultrasound detectors for bat studies in Europe: experiences from field identification, surveys, and monitoring', *Acta Chiropterologica* [Preprint]. Available at: <https://www.scinapse.io/papers/2005595525> (Accessed: 16 August 2023).
- Ancillotto, L. et al. (2019) 'The importance of ponds for the conservation of bats in urban landscapes', *Landscape and Urban Planning*, 190, p. 103607. Available at: <https://doi.org/10.1016/j.landurbplan.2019.103607>.
- Ancillotto, L., Tomassini, A. and Russo, D. (2015) 'The fancy city life: Kuhl's pipistrelle, *Pipistrellus kuhlii*, benefits from urbanisation', *Wildlife Research*, 42(7), p. 598. Available at: <https://doi.org/10.1071/WR15003>.
- Anthony, E.L.P. and Kunz, T.H. (1977) 'Feeding Strategies of the Little Brown Bat, *Myotis Lucifugus*, in Southern New Hampshire', *Ecology*, 58(4), pp. 775–786. Available at: <https://doi.org/10.2307/1936213>.
- Anthony, E.L.P., Stack, M.H. and Kunz, T.H. (1981) 'Night roosting and the nocturnal time budget of the little brown bat, *Myotis lucifugus*: Effects of reproductive status, prey density, and environmental conditions', *Oecologia*, 51(2), pp. 151–156. Available at: <https://doi.org/10.1007/BF00540593>.
- Aodha, O.M. et al. (2018) 'Bat detective—Deep learning tools for bat acoustic signal detection', *PLOS Computational Biology*, 14(3), p. e1005995. Available at: <https://doi.org/10.1371/journal.pcbi.1005995>.

Appel, G. et al. (2021) 'Use of complementary methods to sample bats in the Amazon', *Acta Chiropterologica*, 23(2), pp. 499–511. Available at: <https://doi.org/10.3161/15081109ACC2021.23.2.017>.

Arlettaz, R. (1999) 'Habitat selection as a major resource partitioning mechanism between the two sympatric sibling bat species *Myotis myotis* and *Myotis blythii*', *Journal of Animal Ecology*, 68(3), pp. 460–471. Available at: <https://doi.org/10.1046/j.1365-2656.1999.00293.x>.

Arlettaz, R., Perrin, N. and Hausser, J. (1997) 'Trophic Resource Partitioning and Competition between the Two Sibling Bat Species *Myotis myotis* and *Myotis blythii*', *Journal of Animal Ecology*, 66(6), pp. 897–911. Available at: <https://doi.org/10.2307/6005>.

Armitage, D.W. and Ober, H.K. (2010) 'A comparison of supervised learning techniques in the classification of bat echolocation calls', *Ecological Informatics*, 5(6), pp. 465–473. Available at: <https://doi.org/10.1016/j.ecoinf.2010.08.001>.

Avila-Flores, R. and Fenton, M.B. (2005) 'Use of Spatial Features by Foraging Insectivorous Bats in a Large Urban Landscape', *Journal of Mammalogy*, 86(6), pp. 1193–1204. Available at: <https://doi.org/10.1644/04-MAMM-A-085R1.1>.

Banerjee, A. et al. (2009) 'Hypothesis testing, type I and type II errors', *Industrial Psychiatry Journal*, 18(2), pp. 127–131. Available at: <https://doi.org/10.4103/0972-6748.62274>.

Joint Nature Conservation Committee. (1994) The UK Biodiversity Action Plan (UK BAP) 1992–2012. Available at: <http://jncc.defra.gov.uk> (Accessed: 10 February 2017).

Barclay, R.M.R. (1982) 'Night Roosting Behavior of the Little Brown Bat, *Myotis lucifugus*', *Journal of Mammalogy*, 63(3), pp. 464–474. Available at: <https://doi.org/10.2307/1380444>.

Barclay, R.M.R. (1989) 'The effect of reproductive condition on the foraging behavior of female hoary bats, *Lasiurus cinereus*', *Behavioral Ecology and Sociobiology*, 24(1), pp. 31–37. Available at: <https://doi.org/10.1007/BF00300115>.

Barclay, R.M.R. (1991) 'Population Structure of Temperate Zone Insectivorous Bats in Relation to Foraging Behaviour and Energy Demand', *Journal of Animal Ecology*, 60(1), pp. 165–178. Available at: <https://doi.org/10.2307/5452>.

Barclay, R.M.R. (1999a) 'Bats are Not Birds—a Cautionary Note on Using Echolocation Calls to Identify Bats: a Comment', *Journal of Mammalogy*, 80(1), pp. 290–296. Available at: <https://doi.org/10.2307/1383229>.

Barclay, R.M.R. (1999b) 'Bats are Not Birds—a Cautionary Note on Using Echolocation Calls to Identify Bats: a Comment', *Journal of Mammalogy*, 80(1), pp. 290–296. Available at: <https://doi.org/10.2307/1383229>.

Barlow, K.E., Jones, G. and Barratt, E.M. (1997) 'Can skull morphology be used to predict ecological relationships between bat species? A test using two cryptic species of pipistrelle', *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 264(1388), pp. 1695–1700. Available at: <https://doi.org/10.1098/rspb.1997.0235>.

Barnett, A.A. et al. (2006) 'Bats of Jaú National Park, central Amazônia, Brazil', *Acta Chiropterologica*, 8(1), pp. 103–128. Available at: <https://doi.org/10.3161/150811006777070820>.

Barré, K. et al. (2021) 'Artificial light may change flight patterns of bats near bridges along urban waterways', *Animal Conservation*, 24(2), pp. 259–267. Available at: <https://doi.org/10.1111/acv.12635>.

Bartonička, T., Řehák, Z. and Gaisler, J. (2007) 'Can pipistrelles, *Pipistrellus pipistrellus* (Schreber, 1774) and *Pipistrellus pygmaeus* (Leach, 1825), foraging in a group, change parameters of their signals?', *Journal of Zoology*, 272(2), pp. 194–201. Available at: <https://doi.org/10.1111/j.1469-7998.2006.00255.x>.

Bat Conservation Trust (no date a) *Insect control - Why bats matter*, Bat Conservation Trust. Available at: <https://www.bats.org.uk/about-bats/why-bats-matter/bats-as-pest-controllers> (Accessed: 28 July 2023).

Bat Conservation Trust (no date b) *UK Bats - Types of bats*, Bat Conservation Trust. Available at: <https://www.bats.org.uk/about-bats/what-are-bats/uk-bats> (Accessed: 28 July 2023).

Bateman, G.C. and Vaughan, T.A. (1974) 'Nightly Activities of Mormoopid Bats', *Journal of Mammalogy*, 55(1), pp. 45–65. Available at: <https://doi.org/10.2307/1379256>.

BBC News (2022) 'Heatwave: England has had joint hottest summer on record, Met Office says', BBC News, 1 September. Available at: <https://www.bbc.com/news/uk-62758367> (Accessed: 3 August 2023).

- Benda, P. *et al.* (2003) 'Notes on the distribution of *Pipistrellus pipistrellus* complex in the Eastern Mediterranean: First records of *P. pipistrellus* for Syria and of *P. pygmaeus* for Turkey', *Vespertilio*, 7, pp. 87–95.
- Bender, M.J. and Hartman, G.D. (2015) 'Bat Activity Increases with Barometric Pressure and Temperature during Autumn in Central Georgia', *Southeastern Naturalist*, 14(2), pp. 231–242. Available at: <https://doi.org/10.1656/058.014.0203>.
- Berthier, P., Excoffier, L. and Ruedi, M. (2006) 'Recurrent replacement of mtDNA and cryptic hybridization between two sibling bat species *Myotis myotis* and *Myotis blythii*', *Proceedings of the Royal Society B: Biological Sciences*, 273(1605), pp. 3101–3123. Available at: <https://doi.org/10.1098/rspb.2006.3680>.
- Berthinussen, A., Richardson, O.C. and Altringham, J.D. (2014) *Bat Conservation: Global evidence for the effects of interventions*. Pelagic Publishing Ltd.
- Bogdanowicz, W., Fenton, M.B. and Daleszczyk, K. (1999) 'The relationships between echolocation calls, morphology and diet in insectivorous bats', *Journal of Zoology*, 247(3), pp. 381–393. Available at: <https://doi.org/10.1111/j.1469-7998.1999.tb01001.x>.
- Bolker, B.M. *et al.* (2009) 'Generalized linear mixed models: a practical guide for ecology and evolution', *Trends in Ecology & Evolution*, 24(3), pp. 127–135. Available at: <https://doi.org/10.1016/j.tree.2008.10.008>.
- Boughey, K.L. *et al.* (2011) 'Improving the biodiversity benefits of hedgerows: How physical characteristics and the proximity of foraging habitat affect the use of linear features by bats', *Biological Conservation*, 144(6), pp. 1790–1798. Available at: <https://doi.org/10.1016/j.biocon.2011.02.017>.
- Boyles, J.G. *et al.* (2011) 'Economic Importance of Bats in Agriculture', *Science*, 332(6025), pp. 41–42. Available at: <https://doi.org/10.1126/science.1201366>.
- Bradley, S. (2006) *The Ecology of Bat Reproduction*. Nottingham, UK: The University of Nottingham.
- Browning, E. *et al.* (2021a) 'Drivers of European bat population change: a review reveals evidence gaps', *Mammal Review*, 51(3), pp. 353–368. Available at: <https://doi.org/10.1111/mam.12239>.

Browning, E. et al. (2021b) 'Drivers of European bat population change: a review reveals evidence gaps', *Mammal Review*, 51(3), pp. 353–368. Available at: <https://doi.org/10.1111/mam.12239>.

Ciechanowski, M. et al. (2007) 'Spatiotemporal variation in activity of bat species differing in hunting tactics: effects of weather, moonlight, food abundance, and structural clutter', *Canadian Journal of Zoology*, 85(12), pp. 1249–1263. Available at: <https://doi.org/10.1139/Z07-090>.

Ciechanowski, M. et al. (2010) 'Seasonal activity patterns of seven vespertilionid bat species in Polish lowlands', *Acta Theriologica*, 55(4), pp. 301–314. Available at: <https://doi.org/10.1007/BF03193234>.

Coleman, J.L. and Barclay, R.M.R. (2013) 'Prey availability and foraging activity of grassland bats in relation to urbanization', *Journal of Mammalogy*, 94(5), pp. 1111–1122. Available at: <https://doi.org/10.1644/12-MAMM-A-217.1>.

Cruz, J.L.D.L., Ward, R.L. and Schroder, E.S. (2018) 'Landscape Characteristics Related to Use of Artificial Roosts by Northern Long-Eared Bats in North-Central West Virginia', *Northeastern Naturalist*, 25(3), pp. 487–501. Available at: <https://doi.org/10.1656/045.025.0312>.

Culina, A., Linton, D.M. and Macdonald, D.W. (2017) 'Age, sex, and climate factors show different effects on survival of three different bat species in a woodland bat community', *Global Ecology and Conservation*, 12, pp. 263–271. Available at: <https://doi.org/10.1016/j.gecco.2017.11.009>.

Cunto, G.C. and Bernard, E. (2012) 'Neotropical bats as indicators of environmental disturbance: what is the emerging message?', *Acta Chiropterologica*, 14(1), pp. 143–151. Available at: <https://doi.org/10.3161/150811012X654358>.

Czenze, Z.J., Noakes, M.J. and Wojciechowski, M.S. (2022) 'Home is where the heat is: Thermoregulation of European bats inhabiting artificial roosts and the threat of heat waves', *Journal of Applied Ecology*, 59(8), pp. 2179–2188. Available at: <https://doi.org/10.1111/1365-2664.14230>.

Davidson-Watts, I. and Jones, G. (2005) 'Differences in foraging behaviour between *Pipistrellus pipistrellus* (Schreber, 1774) and *Pipistrellus pygmaeus* (Leach, 1825)', *Journal of Zoology*, 268, pp. 55–62. Available at: <https://doi.org/10.1111/j.1469-7998.2005.00016.x>.

Davidson-Watts, I., Walls, S. and Jones, G. (2006) 'Differential habitat selection by *Pipistrellus pipistrellus* and *Pipistrellus pygmaeus* identifies distinct conservation needs for cryptic species of echolocating bats', *Biological*

*Conservation*, 133(1), pp. 118–127. Available at:  
<https://doi.org/10.1016/j.biocon.2006.05.027>.

Davis, W.H. and Reite, O.B. (1967) ‘Responses of bats from temperate regions to changes in ambient temperature’, *The Biological Bulletin*, 132(3), pp. 320–328. Available at: <https://doi.org/10.2307/1539637>.

Davy, C.M. et al. (2022) ‘Rapidly declining body size in an insectivorous bat is associated with increased precipitation and decreased survival’, *Ecological Applications*, 32(7), p. e2639. Available at: <https://doi.org/10.1002/eap.2639>.

Decoursey, G. and Decoursey, P.J. (1964) ‘ADAPTIVE ASPECTS OF ACTIVITY RHYTHMS IN BATS’, *The Biological Bulletin*, 126(1), pp. 14–27. Available at: <https://doi.org/10.2307/1539413>.

Dressler, F. et al. (2016) ‘From radio telemetry to ultra-low-power sensor networks: tracking bats in the wild’, *IEEE Communications Magazine*, 54(1), pp. 129–135. Available at: <https://doi.org/10.1109/MCOM.2016.7378438>.

Dunn, O.J. (1964) ‘Multiple Comparisons Using Rank Sums’, *Technometrics*, 6(3), pp. 241–252. Available at:  
<https://doi.org/10.1080/00401706.1964.10490181>.

Dzial, Y.A. and Brigham, R.M. (2013) ‘The tradeoff between torpor use and reproduction in little brown bats (*Myotis lucifugus*)’, *Journal of Comparative Physiology B*, 183(2), pp. 279–288. Available at:  
<https://doi.org/10.1007/s00360-012-0705-4>.

Egert-Berg, K. et al. (2021) ‘Fruit bats adjust their foraging strategies to urban environments to diversify their diet’, *BMC Biology*, 19(1), p. 123. Available at: <https://doi.org/10.1186/s12915-021-01060-x>.

Entwhistle, A.C. et al. (2001) *Habitat management for bats – A guide for land managers*. Peterborough: JNCC. Available at:  
<https://hub.jncc.gov.uk/assets/23745574-3756-40ef-81cd-e6fea30decc0>  
(Accessed: 2 August 2023).

Erickson, J.L. and West, S.D. (2002) ‘The Influence of Regional Climate and Nightly Weather Conditions on Activity Patterns of Insectivorous Bats’, *Acta Chiropterologica*, 4(1), pp. 17–24. Available at:  
<https://doi.org/10.3161/001.004.0103>.

Erkert, H.G. (1978) ‘Sunset-related timing of flight activity in neotropical bats’, *Oecologia*, 37(1), pp. 59–67. Available at:  
<https://doi.org/10.1007/BF00349991>.

- Erkert, H.G. (1982) 'Ecological Aspects of Bat Activity Rhythms', in T.H. Kunz (ed.) *Ecology of Bats*. Boston, MA: Springer US, pp. 201–242. Available at: [https://doi.org/10.1007/978-1-4613-3421-7\\_5](https://doi.org/10.1007/978-1-4613-3421-7_5).
- Festa, F. et al. (2023) 'Bat responses to climate change: a systematic review', *Biological Reviews*, 98(1), pp. 19–33. Available at: <https://doi.org/10.1111/brv.12893>.
- Fidiam, K.L. and Iudica, C.A. (2011) 'Environmental Effects on the Emergence Time of Little Brown Bats (*myotis Lucifugus*) in Central Pennsylvania', *Journal of the Pennsylvania Academy of Science*, 85(2/3), pp. 88–92.
- Flaquer, C. et al. (2009) 'Habitat Selection in *Nathusius' Pipistrelle* (*Pipistrellus nathusii*): The Importance of Wetlands', *Acta Chiropterologica*, 11, pp. 149–155. Available at: <https://doi.org/10.3161/150811009X465767>.
- Flaquer, C., Torre, I. and Arrizabalaga, A. (2007) 'Comparison of Sampling Methods for Inventory of Bat Communities', *Journal of Mammalogy*, 88(2), pp. 526–533. Available at: <https://doi.org/10.1644/06-MAMM-A-135R1.1>.
- Franci, K.E. et al. (2012) 'Capture and Reproductive Trends in Summer Bat Communities in West Virginia: Assessing the Impact of White-Nose Syndrome', *Journal of Fish and Wildlife Management*, 3(1), pp. 33–42. Available at: <https://doi.org/10.3996/062011-JFWM-039>.
- Froidevaux, J.S.P. et al. (2014) 'Optimizing passive acoustic sampling of bats in forests', *Ecology and Evolution*, 4(24), pp. 4690–4700. Available at: <https://doi.org/10.1002/ece3.1296>.
- Fuentes-Montemayor, E., Goulson, D. and Park, K.J. (2011) 'Pipistrelle bats and their prey do not benefit from four widely applied agri-environment management prescriptions', *Biological Conservation*, 144(9), pp. 2233–2246. Available at: <https://doi.org/10.1016/j.biocon.2011.05.015>.
- Gaisler, J. et al. (1998) 'Habitat preference and flight activity of bats in a city', *Journal of Zoology*, 244(3), pp. 439–445. Available at: <https://doi.org/10.1111/j.1469-7998.1998.tb00048.x>.
- Gallacher, S. et al. (2021) 'Shazam for bats: Internet of Things for continuous real-time biodiversity monitoring', *IET Smart Cities*, 3(3), pp. 171–183. Available at: <https://doi.org/10.1049/sm2.12016>.
- Gallo, T. et al. (2018) 'Need for multiscale planning for conservation of urban bats', *Conservation Biology*, 32(3), pp. 638–647. Available at: <https://doi.org/10.1111/cobi.13047>.

Geluso, K.N. and Geluso, K. (2012) 'Effects of environmental factors on capture rates of insectivorous bats, 1971–2005', *Journal of Mammalogy*, 93(1), pp. 161–169. Available at: <https://doi.org/10.1644/11-MAMM-A-107.1>.

Gili, F. *et al.* (2020) 'Bats in urbanising landscapes: habitat selection and recommendations for a sustainable future', *Biological Conservation*, 241, p. 108343. Available at: <https://doi.org/10.1016/j.biocon.2019.108343>.

Ginn, F., Beisel, U. and Barua, M. (2014) 'Flourishing with Awkward Creatures: Togetherness, Vulnerability, Killing', *Environmental Humanities*, 4(1), pp. 113–123. Available at: <https://doi.org/10.1215/22011919-3614953>.

Glendell, M. and Vaughan, N. (2002) 'Foraging activity of bats in historic landscape parks in relation to habitat composition and park management', *Animal Conservation*, 5(4), pp. 309–316. Available at: <https://doi.org/10.1017/S1367943002004067>.

Gorman, K.M. *et al.* (2021) 'Bat activity patterns relative to temporal and weather effects in a temperate coastal environment', *Global Ecology and Conservation*, 30, p. e01769. Available at: <https://doi.org/10.1016/j.gecco.2021.e01769>.

GOV.UK (2021) *Trend Deck 2021: Urbanisation*, GOV.UK. Available at: <https://www.gov.uk/government/publications/trend-deck-2021-urbanisation/trend-deck-2021-urbanisation> (Accessed: 26 July 2023).

Greenfeld, A. *et al.* (2018) 'Managing anthropogenic driven range expansion behaviourally: Mediterranean bats in desert ecosystems', *European Journal of Wildlife Research*, 64(3), p. 24. Available at: <https://doi.org/10.1007/s10344-018-1182-1>.

Griffin, D.R. (1971) 'The importance of atmospheric attenuation for the echolocation of bats (Chiroptera)', *Animal Behaviour*, 19(1), pp. 55–61. Available at: [https://doi.org/10.1016/S0003-3472\(71\)80134-3](https://doi.org/10.1016/S0003-3472(71)80134-3).

Grindal, S.D. *et al.* (1992) 'The Influence of Precipitation on Reproduction by Myotis Bats in British Columbia', *The American Midland Naturalist*, 128(2), pp. 339–344. Available at: <https://doi.org/10.2307/2426468>.

Grinevitch, L., Holroyd, S.L. and Barclay, R.M.R. (1995) 'Sex differences in the use of daily torpor and foraging time by big brown bats (*Eptesicus fuscus*) during the reproductive season', *Journal of Zoology*, 235(2), pp. 301–309. Available at: <https://doi.org/10.1111/j.1469-7998.1995.tb05146.x>.

Hagen, E.M. and Sabo, J.L. (2011) 'A landscape perspective on bat foraging ecology along rivers: does channel confinement and insect availability influence the response of bats to aquatic resources in riverine landscapes?', *Oecologia*, 166(3), pp. 751–760. Available at: <https://doi.org/10.1007/s00442-011-1913-4>.

Harrison, X.A. et al. (2018) 'A brief introduction to mixed effects modelling and multi-model inference in ecology', *PeerJ*, 6, p. e4794. Available at: <https://doi.org/10.7717/peerj.4794>.

Hastie, T.J. and Tibshirani, R.J. (1990) *Generalized Additive Models*. CRC Press.

Hayes, J.P. (1997) 'Temporal Variation in Activity of Bats and the Design of Echolocation-Monitoring Studies', *Journal of Mammalogy*, 78(2), pp. 514–524. Available at: <https://doi.org/10.2307/1382902>.

Hayes, J.P. (2000) 'Assumptions and practical considerations in the design and interpretation of echolocation-monitoring studies', *Acta Chiropterologica*, 2, pp. 225–236.

Hermans, C. et al. (2023) 'Combining acoustic tracking and LiDAR to study bat flight behaviour in three-dimensional space', *Movement Ecology*, 11(1), p. 25. Available at: <https://doi.org/10.1186/s40462-023-00387-0>.

Hodgkison, R. et al. (2003) 'Fruit Bats (Chiroptera: Pteropodidae) as Seed Dispersers and Pollinators in a Lowland Malaysian Rain Forest1', *Biotropica*, 35(4), pp. 491–502. Available at: <https://doi.org/10.1111/j.1744-7429.2003.tb00606.x>.

Hoeh, J.P.S. et al. (2018) 'In artificial roost comparison, bats show preference for rocket box style', *PLOS ONE*, 13(10), p. e0205701. Available at: <https://doi.org/10.1371/journal.pone.0205701>.

Holland, R.A. et al. (2011) 'Emergence time and foraging activity in Pallas' mastiff bat, *Molossus molossus* (Chiroptera: Molossidae) in relation to sunset/sunrise and phase of the moon', *Acta Chiropterologica*, 13(2), pp. 399–404. Available at: <https://doi.org/10.3161/150811011X624875>.

Holloway, G.L. and Barclay, R.M. (2000) 'Importance of prairie riparian zones to bats in southeastern Alberta', *Écoscience*, 7(2), pp. 115–122. Available at: <https://doi.org/10.1080/11956860.2000.11682579>.

Hope, P.R. and Jones, G. (2012) 'Warming up for dinner: torpor and arousal in hibernating Natterer's bats (*Myotis nattereri*) studied by radio telemetry',

*Journal of Comparative Physiology. B, Biochemical, Systemic, and Environmental Physiology*, 182(4), pp. 569–578. Available at: <https://doi.org/10.1007/s00360-011-0631-x>.

Hudson-Smith, A. et al. (2021) ‘Urban IoT: Advances, Challenges, and Opportunities for Mass Data Collection, Analysis, and Visualization’, in W. Shi et al. (eds) *Urban Informatics*. Singapore: Springer (The Urban Book Series), pp. 701–719. Available at: [https://doi.org/10.1007/978-981-15-8983-6\\_38](https://doi.org/10.1007/978-981-15-8983-6_38).

Hulva, P. et al. (2004) ‘Molecular architecture of Pipistrellus pipistrellus/Pipistrellus pygmaeus complex (Chiroptera: Vespertilionidae): further cryptic species and Mediterranean origin of the divergence’, *Molecular Phylogenetics and Evolution*, 32(3), pp. 1023–1035. Available at: <https://doi.org/10.1016/j.ympev.2004.04.007>.

Hurme, E. et al. (2019) ‘Acoustic evaluation of behavioral states predicted from GPS tracking: a case study of a marine fishing bat’, *Movement Ecology*, 7(1), p. 21. Available at: <https://doi.org/10.1186/s40462-019-0163-7>.

Hyzy, B.A. et al. (2020) ‘Occupancy and Detectability of Northern Long-eared Bats in the Lake States Region’, *Wildlife Society Bulletin*, 44(4), pp. 732–740. Available at: <https://doi.org/10.1002/wsb.1138>.

ITIS (2023) ‘The Integrated Taxonomic Information System’. ITIS. Available at: <https://doi.org/10.48580/DFSY-4KY>.

Jackson, R.T., Willcox, E.V. and Bernard, R.F. (2023) ‘Movement Patterns of Two Bat Species Active During Winter in the Southeastern United States’, *Journal of Fish and Wildlife Management*, 14(1), pp. 215–224. Available at: <https://doi.org/10.3996/JFWM-22-049>.

Johnson, J.B., Gates, J.E. and Zegre, N.P. (2011) ‘Monitoring seasonal bat activity on a coastal barrier island in Maryland, USA’, *Environmental Monitoring and Assessment*, 173(1), pp. 685–699. Available at: <https://doi.org/10.1007/s10661-010-1415-6>.

Jones, G. et al. (2009) ‘Carpe noctem: the importance of bats as bioindicators’, *Endangered Species Research*, 8, pp. 93–115. Available at: <https://doi.org/10.3354/esr00182>.

Jones, G. and Froidevaux, J.S.P. (2020) ‘Soprano Pipistrelle Pipistrellus pygmaeus (Leach, 1825)’, in K. Hackländer and F.E. Zachos (eds) *Handbook of the Mammals of Europe*. Cham: Springer International Publishing (欧洲哺乳

动物手册), pp. 1–25. Available at: [https://doi.org/10.1007/978-3-319-65038-8\\_67-1](https://doi.org/10.1007/978-3-319-65038-8_67-1).

Jones, G. and Rydell, J. (1997) ‘Foraging strategy and predation risk as factors influencing emergence time in echolocating bats’, *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, 346(1318), pp. 445–455. Available at: <https://doi.org/10.1098/rstb.1994.0161>.

Jones, K.E. et al. (2013) ‘Indicator Bats Program: A System for the Global Acoustic Monitoring of Bats’, in *Biodiversity Monitoring and Conservation*. John Wiley & Sons, Ltd, pp. 211–247. Available at: <https://doi.org/10.1002/9781118490747.ch10>.

de Jong, J. (1994) ‘Habitat use, home-range and activity pattern of the northern bat, *Eptesicus nilssoni*, in a hemiboreal coniferous forest.’, *Mammalia*, 58(4). Available at: <https://res.slu.se/id/publ/115394> (Accessed: 1 August 2023).

de Jong, J. and Ahlén, I. (1991) ‘Factors Affecting the Distribution Pattern of Bats in Uppland, Central Sweden’, *Holarctic Ecology*, 14(2), pp. 92–96.

Jung, K. and Threlfall, C.G. (2018) ‘Trait-dependent tolerance of bats to urbanization: a global meta-analysis’, *Proceedings of the Royal Society B: Biological Sciences*, 285(1885), p. 20181222. Available at: <https://doi.org/10.1098/rspb.2018.1222>.

Kalcounis-Rueppell, M.C. et al. (2007) ‘Effects of wastewater treatment plant effluent on bat foraging ecology in an urban stream system’, *Biological Conservation*, 138(1), pp. 120–130. Available at: <https://doi.org/10.1016/j.biocon.2007.04.009>.

Kalcounis-Rueppell, M.C. et al. (2013) ‘Hard forest edges act as conduits, not filters, for bats’, *Wildlife Society Bulletin*, 37(3), pp. 571–576. Available at: <https://doi.org/10.1002/wsb.289>.

Kelm, D.H., Toelch, U. and Jones, M.M. (2021) ‘Mixed-species groups in bats: non-random roost associations and roost selection in neotropical understory bats’, *Frontiers in Zoology*, 18, p. 53. Available at: <https://doi.org/10.1186/s12983-021-00437-6>.

Kim, S.-S., Choi, Y.-S. and Yoo, J.-C. (2019) ‘Regional differences in winter activity of hibernating greater horseshoe bats (*Rhinolophus ferrumequinum*) from Korea’, *Journal of Ecology and Environment*, 43(1), p. 2. Available at: <https://doi.org/10.1186/s41610-018-0097-9>.

Klüg-Baerwald, B.J. *et al.* (2016) 'Environmental correlates and energetics of winter flight by bats in southern Alberta, Canada', *Canadian Journal of Zoology*, 94(12), pp. 829–836. Available at: <https://doi.org/10.1139/cjz-2016-0055>.

Kotila, M. *et al.* (2022) 'Atmospheric humidity affects global variation of bat echolocation via indirect effects', *Frontiers in Ecology and Evolution*, 10. Available at: <https://www.frontiersin.org/articles/10.3389/fevo.2022.934876> (Accessed: 15 August 2023).

Kruskal, W.H. and Wallis, W.A. (1952) 'Use of Ranks in One-Criterion Variance Analysis', *Journal of the American Statistical Association*, 47(260), pp. 583–621. Available at: <https://doi.org/10.1080/01621459.1952.10483441>.

Kuenzi, A.J. and Morrison, M.L. (2003) 'Temporal Patterns of Bat Activity in Southern Arizona', *The Journal of Wildlife Management*, 67(1), pp. 52–64. Available at: <https://doi.org/10.2307/3803061>.

Kunz, T.H. (1973) 'Resource Utilization: Temporal and Spatial Components of Bat Activity in Central Iowa', *Journal of Mammalogy*, 54(1), pp. 14–32. Available at: <https://doi.org/10.2307/1378869>.

Kunz, T.H. (1982) 'Roosting Ecology of Bats', in T.H. Kunz (ed.) *Ecology of Bats*. Boston, MA: Springer US, pp. 1–55. Available at: [https://doi.org/10.1007/978-1-4613-3421-7\\_1](https://doi.org/10.1007/978-1-4613-3421-7_1).

Kunz, T.H. (2013) *Ecology of Bats*. Springer Science & Business Media.

Kunz, T.H. and Brock, C.E. (1975) 'A Comparison of Mist Nets and Ultrasonic Detectors for Monitoring Flight Activity of Bats', *Journal of Mammalogy*, 56(4), pp. 907–911. Available at: <https://doi.org/10.2307/1379662>.

Kunz, T.H., Whitaker, J.O. and Wadanoli, M.D. (1995) 'Dietary energetics of the insectivorous Mexican free-tailed bat (*Tadarida brasiliensis*) during pregnancy and lactation', *Oecologia*, 101(4), pp. 407–415. Available at: <https://doi.org/10.1007/BF00329419>.

Kurta, A. *et al.* (1989) 'Energetics of Pregnancy and Lactation in Freeranging Little Brown Bats (*Myotis lucifugus*)', *Physiological Zoology*, 62(3), pp. 804–818. Available at: <https://doi.org/10.1086/physzool.62.3.30157928>.

Lane, D.J.W., Kingston, T. and Lee, B.P.Y.-H. (2006) 'Dramatic decline in bat species richness in Singapore, with implications for Southeast Asia', *Biological Conservation*, 131(4), pp. 584–593. Available at: <https://doi.org/10.1016/j.biocon.2006.03.005>.

Langlois, G.D. *et al.* (2023) 'Habitat differences and roost selection between two disparate landscapes by a neotropical bat (*Artibeus lituratus*) in the Atlantic Forest of Paraguay', *Forest Ecology and Management*, 544, p. 121154. Available at: <https://doi.org/10.1016/j.foreco.2023.121154>.

Le Comber, S.C. *et al.* (2006) 'Geographic profiling and animal foraging', *Journal of Theoretical Biology*, 240(2), pp. 233–240. Available at: <https://doi.org/10.1016/j.jtbi.2005.09.012>.

legislation.gov.uk (2017) *The Conservation of Habitats and Species Regulations (2017) (as amended)*. King's Printer of Acts of Parliament. Available at: <https://www.legislation.gov.uk/uksi/2017/1012/contents/made> (Accessed: 26 July 2023).

Lehrer, E.W. *et al.* (2021) 'Urban bat occupancy is highly influenced by noise and the location of water: Considerations for nature-based urban planning', *Landscape and Urban Planning*, 210, p. 104063. Available at: <https://doi.org/10.1016/j.landurbplan.2021.104063>.

Lentini, P.E. *et al.* (2012) 'Bats in a Farming Landscape Benefit from Linear Remnants and Unimproved Pastures', *PLOS ONE*, 7(11), p. e48201. Available at: <https://doi.org/10.1371/journal.pone.0048201>.

Lewanzik, D. *et al.* (2022) 'Evaluating the potential of urban areas for bat conservation with citizen science data', *Environmental Pollution*, 297, p. 118785. Available at: <https://doi.org/10.1016/j.envpol.2021.118785>.

Li, H. *et al.* (2020) 'The Weekend Effect on Urban Bat Activity Suggests Fine Scale Human-Induced Bat Movements', *Animals*, 10(9), p. 1636. Available at: <https://doi.org/10.3390/ani10091636>.

Lima, S.L. and O'Keefe, J.M. (2013) 'Do predators influence the behaviour of bats?', *Biological Reviews*, 88(3), pp. 626–644. Available at: <https://doi.org/10.1111/brv.12021>.

Lin, Y.-W. *et al.* (2020) 'BatTalk: Monitoring Asian Parti-Colored Bats Through the IoT Technology', in D.-J. Deng, A.-C. Pang, and C.-C. Lin (eds) *Wireless Internet*. Cham: Springer International Publishing (Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering), pp. 172–183. Available at: [https://doi.org/10.1007/978-3-030-52988-8\\_15](https://doi.org/10.1007/978-3-030-52988-8_15).

Luo, B. *et al.* (2021) 'Artificial light reduces foraging opportunities in wild least horseshoe bats', *Environmental Pollution*, 288, p. 117765. Available at: <https://doi.org/10.1016/j.envpol.2021.117765>.

Mace, G.M. et al. (2018) 'Aiming higher to bend the curve of biodiversity loss', *Nature Sustainability*, 1(9), pp. 448–451. Available at: <https://doi.org/10.1038/s41893-018-0130-0>.

Mackey, R.L. and Barclay, R.M.R. (1989) 'The influence of physical clutter and noise on the activity of bats over water', *Canadian Journal of Zoology*, 67(5), pp. 1167–1170. Available at: <https://doi.org/10.1139/z89-168>.

Mackie, I.J. and Racey, P.A. (2007) 'Habitat use varies with reproductive state in noctule bats (*Nyctalus noctula*): Implications for conservation', *Biological Conservation*, 140(1), pp. 70–77. Available at: <https://doi.org/10.1016/j.biocon.2007.07.031>.

MacSwiney G., M.C., Clarke, F.M. and Racey, P.A. (2008) 'What you see is not what you get: the role of ultrasonic detectors in increasing inventory completeness in Neotropical bat assemblages', *Journal of Applied Ecology*, 45(5), pp. 1364–1371. Available at: <https://doi.org/10.1111/j.1365-2664.2008.01531.x>.

Maier, C. (1992) 'Activity patterns of pipistrelle bats (*Pipistrellus pipistrellus*) in Oxfordshire', *Journal of Zoology*, 228(1), pp. 69–80. Available at: <https://doi.org/10.1111/j.1469-7998.1992.tb04433.x>.

Makanya, A.N. and Mortola, J.P. (2007) 'The structural design of the bat wing web and its possible role in gas exchange', *Journal of Anatomy*, 211(6), pp. 687–697. Available at: <https://doi.org/10.1111/j.1469-7580.2007.00817.x>.

Mathews, F. (2020) *Bats on the Red List*. Mammal SOCIETY. Available at: <https://www.mammal.org.uk/2020/08/bats-on-the-red-list/> (Accessed: 29 July 2023).

Mathews, F. et al. (2020) 'Common Pipistrelle *Pipistrellus pipistrellus* (Schreber, 1774)', in K. Hackländer and F.E. Zachos (eds) *Handbook of the Mammals of Europe*. Cham: Springer International Publishing (Handbook of the Mammals of Europe), pp. 1–35. Available at: [https://doi.org/10.1007/978-3-319-65038-8\\_66-1](https://doi.org/10.1007/978-3-319-65038-8_66-1).

Mayfield, H. et al. (2017) *Twenty years of bat monitoring at the London Wetland Centre: Showing the biodiversity value of a man-made urban reserve*: London Naturalist 2017, pages 102-114.

McHugh, M.L. (2013) 'The Chi-square test of independence', *Biochimia Medica*, 23(2), pp. 143–149. Available at: <https://doi.org/10.11613/BM.2013.018>.

- McLean, J.A. and Speakman, J.R. (1999) 'Energy budgets of lactating and non-reproductive Brown Long-Eared Bats (*Plecotus auritus*) suggest females use compensation in lactation', *Functional Ecology*, 13(3), pp. 360–372. Available at: <https://doi.org/10.1046/j.1365-2435.1999.00321.x>.
- Michaelsen, T.C. (2016) 'Summer temperature and precipitation govern bat diversity at northern latitudes in Norway', *Mammalia*, 80(1), pp. 1–9. Available at: <https://doi.org/10.1515/mammalia-2014-0077>.
- Mickleburgh, S.P., Hutson, A.M. and Racey, P.A. (2002) 'A review of the global conservation status of bats', *Oryx*, 36(1), pp. 18–34. Available at: <https://doi.org/10.1017/S0030605302000054>.
- Mohdin, A. (2019) 'UK experiences hottest winter day ever as 21.2C is recorded in London', *The Guardian*, 26 February. Available at: <https://www.theguardian.com/uk-news/2019/feb/26/uk-hottest-winter-day-ever> (Accessed: 3 August 2023).
- Montoya-Aiona, K., Pinzari, C. and Bonaccorso, F. (2019) 'Hawaiian Hoary Bat (*Lasiurus cinereus semotus*) Activity and Prey Availability at Kaloko-Honōkohau National Historical Park'. Available at: <http://hdl.handle.net/10790/4598> (Accessed: 3 August 2023).
- Morris, A.D., Miller, D.A. and Kalcounis-Rueppell, M.C. (2010) 'Use of Forest Edges by Bats in a Managed Pine Forest Landscape', *The Journal of Wildlife Management*, 74(1), pp. 26–34. Available at: <https://doi.org/10.2193/2008-471>.
- Mukherjee Wilske, A. and Korine, C. (2002) 'The influence of biotic and abiotic factors on bat activity in Negev Desert, Israel', *Zoos' Print Journal*, 18. Available at: <https://doi.org/10.11609/JoTT.ZPJ.18.1.982-6>.
- Müller, J. *et al.* (2013) 'From ground to above canopy—Bat activity in mature forests is driven by vegetation density and height', *Forest Ecology and Management*, 306, pp. 179–184. Available at: <https://doi.org/10.1016/j.foreco.2013.06.043>.
- Murray, K. *et al.* (1999) 'Surveying bat communities: a comparison between mist nets and the Anabat II bat detector system', *Acta Chiropterologica* [Preprint]. Available at: <https://www.semanticscholar.org/paper/Surveying-bat-communities%3A-a-comparison-between-and-Murray-Brizke/c78a3c33ca63993538ef8e49f6945bb7a1406043> (Accessed: 16 August 2023).

- Nanni, V. *et al.* (2022) 'Global response of conservationists across mass media likely constrained bat persecution due to COVID-19', *Biological Conservation*, 272, p. 109591. Available at: <https://doi.org/10.1016/j.biocon.2022.109591>.
- Nelder, J.A. and Wedderburn, R.W.M. (1972) 'Generalized Linear Models', *Journal of the Royal Statistical Society. Series A (General)*, 135(3), pp. 370–384. Available at: <https://doi.org/10.2307/2344614>.
- Newman, B.A., Loeb, S.C. and Jachowski, D.S. (2021) 'Winter roosting ecology of tricolored bats (*Perimyotis subflavus*) in trees and bridges', *Journal of Mammalogy*, 102(5), pp. 1331–1341. Available at: <https://doi.org/10.1093/jmammal/gyab080>.
- Nicholls, B. and A. Racey, P. (2006) 'Habitat selection as a mechanism of resource partitioning in two cryptic bat species *Pipistrellus pipistrellus* and *Pipistrellus pygmaeus*', *Ecography*, 29(5), pp. 697–708. Available at: <https://doi.org/10.1111/j.2006.0906-7590.04575.x>.
- Niebuhr, B.B.S. *et al.* (2015) 'Survival in patchy landscapes: the interplay between dispersal, habitat loss and fragmentation', *Scientific Reports*, 5(1), p. 11898. Available at: <https://doi.org/10.1038/srep11898>.
- Nix, J.H. *et al.* (2018) 'The influence of periodic increases of human activity on crepuscular and nocturnal mammals: Testing the weekend effect', *Behavioural Processes*, 146, pp. 16–21. Available at: <https://doi.org/10.1016/j.beproc.2017.11.002>.
- Ochoa G., J., O'Farrell, M.J. and Miller, B. (2000) 'Contribution of acoustic methods to the study of insectivorous bat diversity in protected areas from northern Venezuela', *Acta Chiropterologica*, 2, pp. 171–183.
- O'Farrell, M.J. and Bradley, W.G. (1970) 'Activity Patterns of Bats over a Desert Spring', *Journal of Mammalogy*, 51(1), pp. 18–26. Available at: <https://doi.org/10.2307/1378527>.
- Oprea, M. *et al.* (2009) 'Do wooded streets provide connectivity for bats in an urban landscape?', *Biodiversity and Conservation*, 18(9), pp. 2361–2371. Available at: <https://doi.org/10.1007/s10531-009-9593-7>.
- O'Shea TJ and Bogan MA (2003) *Monitoring trends in bat populations of the United States and territories: problems and prospects*. USGS/BRD/ITR-2003-003. Washington, DC.

- Park, K.J. (2015) 'Mitigating the impacts of agriculture on biodiversity: bats and their potential role as bioindicators', *Mammalian Biology*, 80(3), pp. 191–204. Available at: <https://doi.org/10.1016/j.mambio.2014.10.004>.
- Parker, D.M. (2021) 'Three decades later in the Northern Kruger National Park: multiple acoustic and capture surveys may underestimate the true local richness of bats based on historical collections.' Available at: <https://doi.org/10.4404/hystrix-00319-2020>.
- Parkins, K.L. and Clark, J.A. (2015) 'Green roofs provide habitat for urban bats', *Global Ecology and Conservation*, 4, pp. 349–357. Available at: <https://doi.org/10.1016/j.gecco.2015.07.011>.
- Patten, M.A. (2004) 'Correlates of species richness in North American bat families', *Journal of Biogeography*, 31(6), pp. 975–985. Available at: <https://doi.org/10.1111/j.1365-2699.2004.01087.x>.
- Patterson, B., Willig, M. and Stevens, R. (2003) 'Trophic strategies, niche partitioning, and patterns of ecological organization', in *Bat ecology*, pp. 536–579.
- Perks, S.J. and Goodenough, A.E. (2020) 'Abiotic and spatiotemporal factors affect activity of European bat species and have implications for detectability for acoustic surveys', *Wildlife Biology*, 2020(2), p. wlb.00659. Available at: <https://doi.org/10.2981/wlb.00659>.
- Pfeiffer, B. and Mayer, F. (2013) 'Spermatogenesis, sperm storage and reproductive timing in bats', *Journal of Zoology*, 289(2), pp. 77–85. Available at: <https://doi.org/10.1111/j.1469-7998.2012.00970.x>.
- PIERSON, E.D. (1998) 'Tall trees, deep holes and scarred landscapes: conservation biology of North American bats.', in *Bat biology and conservation*. Washington, D.C.: Smithsonian Institution Press, pp. 309–325.
- Pineda, E. et al. (2005) 'Frog, Bat, and Dung Beetle Diversity in the Cloud Forest and Coffee Agroecosystems of Veracruz, Mexico', *Conservation Biology*, 19, pp. 400–410. Available at: <https://doi.org/10.1111/j.1523-1739.2005.00531.x>.
- Power, E.F., Kelly, D.L. and Stout, J.C. (2012) 'Organic Farming and Landscape Structure: Effects on Insect-Pollinated Plant Diversity in Intensively Managed Grasslands', *PLOS ONE*, 7(5), p. e38073. Available at: <https://doi.org/10.1371/journal.pone.0038073>.

Press Office (2018) 'Was summer 2018 the hottest on record?', *Met Office*. Available at: <https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2018/end-of-summer-stats> (Accessed: 3 August 2023).

Puechmaille, S.J., Mathy, G. and Petit, E.J. (2007) 'Good DNA from bat droppings', *Acta Chiropterologica*, 9(1), pp. 269–276. Available at: <https://doi.org/10.3161/150811007781694435>.

Queen Elizabeth Olympic Park (2019) *Biodiversity Action Plan*. Strategic Plan. London: Queen Elizabeth Olympic Park. Available at: <https://www.queenelizabetholympicpark.co.uk/our-story/how-we-work/environmental-sustainability/biodiversity> (Accessed: 4 August 2023).

Queen Elizabeth Olympic Park (2023) *Opening Hours*, Queen Elizabeth Olympic Park. Available at: <https://www.queenelizabetholympicpark.co.uk/the-park/plan-your-visit/opening-hours> (Accessed: 4 August 2023).

Racey, P. and Speakman, J. (1987) 'The energy costs of pregnancy and lactation in heterothermic bats', *Symp. Zool. Soc. Lond.*, 57, pp. 107–125.

Ramírez-Fráncel, L.A. et al. (2022) 'Bats and their vital ecosystem services: a global review', *Integrative Zoology*, 17(1), pp. 2–23. Available at: <https://doi.org/10.1111/1749-4877.12552>.

Razgour, O., Hanmer, J. and Jones, G. (2011) 'Using multi-scale modelling to predict habitat suitability for species of conservation concern: The grey long-eared bat as a case study', *Biological Conservation*, 144(12), pp. 2922–2930. Available at: <https://doi.org/10.1016/j.biocon.2011.08.010>.

Reynolds, D.S. (2006) 'Monitoring the Potential Impact of A Wind Development Site on Bats in the Northeast', *The Journal of Wildlife Management*, 70(5), pp. 1219–1227. Available at: [https://doi.org/10.2193/0022-541X\(2006\)70\[1219:MTPIOA\]2.0.CO;2](https://doi.org/10.2193/0022-541X(2006)70[1219:MTPIOA]2.0.CO;2).

Ruczyński, I. and Bartoń, K.A. (2020) 'Seasonal changes and the influence of tree species and ambient temperature on the fission-fusion dynamics of tree-roosting bats', *Behavioral Ecology and Sociobiology*, 74(5), p. 63. Available at: <https://doi.org/10.1007/s00265-020-02840-1>.

Ruiz, J.S. et al. (2023) *Generalized Linear Mixed Models with Applications in Agriculture and Biology*. Springer Nature.

Russ, J.M., Briffa, M. and Montgomery, W.I. (2003) 'Seasonal patterns in activity and habitat use by bats (*Pipistrellus* spp. and *Nyctalus leisleri*) in

Northern Ireland, determined using a driven transect', *Journal of Zoology*, 259(3), pp. 289–299. Available at: <https://doi.org/10.1017/S0952836902003254>.

Russ, J.M. and Montgomery, W.I. (2002) 'Habitat associations of bats in Northern Ireland: implications for conservation', *Biological Conservation*, 108(1), pp. 49–58. Available at: [https://doi.org/10.1016/S0006-3207\(02\)00089-7](https://doi.org/10.1016/S0006-3207(02)00089-7).

Russo, D. and Ancillotto, L. (2015) 'Sensitivity of bats to urbanization: a review', *Mammalian Biology*, 80(3), pp. 205–212. Available at: <https://doi.org/10.1016/j.mambio.2014.10.003>.

Rydell, J., Entwistle, A. and Racey, P.A. (1996) 'Timing of Foraging Flights of Three Species of Bats in Relation to Insect Activity and Predation Risk', *Oikos*, 76(2), pp. 243–252. Available at: <https://doi.org/10.2307/3546196>.

Salsamendi, E. et al. (2012) 'Foraging ecology in Mehely's horseshoe bats: influence of habitat structure and water availability', *Acta Chiropterologica*, 14(1), pp. 121–132. Available at: <https://doi.org/10.3161/150811012X654330>.

Scanlon, A.T. et al. (2008) 'Effects of site, time, weather and light on urban bat activity and richness: considerations for survey effort', *Wildlife Research*, 35(8), pp. 821–834. Available at: <https://doi.org/10.1071/WR08035>.

Sedgwick, P. (2012) 'Multiple significance tests: the Bonferroni correction', *BMJ (online)*, 344, pp. e509–e509. Available at: <https://doi.org/10.1136/bmj.e509>.

Seibold, S. et al. (2013) 'Ponds in acidic mountains are more important for bats in providing drinking water than insect prey', *Journal of Zoology*, 290(4), pp. 302–308. Available at: <https://doi.org/10.1111/jzo.12041>.

Sharma, H., Haque, A. and Blaabjerg, F. (2021) 'Machine Learning in Wireless Sensor Networks for Smart Cities: A Survey', *Electronics*, 10(9), p. 1012. Available at: <https://doi.org/10.3390/electronics10091012>.

Shilton, L.A. et al. (1999) 'Old World fruit bats can be long-distance seed dispersers through extended retention of viable seeds in the gut', *Proceedings of the Royal Society B: Biological Sciences*, 266(1416), p. 219. Available at: <https://doi.org/10.1098/rspb.1999.0625>.

Simmons N.B. and Cirranello A.L. (2020) 'Bat species of the world: a taxonomic and geographic database'. Available at: batnames.org (Accessed: 28 July 2023).

Sivasekaran, K., Sivankalai, S. and Stanleay, P. (2021) 'Bats are the only flying Mammal: A Scientometric Analysis', *Library Philosophy and Practice*, 4, pp. 1–21.

Skalak, S.L., Sherwin, R.E. and Brigham, R.M. (2012) 'Sampling period, size and duration influence measures of bat species richness from acoustic surveys', *Methods in Ecology and Evolution*, 3(3), pp. 490–502. Available at: <https://doi.org/10.1111/j.2041-210X.2011.00177.x>.

Skowronski, M.D. and Harris, J.G. (2006) 'Acoustic detection and classification of microchiroptera using machine learning: Lessons learned from automatic speech recognition', *The Journal of the Acoustical Society of America*, 119(3), pp. 1817–1833. Available at: <https://doi.org/10.1121/1.2166948>.

Smeraldo, S. et al. (2021) 'Generalists yet different: distributional responses to climate change may vary in opportunistic bat species sharing similar ecological traits', *Mammal Review*, 51(4), pp. 571–584. Available at: <https://doi.org/10.1111/mam.12247>.

Smith, A.D. and McWilliams, S.R. (2016) 'Bat activity during autumn relates to atmospheric conditions: implications for coastal wind energy development', *Journal of Mammalogy*, 97(6), pp. 1565–1577. Available at: <https://doi.org/10.1093/jmammal/gyw116>.

Smith, J.D. (1977) 'Comments on Flight and the Evolution of Bats', in M.K. Hecht, P.C. Goody, and B.M. Hecht (eds) *Major Patterns in Vertebrate Evolution*. Boston, MA: Springer US (NATO Advanced Study Institutes Series), pp. 427–437. Available at: [https://doi.org/10.1007/978-1-4684-8851-7\\_15](https://doi.org/10.1007/978-1-4684-8851-7_15).

Soetewey, A. (2022) *Kruskal-Wallis test, or the nonparametric version of the ANOVA, Stats and R*. Available at: <https://statsandr.com/blog/kruskal-wallis-test-nonparametric-version-anova/> (Accessed: 1 August 2023).

Soper, K.D. and Fenton, M.B. (2007) 'Availability of building roosts for bats in four towns in southwestern Ontario, Canada', *Acta Chiropterologica*, 9(2), pp. 542–546. Available at: [https://doi.org/10.3161/1733-5329\(2007\)9\[542:AOBRFB\]2.0.CO;2](https://doi.org/10.3161/1733-5329(2007)9[542:AOBRFB]2.0.CO;2).

Speakman J R (1995) 'Chiropteran nocturnality', *Symposia of the zoological society of London. London: The Society, 1960-1999.*, 67, pp. 187–201.

Speakman, J.R. and Racey, P.A. (1986) 'The influence of body condition on sexual development of male Brown long-eared bats (*Plecotus auritus*) in the

wild', *Journal of Zoology*, 210(4), pp. 515–525. Available at: <https://doi.org/10.1111/j.1469-7998.1986.tb03653.x>.

Spector, S. and A.B. Forsyth (1998) 'Indicator taxa in the vanishing tropics.', in *Conservation in a changing world*. Cambridge [England]: Cambridge University Press (Conservation biology series (Cambridge, England)), pp. 181–209. Available at: <http://catdir.loc.gov/catdir/toc/cam026/98024393.html> (Accessed: 27 July 2023).

Stapelfeldt, B. et al. (2022) 'Precipitation during two weeks in spring influences reproductive success of first-year females in the long-lived Natterer's bat', *Royal Society Open Science*, 9(2), p. 211881. Available at: <https://doi.org/10.1098/rsos.211881>.

Stone, E.L., Harris, S. and Jones, G. (2015) 'Impacts of artificial lighting on bats: a review of challenges and solutions', *Mammalian Biology*, 80(3), pp. 213–219. Available at: <https://doi.org/10.1016/j.mambio.2015.02.004>.

Stowell, D. and Plumley, M.D. (2014) 'Automatic large-scale classification of bird sounds is strongly improved by unsupervised feature learning', *PeerJ*, 2, p. e488. Available at: <https://doi.org/10.7717/peerj.488>.

Straka, T.M. et al. (2019) 'Tree Cover Mediates the Effect of Artificial Light on Urban Bats', *Frontiers in Ecology and Evolution*, 7. Available at: <https://www.frontiersin.org/articles/10.3389/fevo.2019.00091> (Accessed: 4 August 2023).

Stroup, W.W. (2012) *Generalized Linear Mixed Models: Modern Concepts, Methods and Applications*. CRC Press.

Swift, S.M. (1980) 'Activity patterns of Pipistrelle bats (*Pipistrellus pipistrellus*) in north-east Scotland', *Journal of Zoology*, 190(3), pp. 285–295. Available at: <https://doi.org/10.1111/j.1469-7998.1980.tb01428.x>.

Sztencel-Jablonka, A. and Bogdanowicz, W. (2012) 'Population genetics study of common (*Pipistrellus pipistrellus*) and soprano (*Pipistrellus pygmaeus*) pipistrelle bats from central Europe suggests interspecific hybridization', *Canadian Journal of Zoology*, 90(10), pp. 1251–1260. Available at: <https://doi.org/10.1139/z2012-092>.

Sztencel-Jablonka, A., Jones, G. and Bogdanowicz, W. (2009) 'Skull Morphology of Two Cryptic Bat Species: *Pipistrellus pipistrellus* and *P. pygmaeus* — A 3D Geometric Morphometrics Approach with Landmark Reconstruction', *Acta Chiropterologica*, 11(1), pp. 113–126. Available at: <https://doi.org/10.3161/150811009X465730>.

- Thomas, J.P. *et al.* (2021) 'Foraging habitat drives the distribution of an endangered bat in an urbanizing boreal landscape', *Ecosphere*, 12(3), p. e03457. Available at: <https://doi.org/10.1002/ecs2.3457>.
- UN, I. (1992) 'CONVENTION ON BIOLOGICAL DIVERSITY', *Treaty Collection* [Preprint].
- Vaughan, N., Jones, G. and Harris, S. (1997) 'Habitat Use by Bats (Chiroptera) Assessed by Means of a Broad-Band Acoustic Method', *Journal of Applied Ecology*, 34(3), pp. 716–730. Available at: <https://doi.org/10.2307/2404918>.
- Verboom, B. and Huitema, H. (1997) 'The importance of linear landscape elements for the pipistrelle *Pipistrellus pipistrellus* and the serotine bat *Eptesicus serotinus*', *Landscape Ecology*, 12(2), pp. 117–125. Available at: <https://doi.org/10.1007/BF02698211>.
- Vlaschenko, A. *et al.* (2019) 'An example of ecological traps for bats in the urban environment', *European Journal of Wildlife Research*, 65(2), p. 20. Available at: <https://doi.org/10.1007/s10344-019-1252-z>.
- Wainwright, P.C. and Reilly, S.M. (1994) 'Wing Design, Flight Performance, and Habitat Use in Bats', in *Ecological Morphology: Integrative Organismal Biology*. Chicago. University of Chicago Press, p. 205.
- Walsh, A. *et al.* (2001) 'The UK's National Bat Monitoring Programme: Final Report'. Available at: <https://abdn.pure.elsevier.com/en/publications/the-uks-national-bat-monitoring-programme-final-report> (Accessed: 16 August 2023).
- Walsh, A.L. and Harris, S. (1996) 'Foraging Habitat Preferences of Vespertilionid Bats in Britain', *Journal of Applied Ecology*, 33(3), pp. 508–518. Available at: <https://doi.org/10.2307/2404980>.
- Warren, R.D. *et al.* (2000) 'The distribution of Daubenton's bats (*Myotis daubentonii*) and pipistrelle bats (*Pipistrellus pipistrellus*) (Vespertilionidae) in relation to small-scale variation in riverine habitat', *Biological Conservation*, 92(1), pp. 85–91. Available at: [https://doi.org/10.1016/S0006-3207\(99\)00062-2](https://doi.org/10.1016/S0006-3207(99)00062-2).
- Warwickshire Bat Group (no date) *Taxonomy*, Warwickshire Bat Group. Available at: <https://www.warksbats.co.uk/aboutbats/taxonomy.aspx> (Accessed: 28 July 2023).
- Webb, P., Speakman, J. and Racey, P. (2009) 'Evaporative water loss in two sympatric species of vespertilionid bat, *Plecotus auritus* and *Myotis*

daubentoni: Relation to foraging mode and implications for roost site selection', *Journal of Zoology*, 235, pp. 269–278. Available at: <https://doi.org/10.1111/j.1469-7998.1995.tb05143.x>.

Węgiel, A. et al. (2023) 'Comparison of the Foraging Activity of Bats in Coniferous, Mixed, and Deciduous Managed Forests', *Forests*, 14(3), p. 481. Available at: <https://doi.org/10.3390/f14030481>.

Welch, J.N. and Leppanen, C. (2017) 'The threat of invasive species to bats: a review', *Mammal Review*, 47(4), pp. 277–290. Available at: <https://doi.org/10.1111/mam.12099>.

Weller, T.J. and Baldwin, J.A. (2012) 'Using echolocation monitoring to model bat occupancy and inform mitigations at wind energy facilities', *The Journal of Wildlife Management*, 76(3), pp. 619–631. Available at: <https://doi.org/10.1002/jwmg.260>.

Wermundsen, T. and Siivonen, Y. (2010) 'Seasonal variation in use of winter roosts by five bat species in south-east Finland', *Open Life Sciences*, 5(2), pp. 262–273. Available at: <https://doi.org/10.2478/s11535-009-0063-8>.

Wickramasinghe, L.P. et al. (2003) 'Bat activity and species richness on organic and conventional farms: impact of agricultural intensification', *Journal of Applied Ecology*, 40(6), pp. 984–993. Available at: <https://doi.org/10.1111/j.1365-2664.2003.00856.x>.

Williams, J.A., O'Farrell, M.J. and Riddle, B.R. (2006) 'Habitat Use by Bats in a Riparian Corridor of the Mojave Desert in Southern Nevada', *Journal of Mammalogy*, 87(6), pp. 1145–1153. Available at: <https://doi.org/10.1644/06-MAMM-A-085R2.1>.

Wimsatt, W.A. (1969) 'Transient Behavior, Nocturnal Activity Patterns, and Feeding Efficiency of Vampire Bats (*Desmodus Rotundus*) under Natural Conditions', *Journal of Mammalogy*, 50(2), pp. 233–244. Available at: <https://doi.org/10.2307/1378339>.

Wolbert, S.J., Zellner, A.S. and Whidden, H.P. (2014) 'Bat Activity, Insect Biomass, and Temperature Along an Elevational Gradient', *Northeastern Naturalist*, 21(1), pp. 72–85. Available at: <https://doi.org/10.1656/045.021.0106>.

Wolcott, K.A. and Vulinec, K. (2012) 'Bat Activity at Woodland/Farmland Interfaces in Central Delaware', *Northeastern Naturalist*, 19(1), pp. 87–98. Available at: <https://doi.org/10.1656/045.019.0107>.

Wolf, J.M. *et al.* (2022) 'Urban affinity and its associated traits: A global analysis of bats', *Global Change Biology*, 28(19), pp. 5667–5682. Available at: <https://doi.org/10.1111/gcb.16320>.

Wright, K. (2014) 'Becoming-with', *Environmental Humanities*, 5(1), pp. 277–281. Available at: <https://doi.org/10.1215/22011919-3615514>.

Yoshikura, S., Yasui, S. and Kamijo, T. (2011) 'Comparative Study of Forest-Dwelling Bats' Abundances and Species Richness between Old-Growth Forests and Conifer Plantations in Nikko National Park, Central Japan', *Mammal Study*, 36(4), pp. 189–198. Available at: <https://doi.org/10.3106/041.036.0402>.

Young, J. *et al.* (2005) 'Towards sustainable land use: identifying and managing the conflicts between human activities and biodiversity conservation in Europe', *Biodiversity & Conservation*, 14(7), pp. 1641–1661. Available at: <https://doi.org/10.1007/s10531-004-0536-z>.

Zahn, A. and Kriner, E. (2016) 'Winter foraging activity of Central European Vespertilionid bats', *Mammalian Biology*, 81(1), pp. 40–45. Available at: <https://doi.org/10.1016/j.mambio.2014.10.005>.

Zeale, M.R.K., Davidson-Watts, I. and Jones, G. (2012) 'Home range use and habitat selection by barbastelle bats (*Barbastella barbastellus*): implications for conservation', *Journal of Mammalogy*, 93(4), pp. 1110–1118. Available at: <https://doi.org/10.1644/11-MAMM-A-366.1>.

Zhang, X.Q. (2016) 'The trends, promises and challenges of urbanisation in the world', *Habitat International*, 54, pp. 241–252. Available at: <https://doi.org/10.1016/j.habitatint.2015.11.018>.

Zortéa, M. (2003) 'Reproductive patterns and feeding habits of three nectarivorous bats (Phyllostomidae: Glossophaginae) from the Brazilian Cerrado', *Brazilian Journal of Biology*, 63, pp. 159–168. Available at: <https://doi.org/10.1590/S1519-69842003000100020>.

Zualkernan, I. *et al.* (2021) 'An IoT System for Bat Species Classification', in *2020 IEEE International Conference on Internet of Things and Intelligence System (IoTaIS). 2020 IEEE International Conference on Internet of Things and Intelligence System (IoTaIS)*, pp. 155–160. Available at: <https://doi.org/10.1109/IoTaIS50849.2021.9359704>.

Zukalova, K. *et al.* (2022) 'One or two pups - optimal reproduction strategies of common noctule females', *BMC Zoology*, 7(1), p. 18. Available at: <https://doi.org/10.1186/s40850-022-00119-8>.

Zuur, A.F. *et al.* (2009) *Mixed effects models and extensions in ecology with R*. New York, NY: Springer (Statistics for Biology and Health). Available at: <https://doi.org/10.1007/978-0-387-87458-6>.

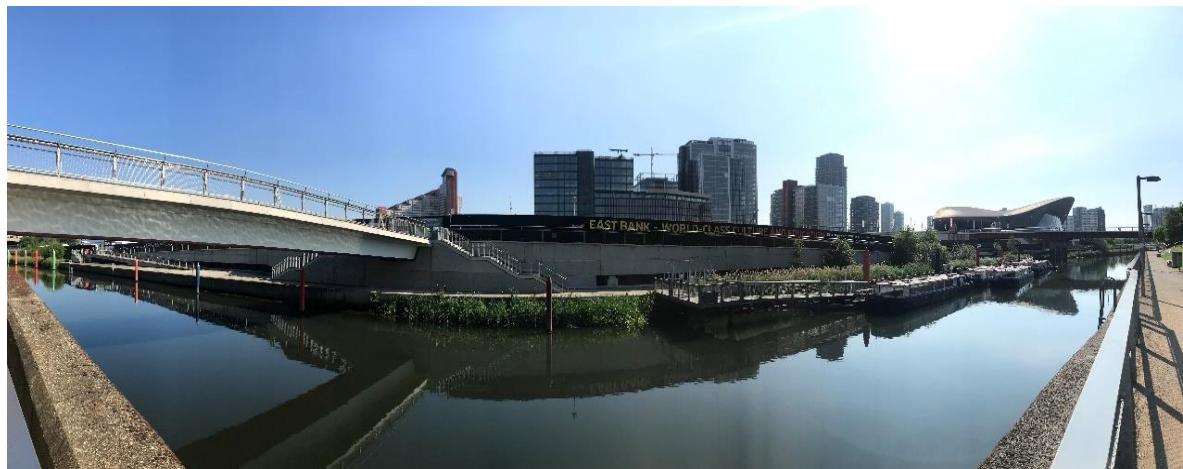
## Appendix

**Appendix A:** “Echo boxes” Acoustic Monitor installed in Queen Elizabeth Olympic Park



*Source: [https://www.flickr.com/search/?sort=date-taken-desc&safe\\_search=1&tags=shazam&user\\_id=96635144%40N00&view\\_all=1](https://www.flickr.com/search/?sort=date-taken-desc&safe_search=1&tags=shazam&user_id=96635144%40N00&view_all=1)*

## **Appendix B: Riverbank fencing in Queen Elizabeth Olympic Park**



**Source:** [https://www.flickr.com/search/?sort=date-taken-desc&safe\\_search=1&tags=shazam&user\\_id=96635144%40N00&view\\_all=1](https://www.flickr.com/search/?sort=date-taken-desc&safe_search=1&tags=shazam&user_id=96635144%40N00&view_all=1)

## **Appendix C: Grassland in Queen Elizabeth Olympic Park**



**Source:** [https://www.flickr.com/search/?sort=date-taken-desc&safe\\_search=1&tags=shazam&user\\_id=96635144%40N00&view\\_all=1](https://www.flickr.com/search/?sort=date-taken-desc&safe_search=1&tags=shazam&user_id=96635144%40N00&view_all=1)

## Appendix D: All candidate models tested by Akaike information criterion (all species)

No.	Model	AIC	ΔAIC
1	All_Calls_Volume ~ hour_sunset + season + Humidity + Temperature + Windspeed*Windgust + Dew_point + Pressure*Pressure_Trend + Precipitation_rate*Precipitation_total + Wind_chill*Heat_Index + (1 sensor_number)	64935.97	0.00
2	All_Calls_Volume ~ hour_sunset + season + Temperature + Windspeed*Windgust + Pressure*Pressure_Trend + Wind_chill*Heat_Index + (1 sensor_number)	65068.24	132.27
3	All_Calls_Volume ~ hour_sunset + season + Temperature + Windspeed*Windgust + Dew_point + Wind_chill*Heat_Index + (1 sensor_number)	65093.03	157.06
4	All_Calls_Volume ~ hour_sunset + season + Temperature + Windspeed*Windgust + Wind_chill*Heat_Index + (1 sensor_number)	65097.88	161.91
5	All_Calls_Volume ~ hour_sunset + season + Temperature + Dew_point + Pressure*Pressure_Trend + Wind_chill*Heat_Index + (1 sensor_number)	65121.23	185.26
6	All_Calls_Volume ~ hour_sunset + season + Temperature + Pressure*Pressure_Trend + Wind_chill*Heat_Index + (1 sensor_number)	65128.51	192.54
7	All_Calls_Volume ~ hour_sunset + season + Temperature + Humidity + Wind_chill*Heat_Index + (1 sensor_number)	65157.13	221.16
8	All_Calls_Volume ~ hour_sunset + season + Temperature + Dew_point + Wind_chill*Heat_Index + (1 sensor_number)	65162.13	226.16
9	All_Calls_Volume ~ hour_sunset + season + Temperature + Wind_chill*Heat_Index + (1 sensor_number)	65171.03	235.06
10	All_Calls_Volume ~ hour_sunset + season + Humidity + Temperature + Windspeed + Windgust + Dew_point + Pressure + Pressure_Trend + Precipitation_rate + Precipitation_total + Wind_chill + Heat_Index + (1 sensor_number)	65200.80	264.83
11	All_Calls_Volume ~ hour_sunset + season + Temperature + Windspeed + Windgust + Pressure + Pressure_Trend + Wind_chill + Heat_Index + (1 sensor_number)	65317.35	381.38
12	All_Calls_Volume ~ hour_sunset + season + Temperature + Windspeed + Windgust + Wind_chill + Heat_Index + (1 sensor_number)	65322.26	386.29
13	All_Calls_Volume ~ hour_sunset + season + Temperature + Windspeed + Windgust + Dew_point + Wind_chill + Heat_Index + (1 sensor_number)	65323.13	387.17
14	All_Calls_Volume ~ hour_sunset + season + Temperature + Pressure + Pressure_Trend + Wind_chill + Heat_Index + (1 sensor_number)	65342.03	406.06
15	All_Calls_Volume ~ hour_sunset + season + Temperature + Dew_point + Pressure + Pressure_Trend + Wind_chill + Heat_Index + (1 sensor_number)	65343.18	407.21
16	All_Calls_Volume ~ hour_sunset + season + Temperature + Precipitation_rate*Precipitation_total + (1 sensor_number)	65344.45	408.48
17	All_Calls_Volume ~ hour_sunset + season + Temperature + Humidity + Precipitation_rate*Precipitation_total + (1 sensor_number)	65346.45	410.48
18	All_Calls_Volume ~ hour_sunset + season + Temperature + Humidity + Wind_chill + Heat_Index + (1 sensor_number)	65350.67	414.70
19	All_Calls_Volume ~ hour_sunset + season + Temperature + Dew_point + Wind_chill + Heat_Index + (1 sensor_number)	65354.80	418.83
20	All_Calls_Volume ~ hour_sunset + season + Temperature + Wind_chill + Heat_Index + (1 sensor_number)	65354.89	418.92
21	All_Calls_Volume ~ hour_sunset + season + Temperature + Windspeed*Windgust + Pressure*Pressure_Trend + (1 sensor_number)	65365.12	429.15
22	All_Calls_Volume ~ hour_sunset + season + Temperature + Windspeed*Windgust + Dew_point + Pressure*Pressure_Trend + (1 sensor_number)	65367.11	431.14
23	All_Calls_Volume ~ hour_sunset + season + Temperature + Precipitation_rate + Precipitation_total + (1 sensor_number)	65379.94	443.97
24	All_Calls_Volume ~ hour_sunset + season + Temperature + Humidity + Precipitation_rate + Precipitation_total + (1 sensor_number)	65381.63	445.66
25	All_Calls_Volume ~ hour_sunset + season + Temperature + Windspeed + Windgust + Pressure + Pressure_Trend + (1 sensor_number)	65401.75	465.78
26	All_Calls_Volume ~ hour_sunset + season + Temperature + Windspeed + Windgust + Dew_point + Pressure + Pressure_Trend + (1 sensor_number)	65403.70	467.73
27	All_Calls_Volume ~ hour_sunset + season + Temperature + Windspeed*Windgust + (1 sensor_number)	65405.73	469.77
28	All_Calls_Volume ~ hour_sunset + season + Temperature + Windspeed + Windgust + (1 sensor_number)	65406.89	470.92
29	All_Calls_Volume ~ hour_sunset + season + Temperature + Humidity + Windspeed*Windgust + (1 sensor_number)	65407.19	471.22
30	All_Calls_Volume ~ hour_sunset + season + Temperature + Windspeed*Windgust + Dew_point + (1 sensor_number)	65407.72	471.75
31	All_Calls_Volume ~ hour_sunset + season + Temperature + Humidity + Windspeed + Windgust + (1 sensor_number)	65408.00	472.04
32	All_Calls_Volume ~ hour_sunset + season + Temperature + Windspeed + Windgust + Dew_point + (1 sensor_number)	65408.88	472.91
33	All_Calls_Volume ~ hour_sunset + season + Temperature + Pressure*Pressure_Trend + (1 sensor_number)	65434.13	498.16
34	All_Calls_Volume ~ hour_sunset + season + Temperature + Humidity + Pressure*Pressure_Trend + (1 sensor_number)	65435.19	499.23
35	All_Calls_Volume ~ hour_sunset + season + Temperature + Dew_point + Pressure*Pressure_Trend + (1 sensor_number)	65436.12	500.15
36	All_Calls_Volume ~ hour_sunset + season + Temperature + Pressure + Pressure_Trend + (1 sensor_number)	65470.38	534.41
37	All_Calls_Volume ~ hour_sunset + season + Temperature + Humidity + Pressure + Pressure_Trend + (1 sensor_number)	65471.90	535.93
38	All_Calls_Volume ~ hour_sunset + season + Temperature + Humidity + Dew_point + (1 sensor_number)	65472.18	536.21
39	All_Calls_Volume ~ hour_sunset + season + Temperature + Dew_point + Pressure + Pressure_Trend + (1 sensor_number)	65472.36	536.39
40	All_Calls_Volume ~ hour_sunset + season + Temperature + Humidity + (1 sensor_number)	65491.63	555.66
41	All_Calls_Volume ~ hour_sunset + season + Temperature + (1 sensor_number)	65492.04	556.07
42	All_Calls_Volume ~ hour_sunset + season + Temperature + Dew_point + (1 sensor_number)	65493.82	557.85
43	All_Calls_Volume ~ hour_sunset + season + (1 sensor_number)	65761.40	825.43

## Appendix E: All candidate models tested by Akaike information criterion (*Pipistrellus nathusii*)

No.	Model	AIC	$\Delta AIC$
1	V_Pipistrellus_nathusii ~ hour_sunset + season + Humidity + Temperature + Windspeed*Windgust + Dew_point + Pressure*Pressure_Trend + Precipitation_rate*Precipitation_total + Wind_chill*Heat_index + (1 sensor_number)	35598.71	0.00
2	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Windspeed*Windgust + Pressure*Pressure_Trend + Wind_chill*Heat_index + (1 sensor_number)	35707.13	21.39
3	V_Pipistrellus_nathusii ~ hour_sunset + season + Humidity + Temperature + Windspeed + Windgust + Dew_point + Pressure + Pressure_Trend + Precipitation_rate + Precipitation_total + Wind_chill + Heat_index + (1 sensor_number)	35728.52	47.63
4	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Windspeed*Windgust + Wind_chill*Heat_index + (1 sensor_number)	35754.76	49.61
5	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Windspeed*Windgust + Dew_point + Wind_chill*Heat_index + (1 sensor_number)	35756.74	60.35
6	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Pressure*Pressure_Trend + Wind_chill*Heat_index + (1 sensor_number)	35767.48	62.29
7	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Dew_point + Pressure*Pressure_Trend + Wind_chill*Heat_index + (1 sensor_number)	35769.41	126.25
8	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Windspeed*Windgust + Dew_point + Pressure*Pressure_Trend + (1 sensor_number)	35833.38	130.05
9	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Windspeed*Windgust + Pressure*Pressure_Trend + (1 sensor_number)	35837.18	130.08
10	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Windspeed + Windgust + Pressure + Pressure_Trend + Wind_chill + Heat_index + (1 sensor_number)	35837.21	133.55
11	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Wind_chill*Heat_index + (1 sensor_number)	35840.68	134.05
12	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Humidity + Wind_chill*Heat_index + (1 sensor_number)	35841.18	135.24
13	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Dew_point + Wind_chill*Heat_index + (1 sensor_number)	35842.37	154.89
14	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Windspeed + Windgust + Dew_point + Wind_chill + Heat_index + (1 sensor_number)	35862.02	155.99
15	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Windspeed + Windgust + Wind_chill + Heat_index + (1 sensor_number)	35863.12	160.76
16	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Windspeed + Windgust + Dew_point + Pressure + Pressure_Trend + (1 sensor_number)	35867.89	166.18
17	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Windspeed + Windgust + Pressure + Pressure_Trend + (1 sensor_number)	35873.31	166.94
18	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Dew_point + Pressure + Pressure_Trend + Wind_chill + Heat_index + (1 sensor_number)	35874.06	168.20
19	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Pressure + Pressure_Trend + Wind_chill + Heat_index + (1 sensor_number)	35875.32	172.99
20	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Humidity + Precipitation_rate*Precipitation_total + (1 sensor_number)	35880.11	174.13
21	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Precipitation_rate*Precipitation_total + (1 sensor_number)	35881.26	179.47
22	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Humidity + Precipitation_rate + Precipitation_total + (1 sensor_number)	35886.59	179.93
23	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Precipitation_rate + Precipitation_total + (1 sensor_number)	35887.06	185.86
24	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Windspeed + Windgust + Dew_point + (1 sensor_number)	35892.99	186.99
25	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Windspeed*Windgust + Dew_point + (1 sensor_number)	35894.12	188.21
26	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Humidity + Windspeed + Windgust + (1 sensor_number)	35895.34	189.01
27	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Windspeed + Windgust + (1 sensor_number)	35896.13	189.15
28	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Humidity + Windspeed*Windgust + (1 sensor_number)	35896.27	189.54
29	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Windspeed*Windgust + (1 sensor_number)	35896.67	200.03
30	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Dew_point + Pressure*Pressure_Trend + (1 sensor_number)	35907.15	202.20
31	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Humidity + Pressure*Pressure_Trend + (1 sensor_number)	35909.32	203.14
32	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Pressure*Pressure_Trend + (1 sensor_number)	35910.26	214.94
33	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Wind_chill + Heat_index + (1 sensor_number)	35922.06	216.01
34	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Dew_point + Wind_chill + Heat_index + (1 sensor_number)	35923.13	216.93
35	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Humidity + Wind_chill + Heat_index + (1 sensor_number)	35924.06	234.37
36	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Dew_point + Pressure + Pressure_Trend + (1 sensor_number)	35941.50	236.67
37	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Humidity + Pressure + Pressure_Trend + (1 sensor_number)	35943.80	238.01
38	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Pressure + Pressure_Trend + (1 sensor_number)	35945.13	278.76
39	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Dew_point + (1 sensor_number)	35985.89	290.72
40	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Dew_point + (1 sensor_number)	35997.85	290.96
41	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + (1 sensor_number)	35998.09	292.66
42	V_Pipistrellus_nathusii ~ hour_sunset + season + Temperature + Humidity + (1 sensor_number)	35999.78	372.30
43	V_Pipistrellus_nathusii ~ hour_sunset + season + (1 sensor_number)	36079.43	-35707.13

## Appendix F: All candidate models tested by Akaike information criterion (*Pipistrellus pipistrellus*)

No.	Model	AIC	$\Delta AIC$
1	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Humidity + Temperature + Windspeed*Windgust + Dew_point + Pressure*Pressure_Trend + Precipitation_rate*Precipitation_total + Wind_chill*Heat_index + (1 sensor_number)	60153.47	0.00
2	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Windspeed*Windgust + Pressure*Pressure_Trend + Wind_chill*Heat_index + (1 sensor_number)	60347.81	194.34
3	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Windspeed*Windgust + Dew_point + Wind_chill*Heat_index + (1 sensor_number)	60371.69	218.22
4	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Windspeed*Windgust + Wind_chill*Heat_index + (1 sensor_number)	60374.99	221.52
5	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Dew_point + Pressure*Pressure_Trend + Wind_chill*Heat_index + (1 sensor_number)	60416.23	262.76
6	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Pressure*Pressure_Trend + Wind_chill*Heat_index + (1 sensor_number)	60423.30	269.83
7	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Humidity + Wind_chill*Heat_index + (1 sensor_number)	60449.51	296.04
8	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Dew_point + Wind_chill*Heat_index + (1 sensor_number)	60454.74	301.27
9	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Wind_chill*Heat_index + (1 sensor_number)	60462.65	309.18
10	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Humidity + Temperature + Windspeed + Windgust + Dew_point + Pressure + Pressure_Trend + Precipitation_rate + Precipitation_total + Wind_chill + Heat_index + (1 sensor_number)	60501.44	347.97
11	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Precipitation_rate*Precipitation_total + (1 sensor_number)	60599.43	445.96
12	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Humidity + Precipitation_rate*Precipitation_total + (1 sensor_number)	60601.41	447.94
13	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Windspeed + Windgust + Wind_chill + Heat_index + (1 sensor_number)	60641.78	488.31
14	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Windspeed + Windgust + Pressure + Pressure_Trend + Wind_chill + Heat_index + (1 sensor_number)	60641.83	488.36
15	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Windspeed + Windgust + Dew_point + Wind_chill + Heat_index + (1 sensor_number)	60642.91	489.44
16	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Pressure + Pressure_Trend + Wind_chill + Heat_index + (1 sensor_number)	60669.67	516.20
17	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Dew_point + Pressure + Pressure_Trend + Wind_chill + Heat_index + (1 sensor_number)	60670.88	517.41
18	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Humidity + Wind_chill + Heat_index + (1 sensor_number)	60672.41	518.94
19	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Wind_chill + Heat_index + (1 sensor_number)	60676.53	523.07
20	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Dew_point + Wind_chill + Heat_index + (1 sensor_number)	60676.75	523.28
21	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Precipitation_rate + Precipitation_total + (1 sensor_number)	60683.19	529.72
22	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Windspeed*Windgust + Pressure*Pressure_Trend + (1 sensor_number)	60683.36	529.89
23	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Humidity + Precipitation_rate + Precipitation_total + (1 sensor_number)	60684.87	531.40
24	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Windspeed*Windgust + Dew_point + Pressure*Pressure_Trend + (1 sensor_number)	60685.31	531.84
25	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Windspeed*Windgust + (1 sensor_number)	60719.53	566.06
26	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Humidity + Windspeed*Windgust + (1 sensor_number)	60721.18	567.71
27	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Windspeed*Windgust + Dew_point + (1 sensor_number)	60721.39	567.92
28	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Windspeed + Windgust + (1 sensor_number)	60725.45	571.98
29	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Windspeed + Windgust + Pressure + Pressure_Trend + (1 sensor_number)	60725.82	572.35
30	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Humidity + Windspeed + Windgust + (1 sensor_number)	60726.61	573.14
31	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Windspeed + Windgust + Dew_point + (1 sensor_number)	60727.45	573.98
32	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Windspeed + Windgust + Dew_point + Pressure + Pressure_Trend + (1 sensor_number)	60727.77	574.31
33	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Pressure*Pressure_Trend + (1 sensor_number)	60760.71	607.24
34	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Humidity + Pressure*Pressure_Trend + (1 sensor_number)	60761.39	607.92
35	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Dew_point + Pressure*Pressure_Trend + (1 sensor_number)	60762.70	609.23
36	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Humidity + Dew_point + (1 sensor_number)	60786.98	633.51
37	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Pressure + Pressure_Trend + (1 sensor_number)	60800.86	647.39
38	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Humidity + Pressure + Pressure_Trend + (1 sensor_number)	60802.13	648.67
39	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Dew_point + Pressure + Pressure_Trend + (1 sensor_number)	60802.82	649.35
40	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Humidity + (1 sensor_number)	60813.29	659.82
41	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + (1 sensor_number)	60813.74	660.27
42	V_Pipistrellus_pipistrellus ~ hour_sunset + season + Temperature + Dew_point + (1 sensor_number)	60815.62	662.15
43	V_Pipistrellus_pipistrellus ~ hour_sunset + season + (1 sensor_number)	61121.34	967.87

## Appendix G: All candidate models tested by Akaike information criterion (*Pipistrellus pygmaeus*)

No.	Model	AIC	$\Delta AIC$
1	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Humidity + Temperature + Windspeed*Windgust + Dew_point + Pressure*Pressure_Trend + Precipitation_rate*Precipitation_total + Wind_chill*Heat_Index + (1 sensor_number)	32519.03	0.00
2	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Windspeed*Windgust + Dew_point + Wind_chill*Heat_Index + (1 sensor_number)	32640.89	121.86
3	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Windspeed*Windgust + Pressure*Pressure_Trend + Wind_chill*Heat_Index + (1 sensor_number)	32654.26	135.23
4	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Windspeed*Windgust + Wind_chill*Heat_Index + (1 sensor_number)	32677.01	157.98
5	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Dew_point + Pressure*Pressure_Trend + Wind_chill*Heat_Index + (1 sensor_number)	32693.40	174.37
6	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Humidity + Temperature + Windspeed + Windgust + Dew_point + Pressure*Pressure_Trend + Precipitation_rate*Precipitation_total + Wind_chill*Heat_Index + (1 sensor_number)	32695.37	176.34
7	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Dew_point + Wind_chill*Heat_Index + (1 sensor_number)	32733.35	214.32
8	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Humidity + Wind_chill*Heat_Index + (1 sensor_number)	32747.05	228.02
9	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Pressure*Pressure_Trend + Wind_chill*Heat_Index + (1 sensor_number)	32754.60	235.57
10	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Windspeed + Windgust + Dew_point + Wind_chill*Heat_Index + (1 sensor_number)	32775.82	256.79
11	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Windspeed*Windgust + Dew_point + Pressure*Pressure_Trend + (1 sensor_number)	32778.50	259.47
12	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Wind_chill*Heat_Index + (1 sensor_number)	32788.22	269.19
13	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Windspeed*Windgust + Pressure*Pressure_Trend + (1 sensor_number)	32799.66	280.63
14	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Windspeed + Windgust + Pressure + Pressure_Trend + Wind_chill*Heat_Index + (1 sensor_number)	32803.60	284.57
15	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Windspeed + Windgust + Wind_chill + Heat_Index + (1 sensor_number)	32803.70	284.67
16	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Windspeed*Windgust + Dew_point + (1 sensor_number)	32808.59	289.56
17	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Windspeed + Windgust + Dew_point + Pressure*Pressure_Trend + (1 sensor_number)	32813.09	294.06
18	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Humidity + Windspeed*Windgust + (1 sensor_number)	32813.48	294.45
19	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Windspeed + Windgust + Dew_point + (1 sensor_number)	32814.64	295.61
20	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Humidity + Windspeed + Windgust + (1 sensor_number)	32820.31	301.28
21	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Windspeed*Windgust + (1 sensor_number)	32823.43	304.40
22	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Humidity + Precipitation_rate*Precipitation_total + (1 sensor_number)	32830.14	311.11
23	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Dew_point + Pressure + Pressure_Trend + Wind_chill + Heat_Index + (1 sensor_number)	32831.15	312.12
24	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Humidity + Precipitation_rate + Precipitation_total + (1 sensor_number)	32832.02	312.99
25	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Windspeed + Windgust + Pressure + Pressure_Trend + (1 sensor_number)	32832.33	313.30
26	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Windspeed + Windgust + (1 sensor_number)	32832.54	313.51
27	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Dew_point + Wind_chill + Heat_Index + (1 sensor_number)	32835.81	316.78
28	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Precipitation_rate*Precipitation_total + (1 sensor_number)	32838.04	319.01
29	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Precipitation_rate + Precipitation_total + (1 sensor_number)	32840.92	321.89
30	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Humidity + Wind_chill + Heat_Index + (1 sensor_number)	32843.64	324.61
31	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Dew_point + Pressure*Pressure_Trend + (1 sensor_number)	32861.05	342.02
32	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Humidity + Pressure*Pressure_Trend + (1 sensor_number)	32866.56	347.53
33	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Pressure + Pressure_Trend + Wind_chill + Heat_Index + (1 sensor_number)	32867.41	348.38
34	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Wind_chill + Heat_Index + (1 sensor_number)	32873.52	354.49
35	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Pressure*Pressure_Trend + (1 sensor_number)	32891.57	372.54
36	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Dew_point + Pressure + Pressure_Trend + (1 sensor_number)	32893.84	374.81
37	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Dew_point + (1 sensor_number)	32897.07	378.04
38	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Humidity + Pressure + Pressure_Trend + (1 sensor_number)	32898.32	379.29
39	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Dew_point + (1 sensor_number)	32898.53	379.51
40	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Humidity + (1 sensor_number)	32903.71	384.69
41	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + Pressure + Pressure_Trend + (1 sensor_number)	32919.10	400.08
42	V_Pipistrellus_pygmaeus ~ hour_sunset + season + Temperature + (1 sensor_number)	32924.96	405.93
43	V_Pipistrellus_pygmaeus ~ hour_sunset + season + (1 sensor_number)	32953.56	434.54

## **Appendix H: Meeting Lists**

### **18th April 2023**

Understand the current status of the bats project and plan for the time ahead.

### **23rd May 2023**

Discussion of initial ideas and framework for the dissertation.

### **14th June 2023**

Discussion on how to deal with missing data.

### **22nd June 2023**

Discussion of a portion of the completed data processing and discussion with Dr Ella Browning.

### **5th July 2023**

Discussion of completed data exploration and a portion of the activity pattern.

### **18th July 2023**

Discussion of completed activity pattern exploration and GLMM modeling, and timing of draft submissions.