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Surveying Insects in a Wind Farm in Southwest Norway: Abundance, Order and Size Distribution, and Influence on Bat Activity

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Preface

This master's thesis concludes my five years of studies within Natural Resource Management at the Norwegian University of Life Sciences. I look back at these years with gratitude for all the knowledge I've gained, and for all the people I've been lucky enough to meet.

This thesis was written as part of the *Noctur* project, led by the Norwegian University of Life Sciences. The project focuses on studying the effects of wind turbines on nocturnal flying wildlife, by monitoring bats, eagle owls and insects along the coast of Rogaland, Norway. The results from the project will be used to improve current and future wind power projects by forming a basis for evidence-based decisions in regards to placement, operation and regulation of wind farms. This will hopefully contribute to mitigate some of the negative ecological effects of wind power in the coming years. Being able to contribute to this important field of research has been a privilege.

I would like to thank my main supervisor Katrine Eldegard, for including me in the project, and for providing me with constructive feedback along the way. Moreover, I would like to thank my two co-supervisors, Lisa Fagerli Lunde and Mara Zebele, for all helpful feedback and support, both during the fieldwork and the writing process. My gratitude also goes out to everyone in Bat Lab Norway for all the important work you do for bats.

Lastly, I would like to thank my friends, my family, and my partner, Nicolai, for supporting me throughout my academic journey and through this thesis writing process. I could not have done this without you.

Ås, May 15th 2025

Ylva Heyn Friberg

Abstract

In the past decades a growing number of studies have shown that wind power development have detrimental effects on bats. Meanwhile, data on insect abundance and communities in wind farms are lacking, making it challenging to successfully predict the effects of wind power on insect populations. As a way of addressing this knowledge gap, the aim of this thesis was to quantify insect abundance, size groups and identify insect orders present in a wind farm situated in southwest Norway. Moreover, I investigated whether insect abundance had an influence on bat activity in the wind farm, and if elevation and distance to freshwater had an effect on insect abundance. Insects were collected from below the base of seven existing wind turbines in Stigafjellet Wind Farm, Rogaland. Individuals were counted, identified to order level and grouped in size categories based on bat prey size preferences. Nightly bat activity and feeding behaviour were recorded using ultrasonic acoustic detectors. I found that insect abundance varied considerably across the study site, and that small flying insects were the most abundant throughout the wind farm. Statistical modelling revealed that turbine elevation had a positive effect on insect abundance, while distance to freshwater had a weak, negative effect on insect abundance. From the collected samples, I identified seven orders of flying insects, with orders Diptera and Hymenoptera being the most abundant. Overall bat activity and bat foraging activity varied greatly throughout the monitoring period, and did not always overlap across sites, indicating that bat activity within the farm was not limited to foraging. Lastly, I found a weak positive, but not statistically significant, relationship between insect abundance and bat activity. The findings of this study maintain that quantifying insect abundance remains a challenging task, especially in a wind farm environment, due to the large temporal and spatial variations in distribution of flying insects. Nonetheless, due to the considerable lack of empirical data on insect presence and community composition in Norwegian wind farms, it is crucial to continue to survey wind farms in order to better understand the effects that wind power development has on both bats and flying insects.

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1 Introduction

In order to meet the increasing demand for renewable energy, the Norwegian government aims to increase wind power production significantly in the coming years (NOU 2023:3). This raises concern about the ecological impacts of wind farms on flying wildlife such as birds, bats and insects in a Norwegian context. A growing collection of international studies have shown that wind farms impact bats in a negative way (e.g., Arnett et al., 2016; Baerwald et al., 2008; Horn et al., 2010; McKay et al., 2024; Reusch et al., 2022; Voigt et al., 2022). In contrast, when it comes to insects, the consequences wind power development has on flying entomofauna are still poorly understood. An increasing number of studies show evidence for large-scale declines in insects throughout Europe and North-America, related to both biomass and abundance (e.g., Habel et al., 2019; Hallmann et al., 2017; Soroye et al., 2020; Wagner et al., 2021). These declines have been linked to anthropogenic stressors such as climate change, agricultural intensification, and land-use changes (Cardoso et al., 2020; Outhwaite et al., 2022; Wagner et al., 2021). However, whether land-use changes due to wind power development could be drivers of insect decline is not yet clear, and insect presence and mortality in wind farms remains largely understudied (Voigt, 2021).

Looking at the existing literature on insect presence in wind farms, especially swarming and hill-topping insects seem to aggregate in wind farm landscapes (Voigt, 2021). Studies argue that insects may be attracted to wind turbines for a number of reasons (Weschler & Tronstad, 2024). Long et al. (2010) suggest that turbine colour plays a role in attracting insects, and that the most common turbine colours, white or light grey, attract more flying insects than colours such as red, purple or blue. This claim has later been supported by Crawford et al. (2023). Other wind farm attraction hypotheses include favourable topography and wind speeds well suited for migration (Trieb, 2018), heat emitted from the turbines (Rydell et al., 2016) and artificial lighting in otherwise undeveloped areas (Weschler & Tronstad, 2024). Nevertheless, insects attracted to wind farms may result in significant insect mortality (Voigt, 2021), having the potential to further drive biodiversity declines, and is as such a cause for concern. In order to better understand the effects wind power has on insect populations, more research on insect presence and behaviour in wind farms is needed.

Although there have been attempts to theoretically quantify insect losses at wind farms in Europe (Trieb, 2018), direct consequences of wind power on insect populations still remains understudied, as the research thus far largely has focused on effects of wind power in relation to birds and bats (Voigt, 2021). Current literature maintain that flying insects are first and foremost at risk of collisions with rotor blades (Weschler & Tronstad, 2024). Secondarily, flying insects may also be at risk of barotrauma, which is physical damage to body tissue caused by pressure differences (Baerwald et al., 2008). This can be caused by low pressure zones created by turbine blades (Trieb, 2018). Still, more empirical data regarding insect abundance patterns and behaviour in wind farms is needed in order to properly estimate the consequences that wind power has on insects (Voigt, 2021). That being said, quantifying insect abundance in wind farms is considered a challenging task, which explains the lack of research done on the topic (Moe et al., 2024).

A selection of methods for monitoring flying insects in wind farms have been tested in Scandinavia in the past years, including the use of Scheimpflug lidar (Chen et al., 2024; Jansson et al., 2020), camera traps (Johns, 2021; McKay et al., 2024; Thomle, 2023), and suction traps (de Jong et al., 2021). Of these, only suction traps provides an opportunity to identify insects in addition to quantify abundance. Although some of these studies have successfully quantified insect abundance in wind farm environments, there is still a lack of research investigating insect communities in wind farms (Moe et al., 2024). Due to this, there is currently a number of unanswered questions regarding the effects of wind power on Norwegian insect populations. It has been argued that the current number of existing wind farms are unlikely to cause large scale declines in insect populations on a national level in Norway (Åström & May, 2019). However, current and future wind power development still have the potential to cause population extirpation on a community level. This may be especially true for migrating insect populations (Moe et al., 2024), as they congregate in time and space.

Insects congregating in wind farms can result in negative ecological consequences that span across trophic levels, affecting predators such as bats (Voigt, 2021). All Fennoscandian bat species are insectivorous, and bat populations can therefore be significantly impacted on a local scale if insect abundance dwindle. Conversely, it has been hypothesised that bats may be attracted to wind farms due to feeding opportunities (de Jong et al., 2021; Foo et al., 2017; Rydell et al., 2010; Rydell et al., 2016), further leading to direct negative consequences for bats. Although the mechanisms attracting bats to wind farms are not fully agreed upon (Guest et al., 2022), it has been shown that wind farms put bats at risk of injury and mortality, both from collision with moving wind turbines and form barotrauma (Baerwald et al., 2008; Grodsky et al., 2011; Horn et al., 2010). Additionally, it is worth noting that bats also face indirect consequences of wind power development in itself, such as loss of roosts and foraging habitat (Barré et al., 2018; Leroux et al., 2023; Reusch et al., 2022). There is a general lack of studies investigating bat populations, migration patterns, and local effects of wind farms on bats in Norway (Hoel & Reinkind, 2019). As insect and bat populations are intricately interweaved, wind power development have the potential to cause detrimental interrelated effects on both bats and insects. Surveying insect abundance, community composition and bat activity in Norwegian wind farms is therefore a crucial step in successfully assessing current and future impacts of wind farms on insect and bat populations (Hoel & Reinkind, 2019; Åström & May, 2019).

In this study, I quantify insect abundance and identify the insect order composition in Stigafjellet Wind Farm, located in southwest Norway. Moreover, I investigate how local variation in elevation and distance to freshwater influence insect abundance. Additionally, I explore different methods for quantifying insect abundance in a wind farm landscape. Lastly, I survey the activity of insectivorous bats, including foraging behaviour, within the wind farm, and investigate whether insect abundance influences bat activity. The overall aim of this study is to gain a better understanding of insect abundance and distribution, as well as the dynamics between bats and flying insects in a wind farm environment.

To address this, I pose following research questions:

1. *How are insect abundance and size groups spatially distributed within the wind farm, and how are they influenced by elevation and distance to freshwater?*

2. *What insect orders are present within the wind farm, and how does the order distribution vary across the study site?*

3. *Does insect abundance influence bat activity at the study site?*

I hypothesize that:

I. Insect abundance and size groups vary between turbine sites due to local variations in microclimate. Turbines located close to bodies of freshwater have higher insect abundance, and a higher abundance of small insects. Elevation at turbine sites do not have any significant effect on insect abundance or size groups.

II. Most major flying insect orders present in Norway are represented in the study area, due to availability of both terrestrial and aquatic habitat. There are no significant variations in order distribution across turbine sites.

III. There is a positive relationship between insect abundance and bat activity in the wind farm, with increased insect abundance correlating with increased bat activity.

2 Materials and methods

2.1 Study area

The study was conducted in Stigafjellet Wind Farm (hereafter *Stigafjellet* or *Stigafjellet WF*), located in Bjerkreim municipality, Rogaland county, in southwest Norway (**Figure 1**). The wind farm is situated between two peaks, Stigafjellet (419 masl[1]) and Kvesfjellet (438 masl), approximately 19 kilometres from the west coast of Norway. The wind farm was commissioned in 2020, and consists of seven wind turbines, each with a tower height of 115 meters, and a rotor diameter of 130 meters (Noregs Vassdrags- og Energidirektorat, s.a.). The turbines are distributed across a curved trajectory of approximately 1.8 kilometres, with approximately 350 to 450 meters between each turbine in linear distance, and connected by a road leading to each of the turbines. Each turbine is positioned at varying elevation (**Appendix A, Table A1**), with the highest turbine basepoint being 422 masl (ST01), and the lowest one is at 376 masl (ST07). The entire infrastructure related to the wind farm covers approximately 66 000 square meters (Westin & Christophersen, 2018).

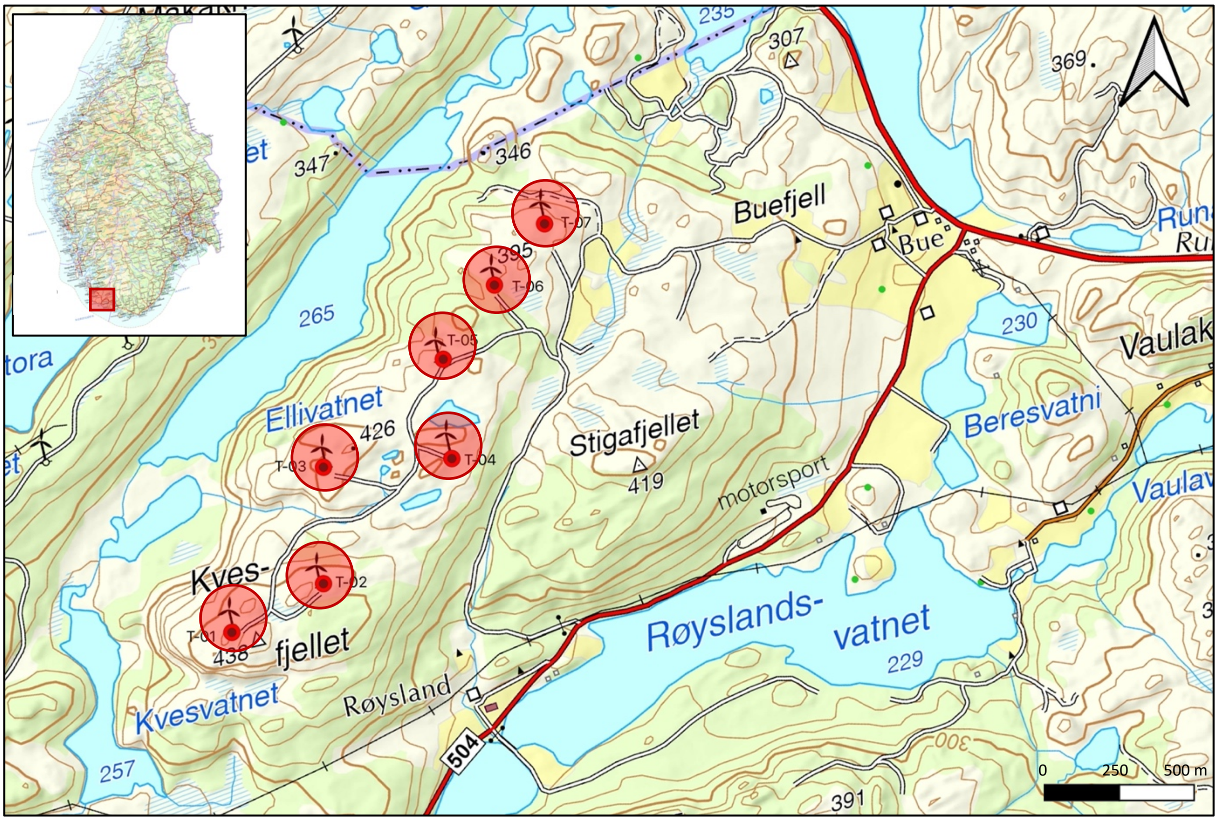

Figure 1. *Map of the study area showing the spatial configuration of the seven wind turbines in Stigafjellet wind farm. Coordinates for each turbine are listed in **Appendix A, Table A1.** Maps generated in QGIS ver. 3.38 (QGIS, 2024).*

[1] Meters above sea level.

The landscape surrounding the study area is mountainous, and is characterized by coastal heathland and bog (Westin & Christophersen, 2018). Parts of the area are dominated by grass and shrub vegetation, and large parts of the wind farm are also used as pasture for livestock during the summer season. There is additionally a considerable number of ponds and larger bodies of water in proximity to the wind turbines. The lake Røyslandsvatnet (229 masl) is situated about one kilometre southeast of the site, while the lake Ellivatnet is located about half a kilometre northwest of the wind farm (**Figure 2**). An additional wind farm, not included in this study, *Måkaknuten Wind Farm*, is situated about 1.2 kilometres north of the study site, across Ellivatnet, and consists of 22 wind turbines (Norsk Vind, 2023).

Figure 2. *Aerial 3D-photos of Stigafjellet Wind Farm showing the topography of the study site and the surrounding area (Norge i bilder, 2025).* ***A.*** *Måkaknuten Wind Farm can be seen to the right (northwest) of Stigafjellet across Ellivatnet, and Røyslandsvatnet to the left (south).* ***B.*** *Stigafjellet consists of seven wind turbines distributed along an approximately 1.8 kilometre long curved trajectory.*

2.2 Study objects

The objects of interest in this study are mainly flying insects, as these are the ones most likely to be affected by wind turbines. However, there is currently a significant knowledge gap regarding insect populations in Norwegian wind farms (Moe et al., 2024). Moreover, it is currently unkown whether some insect taxa are more at attracted to wind farms, and if some are at greater risk of wind turbine related mortality (Voigt, 2021). Consequently, the objective of this study is not to survey the insect community at species level, but rather to gain an understanding of the quantity and distribution of orders in the wind farm. A previous survey of the insect community nearby Røyslandsvatnet, the aforementioned lake situated nearby Stigafjellet, identified arthropod species of the orders Odonata (Dragonflies and damselflies), Diptera (True flies), Plecoptera (Stoneflies), Coleoptera (Beetles), Hemiptera (True bugs), Trichoptera (Caddisflies), Ephemeroptera (Mayflies) and Araneae (Spiders) (Artsdatabanken, 2025). There is also a plenitude of smaller bodies of freshwater providing aquatic habitat within and nearby the study area, providing key habitat for several species of the orders mentioned above. Moreover, the terrestrial habitat in the study area includes heathland, where some typically associated arthropod orders are Lepidoptera (Butterflies and moths, notably moth families such as Geometridae, Tortricidae and Erebidae), Hymenoptera (Sawflies, wasps, bees, and ants, hereunder notably Fam. Apidae), and Araneae (Miljødirektoratet, 2013). Considering this, I expect to find insects belonging to most of the major orders in the study area.

In this study I focus on bats (Chiroptera) as a group, and do not intend to identify particular species. So far, 11 bat species have been confirmed in Norway, all of which are insectivorous. Six bat species are listed as either critically endangered (CR), endangered (EN), vulnerable (VU), or near threatened (NT) on the Norwegian Red List (Artsdatabanken, 2021). Yet, knowledge about the distribution and migration of Norwegian bat species is limited (Hoel & Reinkind, 2019). The aim of this study, however, is to investigate the general bat activity in the area in relation to insect abundance. Many insectivorous bats are generalists, and consume a wide range of insects species, belonging to orders such as Lepidoptera, Coleoptera, Diptera, and Hemiptera, but can also feed on other arthropods, such as spiders (Kunz et al., 2011). Differentiating between bat species is thus not necessarily crucial when studying the influence of insect abundance on bat activity. For instance, a number of boreal bat species in Finland have been found to have a similar diet consisting mainly of dipteran and lepidopteran species (Vesterinen et al., 2018). That being said, insect size and abundance may be better determinants of prey preferences than taxonomic features, as detectability and catchability are some of the most important factors in bat foraging (Rydell et al., 1996). Preferred insect prey size varies according to the size of each bat species, but can generally vary from 1 mm up to 50 mm (Kunz et al., 2011), allowing bats to forage on an extensive range of insect species. Due to this, for the sake of the study, insects are in addition to being identified to order level, also grouped in size categories small, medium, large and extra large, to better reflect physical differences between insect groups, and overall availability to bats.

2.3 Data collection

2.3.1 Insect collection

Insects were collected from below each of the seven wind turbines in Stigafjellet on three occasions between July and August 2024. The collection dates were July 31^{st}, August 4^{th} and 12^{th}, resulting in a total of four and eight days, respectively, between each sampling. All insects were collected from a structure located beneath the platform deck at the base of each turbine, reminiscent of a metal tray split into four sections (**Figure 3**).

Figure 3. *The platform at the base of the turbines seen from ground level.* ***Left****: The metal trays where the insect collection was carried out can be seen below the platform.* ***Right****: Nearly dried out metal trays with accumulated deceased insects. Photos taken by Ylva Heyn Friberg.*

Above the metal tray, there was a ventilation system producing a downward airflow which hindered insects from exiting the trays once in them, creating a natural trapping mechanism. Moreover, the trays filled with water every time it rained, and dried out during periods without rain. This led to the insects drowning in the trays. Almost all individuals collected from the trays were exclusively flying insects, most of which had likely been unable to exit the trays due to the ventilation air stream. During collection, all deceased insect specimens found in the metal trays were put in 30 mL plastic vials filled with 70% ethanol, marked with collection date and turbine number. While some of the trays were filled with water during the sampling, some were nearly dried out, as shown in **Figure 3**.

2.3.2 Acoustic monitoring

Seven ultrasonic bat detectors (*Song Meter SM4BAT FS Ultrasonic Recorder* from Wildlife Acoustics) paired with SMM-U2 ultrasonic microphones were deployed at the base of each of the seven wind turbines at the study site, in order to monitor echolocating bats in a non-invasive manner. Each acoustic detector was mounted on existing turbine platform infrastructure, along with the microphone, which was attached to the end of a wooden stick, and elevated approximately five meters above ground level (**Figure 4**). Acoustic monitoring was conducted throughout the summer season 2024, starting on June 19th, and ending on August 12th. In total, the detectors were deployed for 54 nights.

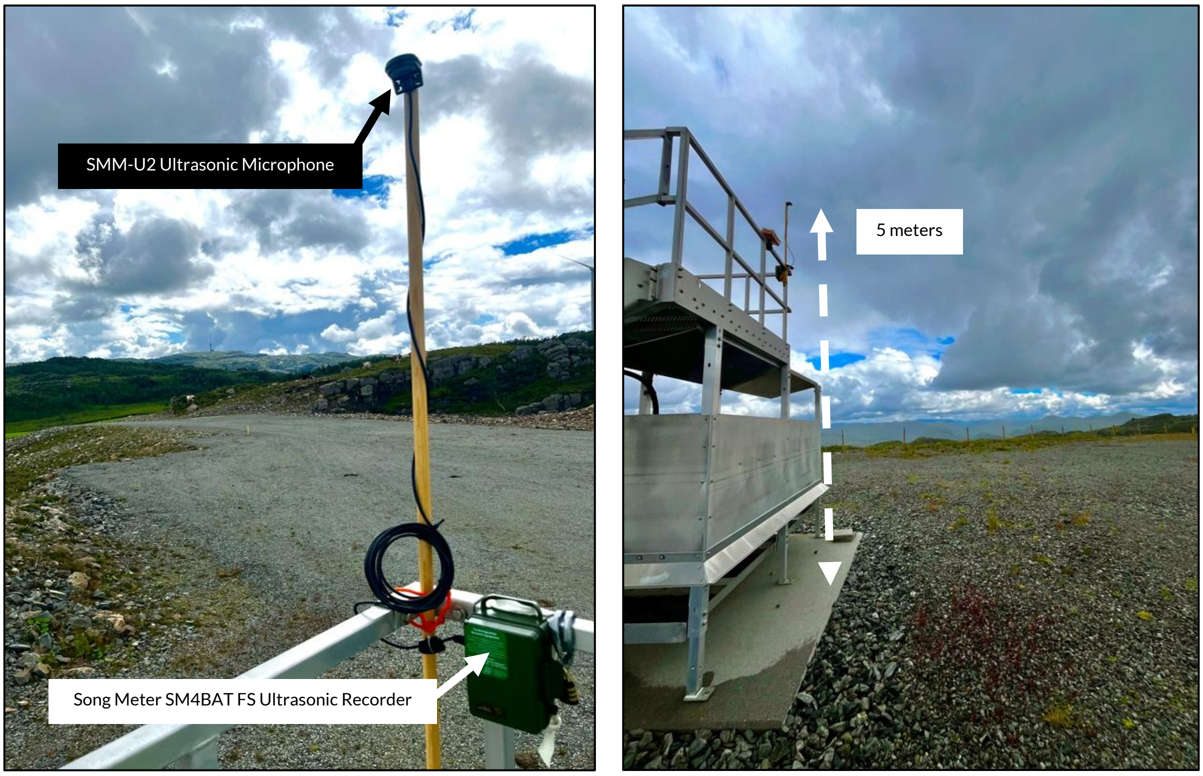

Figure 4. *Acoustic bat monitoring setup. Each acoustic detector was attached to the platform railing at the base of the turbine, along with a microphone that was elevated five meters above ground. Photos taken by Ylva Heyn Friberg.*

Detectors were programmed to activate every night from one hour before sunset until one hour after sunrise, aligning with typical bat activity hours, and to start recording ultrasounds at a 16 KHz trigger frequency. Local changes in time of sunset/sunrise throughout the summer were accounted for through the use of site specific GPS-coordinates set for all detectors. The maximum length of recording time was set to 15 seconds, in order to prevent audio files from becoming too large and taking up excessive storage space. Regular maintenance checks on the equipment were carried out every three weeks to ensure that detectors and microphones were functioning correctly. Maintenance checks consisted of battery change, a microphone test, and SD-card retrieval and redeployment. A complete overview of the detector settings and specifications can be found in **Appendix B, Table B1**.

2.3.3 Other methods used for quantifying insect abundance

In addition to collecting insects, we placed camera traps at each turbine site (see left picture in **fig. 3**, and right picture in **fig. 4**) to monitor abundance of flying insects at night. This method only detected a limited number of insects, and the data was thus not used for further analyses in this study. A complete overview of the method can be found in **Appendix C**. The method is further discussed in **Ch. 4.5.**

A method involving an experimental design of a sticky trap attached to a helium balloon was also tested, as a way to quantify abundance of flying insects and orders present above ground, at about six and a half meters. The method was tested on two occasions in a semi-open forest environment, but was ultimately not used in the wind farm, as the method was not effective in capturing insects. A complete overview of the method can be found in **Appendix D**. The method is briefly discussed in **Ch. 4.5.**

2.4 Data management and preparation

2.4.1 Insect identification

All insects in the collected samples were counted and manually identified by the author to order level. The insects were identified using a stereomicroscope (Wild Heerbrugg M3B) with 6.4, 16 and 40x magnification. If an individual could not be identified due to a lack of recognisable features, e.g., missing body parts or being covered in excessive dirt, the individual would be counted and placed in the category "Unidentifiable". If an individual was not an insect (e.g., arachnids such as spiders and mites), or was not considered realistic bat prey (e.g., Bark lice) it would be counted and recorded in the category "Other".

All individuals were additionally grouped according to size, ranging from small to extra large depending on the length of the body (**Table 1**, **Figure 5)**. The size classes were intended to reflect favourable prey sizes for most Norwegian bat species, that is, size relative to bat jaw size. The size classes small, medium, and large were considered optimal prey size, while the size class extra large was viewed as too big to be considered favourable by most bats, except the common noctule (*Nyctalus noctula*).

In addition to identifying insects to order, in the cases where it was possible, I also identified individuals to family level, in order to get a more detailed impression of the variation within the collected samples. The dipteran identification key *The European Families of the Diptera – Identification, diagnosis, biology* (Oosterbroek, 2006) was used to identify certain recurring dipteran families. In some instances, the application *Artsorakel*, an artificial intelligence photo identification tool created by Artsdatabanken (Artsdatabanken, 2023) was utilised to identify coleopterans and hymenopterans to family level. All suggestions from the *Artsorakel* application were manually verified by the author.

Table 1. *Grouping of insect sizes and examples of representative orders and families of each class.*

Size class	Definition	Measurements	Representative orders or families
1	Small	<5 mm	Diptera (Fam. Culicidae, Simuliidae, Chironomidae), Hemiptera (Fam. Aphididae)
2	Medium	5-10 mm	Plecoptera, Hymenoptera (Fam. Formicidae, Braconidae)
3	Large	10-20 mm	Trichoptera, Lepidoptera (moths)
4	Extra Large	>20 mm	Diptera (Tipulidae, Tabanidae), Lepidoptera (moths), Hymenoptera (Apidae: genus *Bombus*, Vespidae)

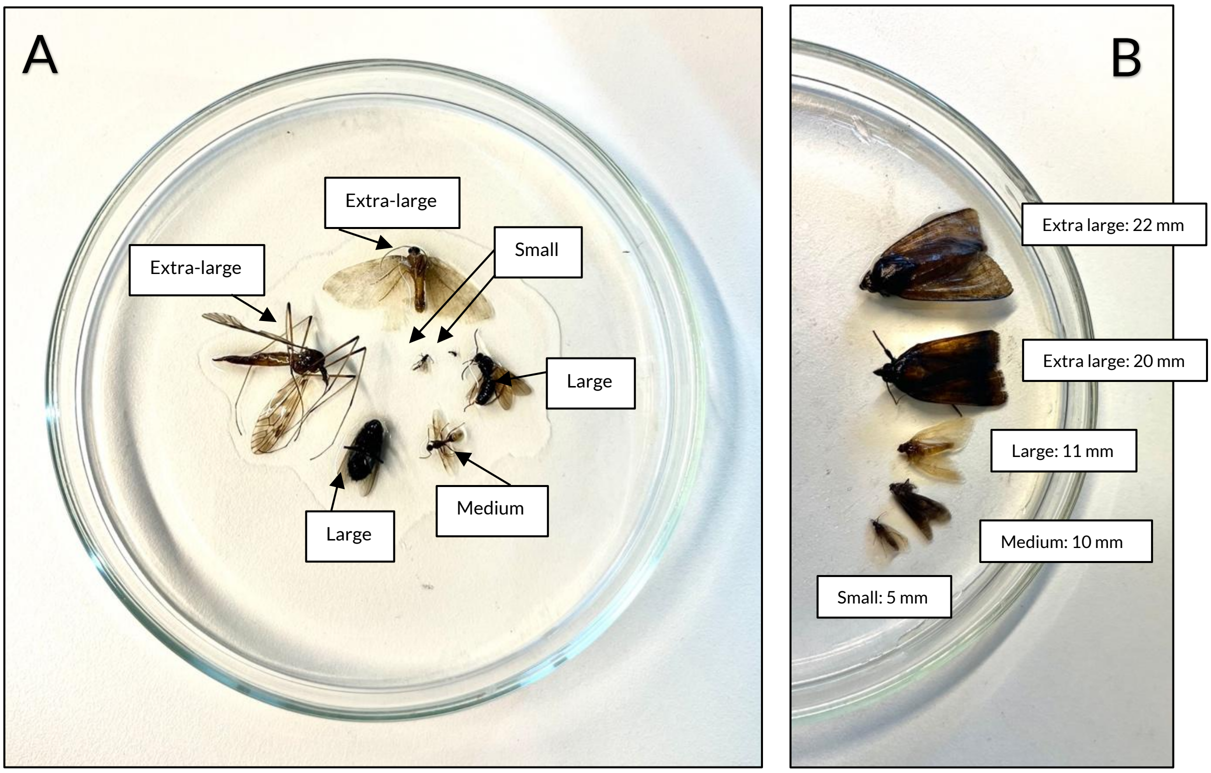

Figure 5. A. *Example of representative individuals of the different size classes: small, medium, large and extra large.* ***B.*** *Lepidopterans of varying size classes with measurements, illustrating the large variation in sizes within orders, and how the size classes in some instances overlapped (e.g., Medium vs. Large individuals at ~10 mm).*

2.4.2 Analysis of acoustic bat data

Analysis of the recorded bat data collected from the acoustic detectors in Stigafjellet was carried out in *Kaleidoscope Pro Analysis Software* from Wildlife Acoustics (Wildlife Acoustics, 2024). All raw recordings (n=9894) were automatically split into five seconds long segments, and processed through an automated (machine-based) species classifier that assigned bat calls to the best species match. In this study, a bat call was defined as a single pulse (a bat vocalization), while a bat pass was defined as a recording containing at least two pulses, with less than one second of separation between them (Wildlife Acoustics, 2024). After the automated analysis, all bat passes were checked manually by one analyst (Mara Zebele), in order to confirm that all automatically identified bat sounds were correctly identified.

When performing manual acoustic analysis, it is possible to identify specific sounds typically correlated to bat foraging activity. For instance, when a bat approaches an insect prey, it elicits a specific series of calls, also called a "feeding buzz". A feeding buzz, or a "terminal phase buzz", is characterized by shorter pulses and a drop in call frequency, compared to the preliminary search phase (Griffin et al., 1960). An example of this change in echolocation emissions can be seen in **Figure 6**. Feeding buzzes are elicited by bats closely chasing insect prey, and can thus be used as an indicator of feeding activity (Jameson, 2024). Therefore, whenever a feeding buzz was detected by the analyst during the manual acoustic analysis, this information was manually added. This provided a possibility to gain more insight into the interactions between bats and insects in the wind farm.

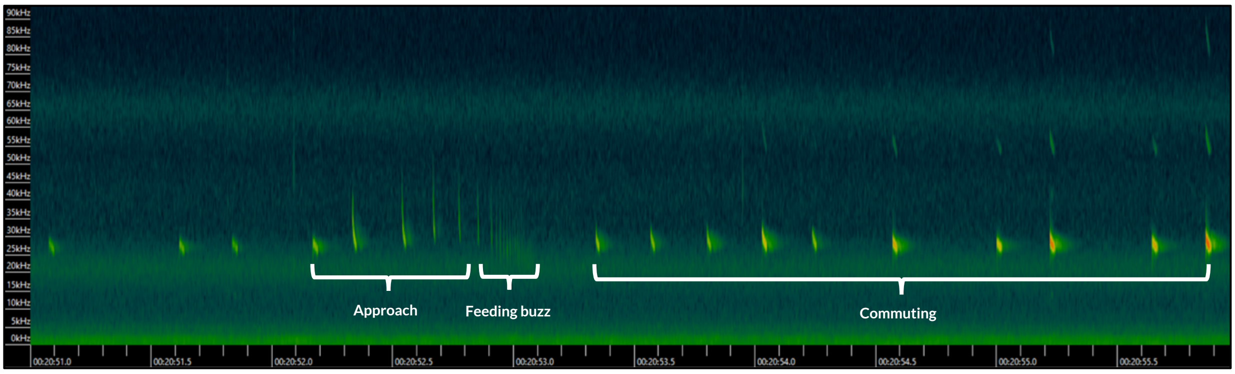

Figure 6. *Sonogram of a northern bat (Eptesicus nilssonii) displaying searching echolocation, prey approach and a feeding buzz. Recorded on August 3rd 2024 at turbine ST02 in Stigafjellet.*

2.5 Statistical modelling

Statistical analyses and data visualisation were carried out in R version 4.4.2., using the packages dplyr, ggplot, lme4, tidyr and lubridate. To model count data I used a generalized linear model (GLM) assuming a Poisson distribution. All models were checked for overdispersion, and if overdispersion was greater than 1, models were refitted. To model count data with overdispersion, which was the case for most of the data, I used a GLM, assuming a negative binomial distribution, using the 'MASS' package. GLMs with negative binomial distribution was used to assess the effect of explanatory variables turbine site, insect size class, distance to freshwater, elevation, insect order on dependant variable *insect abundance*. Model fit was assessed using AIC (Akaike information criterion), i.e., choosing the candidate model with the lowest AIC. To test if insect order composition varied between turbine sites and size groups, I performed a PERMANOVA test using the 'vegan' package, based on Bray-Curtis dissimilarity and 999 permutations. Insect abundance was chosen as the dependant variable, while insect order and turbine site was chosen as explanatory variables. Lastly, to assess the effect of explanatory variables turbine site and insect abundance on nightly bat activity, I used a mixed effect model from the 'glmmTMB' package, assuming a negative binomial distribution, and including nights and turbine site as random effects to account for repeated measures and variation between turbines. When testing the effect of insect abundance on nightly bat activity, I tested multiple subsets of insect abundance (e.g. 1) small, 2) small and medium, 3) small, medium and large), but there were no significant differences between the subsets. Ultimately, the subset containing all insect size groups except extra large (as this group was considered too large for optimal bat prey size). An alpha level of 0.05 was used to determine statistical significance.

3 Results

3.1 Overview of results

A total of 3834 insects were collected in Stigafjellet, then counted and identified to order level. Although not formally a part of the study, a limited number (n=29) of insect families were also identified in the collected samples. An overview of these can be found in **Appendix F**. A total number of 9894 recordings were collected by the acoustic detectors, in which a total of 1499 bat passes were identified, including 54 feeding buzzes (**Table 2**).

Table 2. *Overview of the total number of collected insects, and manually identified bat passes and feeding buzzes across the seven turbines in Stigafjellet. Elevation at the turbine site measured in meters above sea level (masl), and distance to the nearest body of freshwater measured in meters (m) are also included for each turbine site. A complete overview of the number of collected insects per turbine in each sampling can be found in* ***Appendix D****, along with the number of original bat recordings from each acoustic detector.*

Turbine	**n insects**	**n bat passes**	**n feeding buzzes**	**Elevation** *(masl)*	**Proximity to freshwater** *(m)*
ST01	125	247	7	422	450
ST02	1289	237	4	414	560
ST03	457	200	3	405	225
ST04	937	195	7	396	100
ST05	560	322	2	392	155
ST06	350	66	0	397	470
ST07	116	232	16	376	450
∑	**3834**	**1499**	**39**	-	-

3.2 Insect abundance

3.2.1 Sampling effort

Insect abundance ("Total Count") varied substantially across the three samplings (*Sample 1* n=123, *Sample 2* n=849, *Sample 3* n=2862). The third insect sample had the highest abundance of insects, while the first sampling had the lowest abundance (**Figure 7**). The variation between the three samplings was disproportionally high partly due to varying sampling efforts. Therefore, due to these considerable differences between samplings, only data from sampling 3 was used for further statistical modelling, as this sampling was the most meticulous and representative out of the three. The reason for varying sampling effort is further discussed in Ch. **4.2.** A complete overview of the number of identified insects per sampling period and size class across each turbine can be found in **Appendix E, Table E1 and E2.**

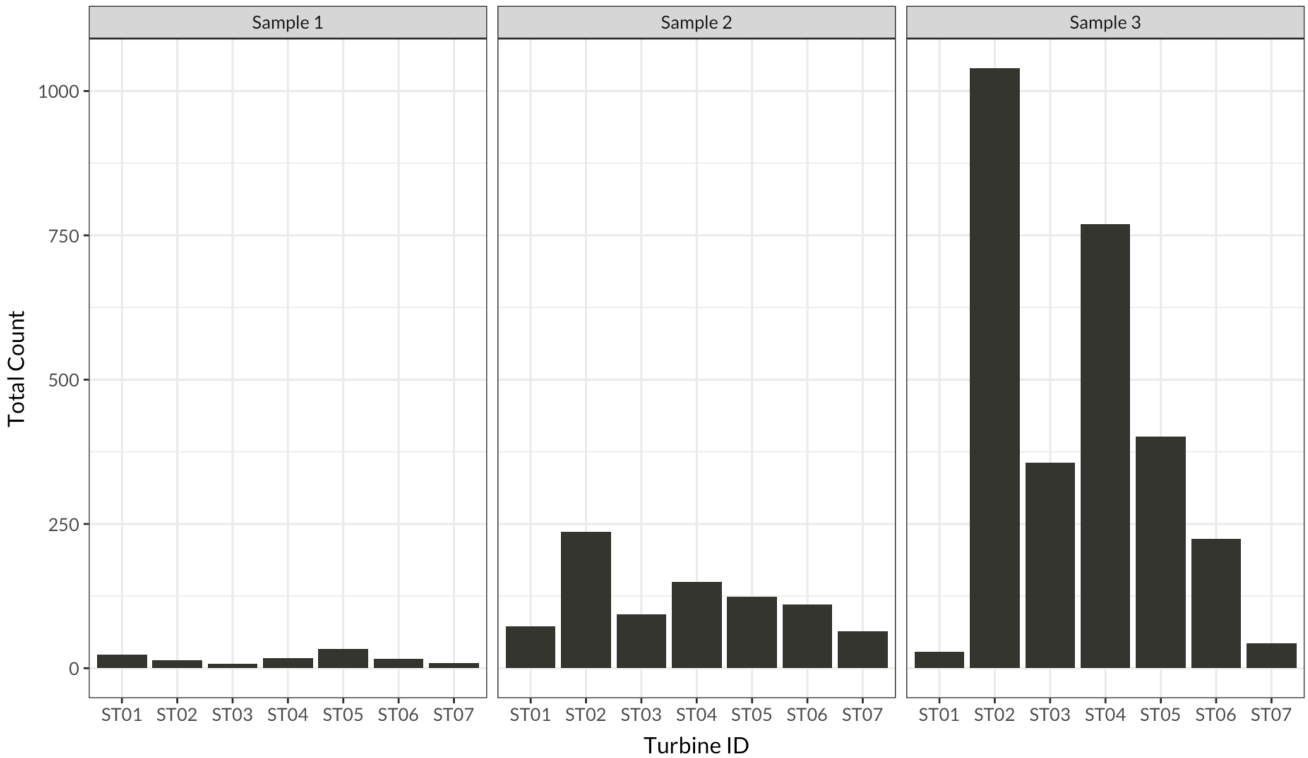

Figure 7. *Variation in number of insects (total count) found in sampling 1, 2 and 3 for each of the seven turbines in Stigafjellet. Sampling 3 had the highest insect abundance, while sampling 1 had the lowest abundance. The considerable variation between samplings occurred partly due to variations in sampling effort, which is further discussed in* ***Ch. 4.2.***

3.2.2 Spatial distribution and between-group variation in insect abundance

Insect abundance varied considerably across the seven turbines in the wind farm. Turbines ST02 (n=1039) and ST04 (n=769) had substantially higher insect abundance than the remaining turbine sites, while turbines ST01 (n=29) and ST07 (n=43) had considerably lower insect abundances compared to the other turbines (**Figure 8, Table 3**).

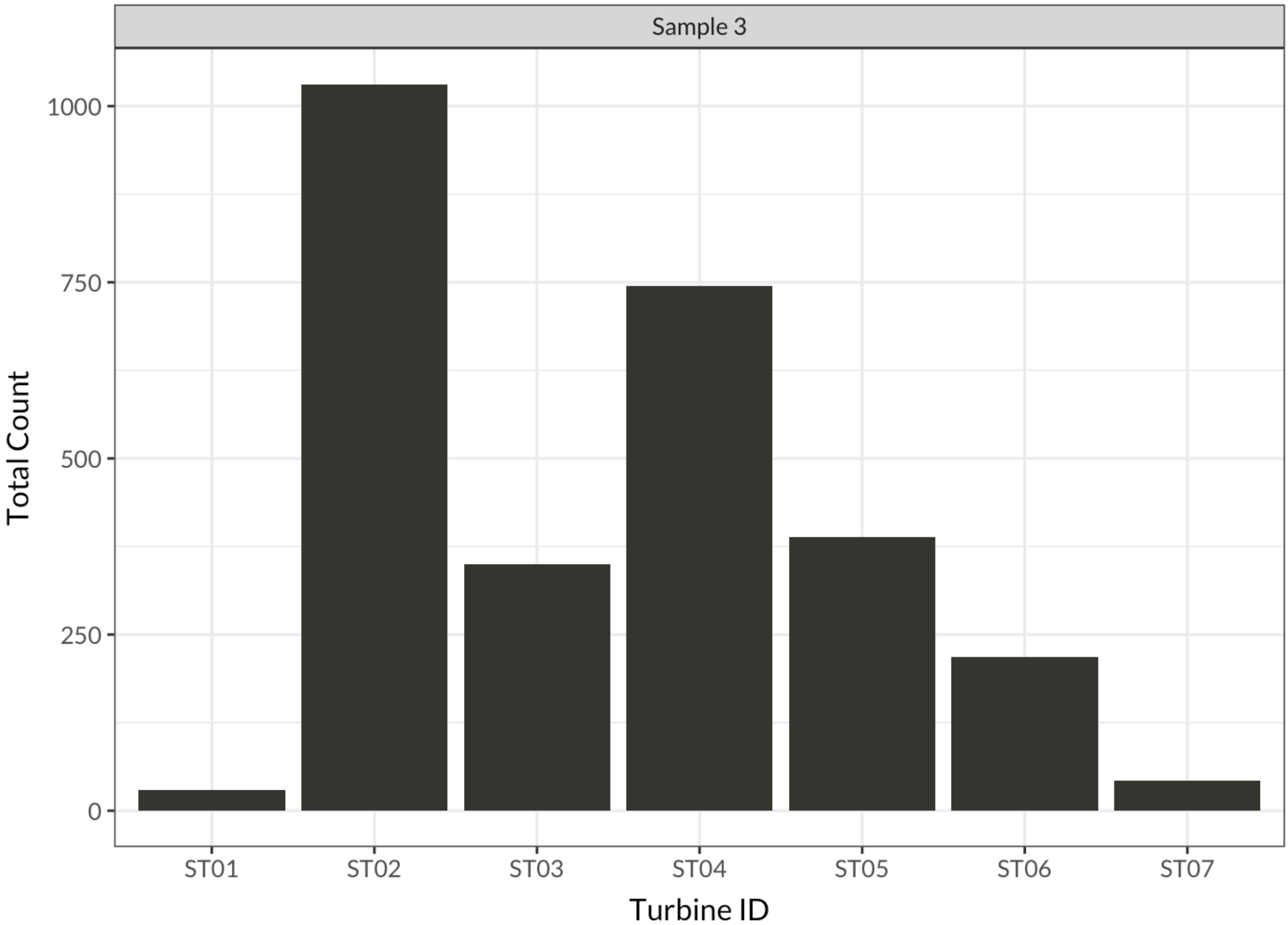

Figure 8. *Number of insects (total count) found in sample 3 for each of the seven turbines in Stigafjellet. Turbines ST02 and ST04 had the highest abundance of insects, while turbines ST01 and ST07 had the lowest abundance.*

Table 3. *Output from a negative binomial generalized linear model. Analysis of the variation in insect abundance between turbine sites during sampling period 3. Theta = 0.1553. The reference category is turbine ST01. P-values <0.001 are emphasised in bold, and underscored if p<0.01.*

Variable	***Estimate***	***Std. Error***	***z***	***p***
Intercept (ST01)	-0.1881	0.4674	-0.402	0.68742
ST02	3.5505	0.6311	5.626	**<0.001**
ST03	2.4795	0.6325	3.920	**<0.001**
ST04	3.2496	0.6313	5.147	**<0.001**
ST05	2.6010	0.6323	4.114	**<0.001**
ST06	2.0162	0.6338	3.181	0.00147
ST07	0.3657	0.6485	0.564	0.57278

When considering size groups, small insects were by far the most abundant (n=2427) across all turbines. Medium sized insects were the second most abundant (n=267), while large (n=110) and extra large (n=58) insects were the least abundant (**Figure 9, Table 4).** Moreover, the abundance of small and medium insects were highest at turbine ST02, while the abundance of large and extra large individuals was highest at ST04.

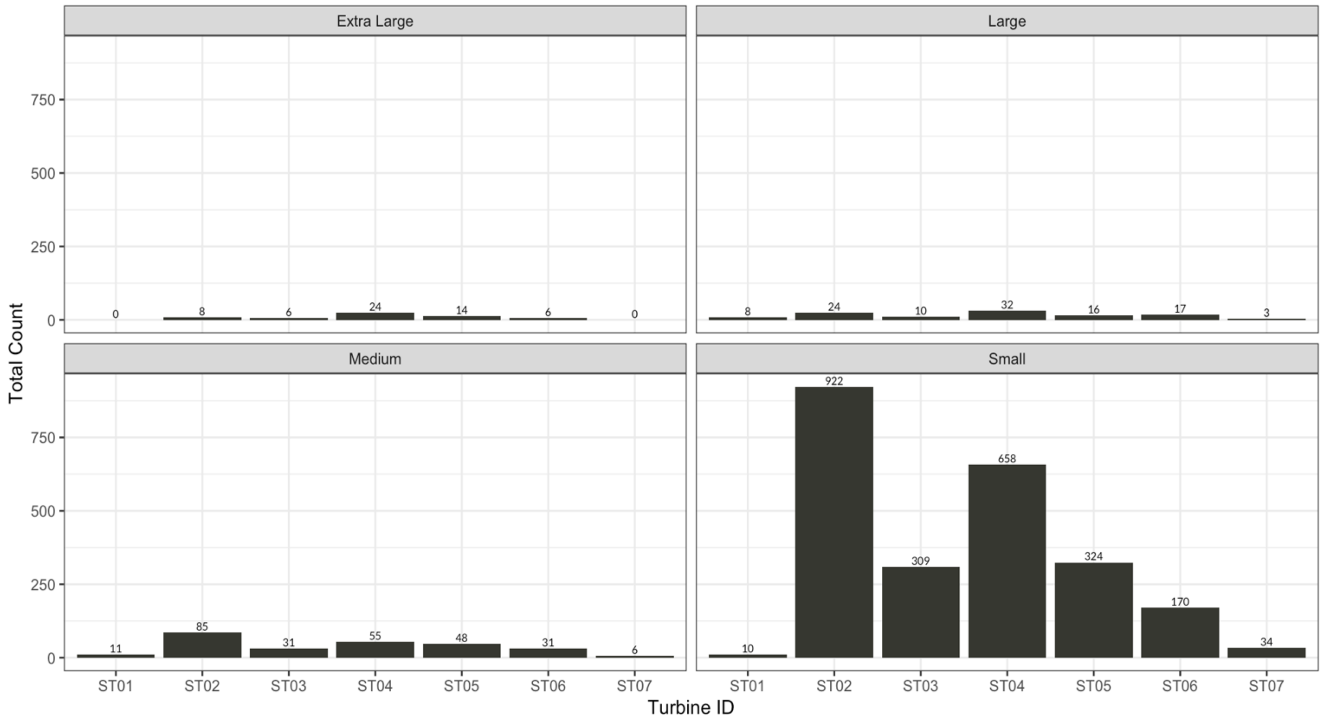

Figure 9. *Distribution of insects across size groups Extra Large, Large, Medium and Small in sample 3. Small insects were the most abundant across all turbine sites, followed by medium sized insects. Large and Extra Large insects were the least abundant groups across all turbine sites. Small, medium and large insects were most abundant at turbines ST02 and ST04, while extra large insects were most abundant at turbines ST04 and ST05.*

Table 4. *Output from a negative binomial generalized linear model. Analysis of the variation in insect abundance between size groups during sampling period 3. Theta = 0.1982. The reference category is size group Extra Large. P-values <0.001 are emphasised in bold, and underscored if p<0.01.*

Variables	***Estimate***	***Std. Error***	***z***	***p***
Intercept (Extra large)	-0.0827	0.3120	-0.265	0.791
Large	0.6560	0.4333	1.514	0.130
Medium	1.5268	0.4256	3.587	**0.0003**
Small	3.7340	0.4217	8.855	**<0.0001**

3.2.3 Influence of elevation and distance to freshwater on insect abundance and size groups

Elevation had a small positive effect on insect abundance, with an estimated 3.6 % increase in number of insects per unit increase in elevation (p<0.001, IRR=1.036) (**Table 5**). This was especially true for small insects (p<0.001). Distance to nearest body of freshwater had a small, negative effect on insect abundance, with <1% estimated decrease in number of insects per unit increase in distance to water (p<0.001, IRR=0.9955). Compared to the reference group, extra-large, the effect of distance to water had less effect on abundance in the other insect size groups, notably small and medium.

Table 5. *Output from a negative binomial generalized linear model with back-transformed estimates (β) included. Analysis of the effect of size class, elevation, and distance to nearest body of freshwater on insect abundance during sampling period 3. Theta = 1.550. P-values <0.001 are emphasised in bold, and underscored if p<0.01.*

Variables	***Estimate***	***IRR***	***Std. Error***	***z***	***p***
Intercept (Extra Large)	-10.610	2.47e-05	1.699	-6.25	<0.001
Elevation	0.0350	1.0356	0.00436	8.03	**<0.001**
Distance to water	-0.00446	0.9955	0.000741	-6.02	**<0.001**
Elevation × Large	-0.000128	0.9999	0.000933	-0.14	0.891
Elevation × Medium	0.00169	1.0017	0.000923	1.83	0.067
Elevation × Small	0.00743	1.0075	0.000916	8.11	**<0.001**
Water distance × Large	0.00256	1.0026	0.00101	2.54	*0.011*
Water distance × Medium	0.00300	1.0030	0.000993	3.02	0.0025
Water distance × Small	0.00259	1.0026	0.000985	2.63	0.0086

3.3 Insect order distribution

3.3.1 Identified insect orders

A total of nine insect orders were identified in the collected samples, of which seven were considered relevant for this study (complete overview of orders and families in **Appendix F**). Diptera was the most abundant insect order across all turbine sites and sampling periods, and accounted for a total of 78.8 % of the insects collected (n=3834) (**Figure 10, Table 6**). Hymenoptera was the next most abundance order, and accounted for 5.5 % of the total collected insects. Coleopterans, lepidopterans and plecopterans each accounted for between 3 and 3.4 % of the total. The remaining orders had low abundances (Hemiptera 2.2 % , Trichoptera 1 %). The two categories “Other” (1.8 %) , and “Unidentifiable” (1.1 %) contained the individuals that I did not consider typical bat prey (*Other*), or was not able to identify due to too much damage to the specimens, e.g., lacking limbs or being covered in dirt (*Unidentifiable*).

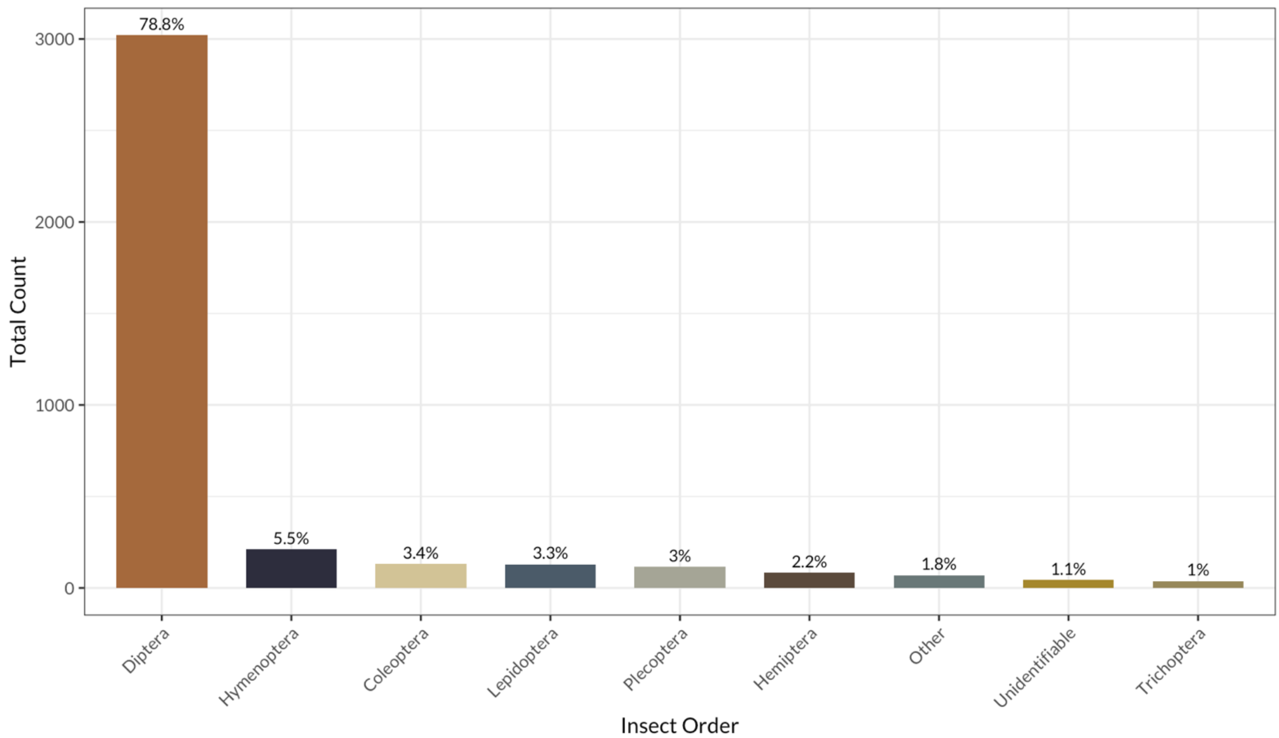

Figure 10. *Insect orders found in Stigafjellet for all three sampling periods combined. The category "Other" refers to orders that were not consider typical bat prey in the wind farm landscape, such as orders Araneae, Thysanoptera, Acari, and Psocoptera. The category "Unidentifiable" refers to individuals that were unidentifiable due to lack of visible features (e.g., excessive dirt on specimens, lacking limbs etc.).*

Table 6. *Output of a negative binomial general linear model with log link function and back-transformed estimates (β) included. Analysis of the variation in insect abundance between insect orders sampling 3. The reference category is insect order Coleoptera. Theta = 0.3015. Statistically significant p-values <0.001 are emphasised in bold, and underscored if p<0.01.*

Variables	***Estimate***	***Exp(Estimate)***	***Std. Error***	***z***	***p***
Intercept (Coleoptera)	1.1221	3.071	0.3607	3.111	0.00186
Diptera	3.3339	28.030	0.4989	6.682	**<0.0001**
Hemiptera	-0.1917	0.8256	0.5125	-0.374	0.7084
Hymenoptera	0.4055	1.500	0.5062	0.801	0.4232
Lepidoptera	-0.7908	0.4535	0.5236	-1.510	0.1310
Other	-0.5225	0.5928	0.5178	-1.009	0.3129
Plecoptera	-0.4841	0.6160	0.5171	-0.936	0.3492
Trichoptera	-1.7463	0.1744	0.5614	-3.110	<u>0.00187</u>
Unidentifiable	-2.6262	0.0723	0.6478	-4.054	**<0.0001**

3.3.2 Distribution of insect orders between turbines

Insect order composition did not vary between turbine sites (**Figure 12**), but did vary between size groups (p = 0.001) (**Table 7**). Turbine site explained 16.6 % (R^2=0.166) of the variation, but the differences in insect abundance between turbines were not statistically significant (p =

0.12). Size class (Small, Medium, Large, Extra Large) on the other hand, explained 48.5 % (R^2=0.485) of the variation in insect order composition, which indicates differences in the order composition between size classes.

Table 7. *Output from PERMANOVA analysis of variations in insect order composition across turbine sites and within size classes. Statistically significant p-values <0.001 are emphasised in bold..*

Variable	***Df***	***Sum of Squares***	***R²***	***f***	***p***
Size class	3	2.8558	0.48464	8.3230	**0.001**
Turbine	6	0.9781	0.16599	1.4253	0.115
Residual	18	2.0587	0.34937		
Total	27	5.8925	1.00000		

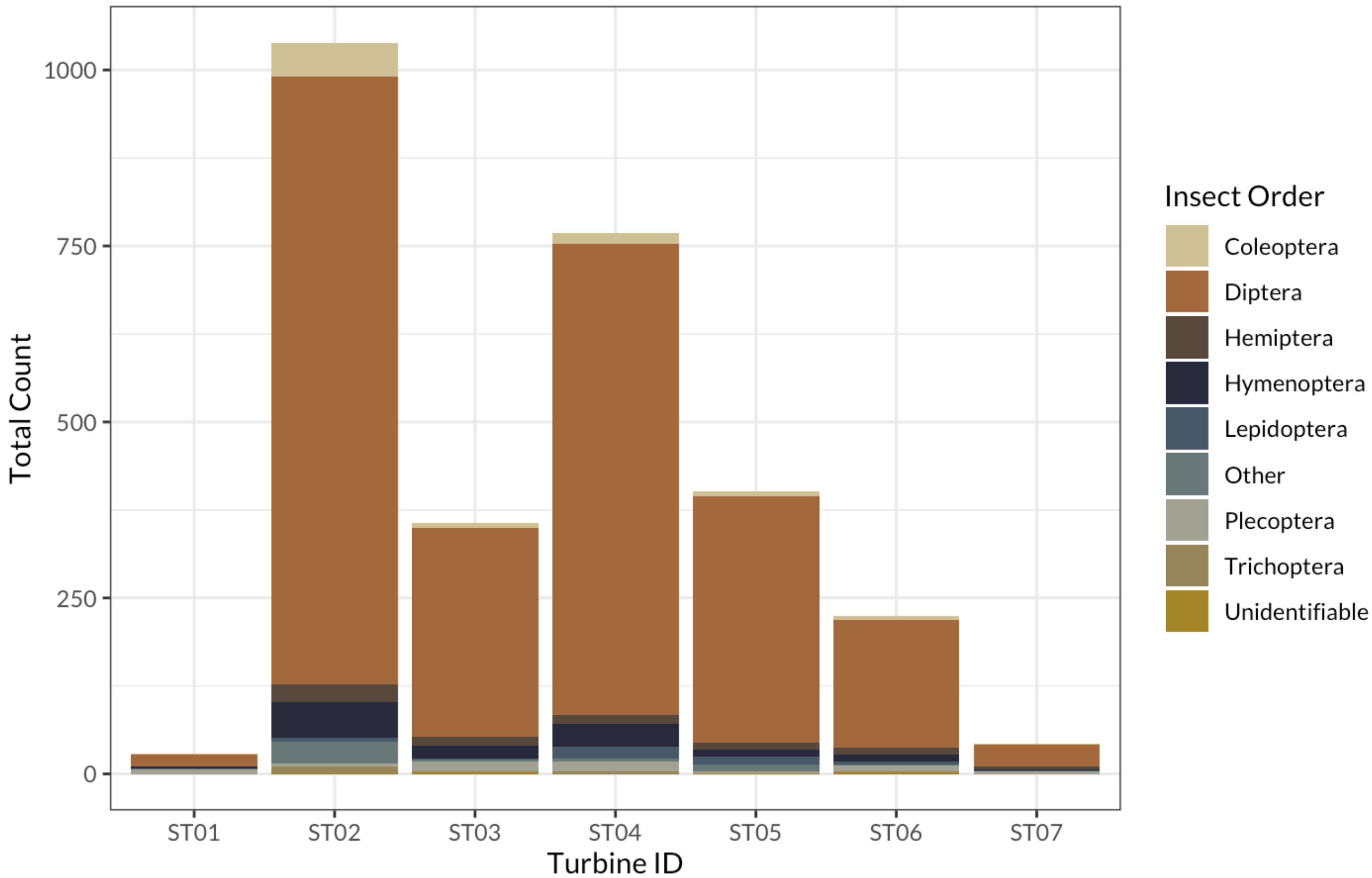

Figure 11. *Distribution of insect orders distribution across the seven turbines in sampling 3. Diptera was by far the most abundant order across all turbines. Distribution of orders did not vary significantly between turbines.*

3.4 Bat activity patterns

3.4.1 Overall bat activity

Bat activity varied during the monitoring period, with notable peaks in activity between July 18th and August 2nd (**Figure 12**). Bat activity was highest at turbine ST05, and lowest at the neighbouring turbine ST06 (**Figure 13, Table 8**). Bat activity was at its lowest between June 23rd and July 17th.

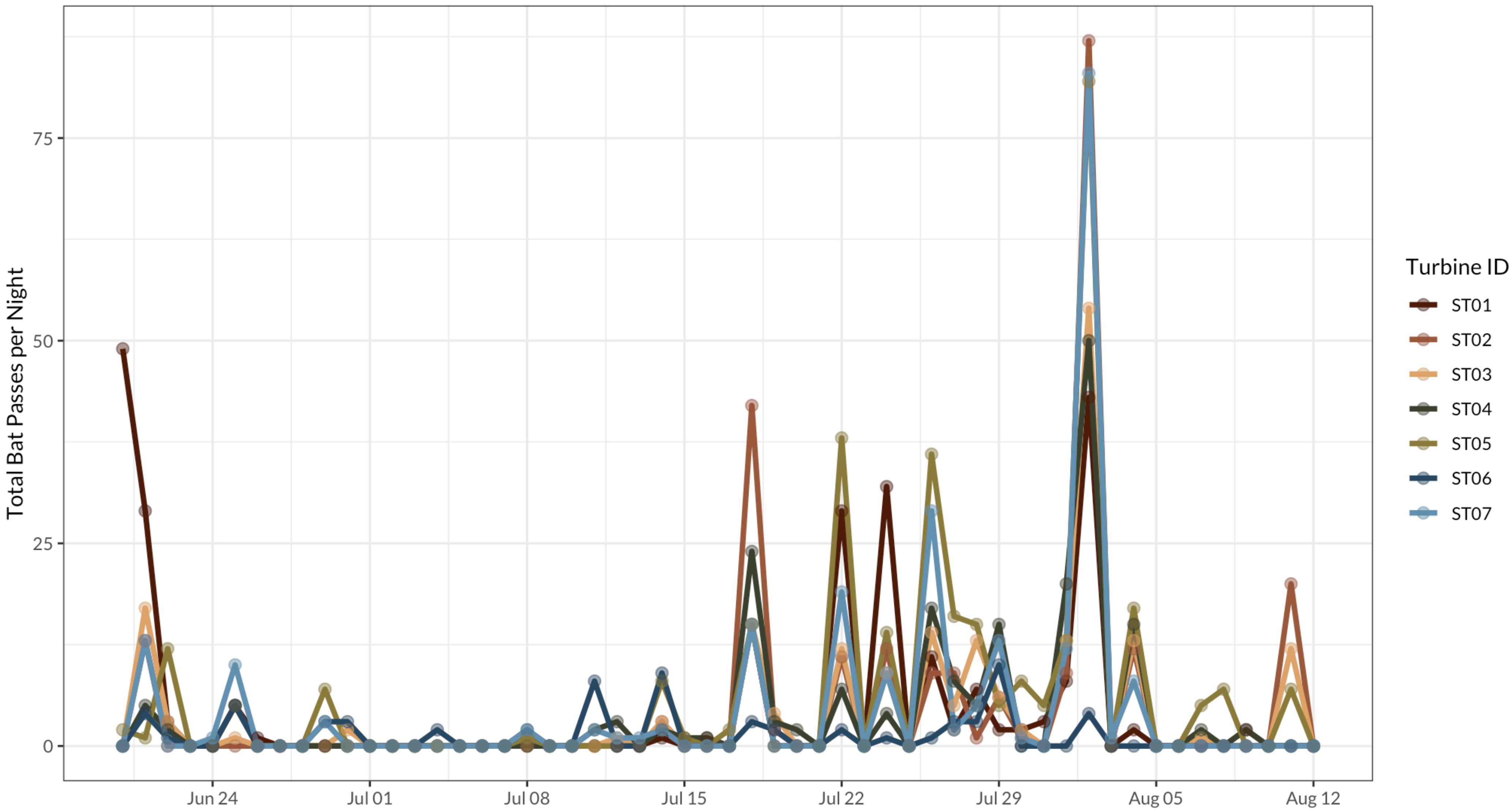

Figure 12. *Nightly bat activity across the eight week monitoring period that started on June 20th and ended on August 12th 2024.*

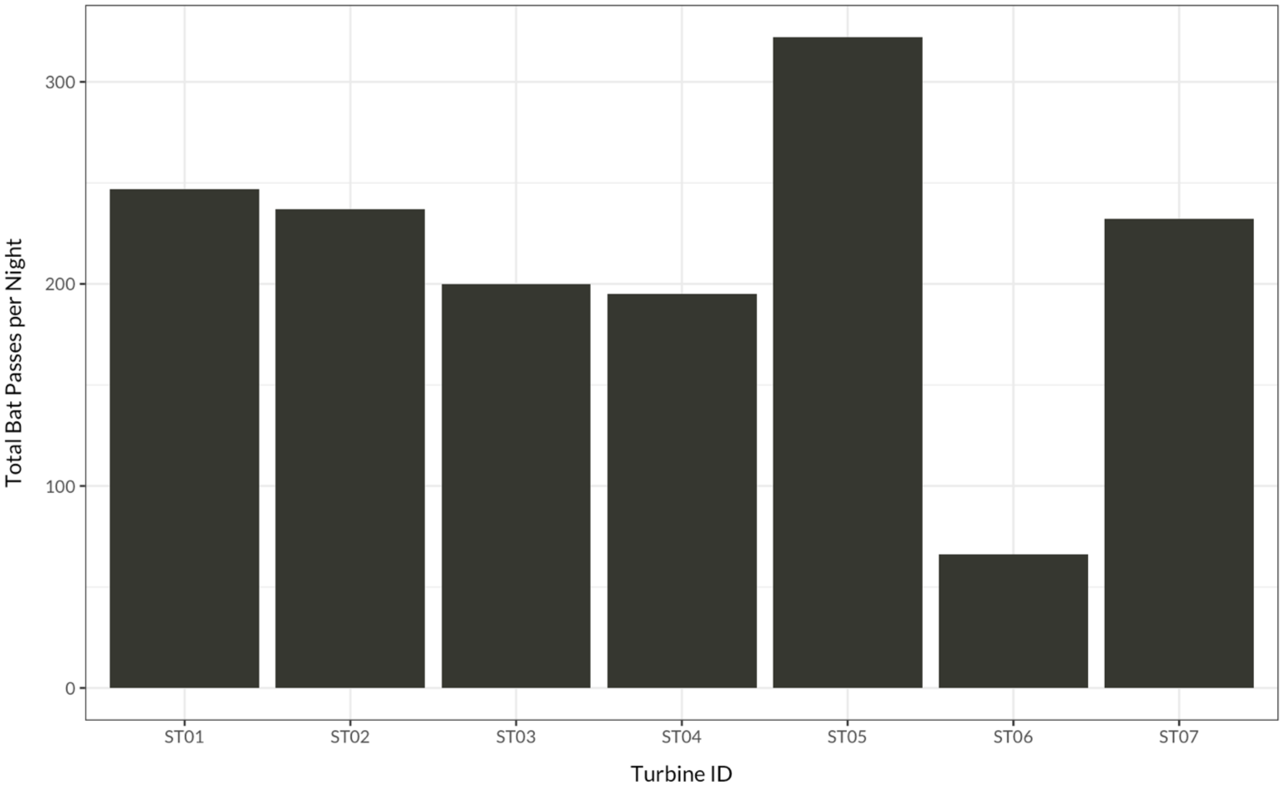

Figure 13. *Nightly bat activity across each turbine across the monitoring period. Recorded activity at turbine ST06 was significantly lower than at the other turbines.*

Table 8. *Output from negative binomial mixed effects model. Analysis of the effect of turbine (site) on nightly bat activity across the acoustic monitoring period. Turbine ST01 is used as reference category. Date is added as a random effect to account for repeated measures at the same night. All estimates are on a log scale.*

Variable	***Estimate***	***Std. Error***	***z***	***p***
Fixed effects				
Intercept (ST01)	-0.717	0.471	-1.52	0.128
ST02	-0.445	0.326	-1.37	0.172
ST03	-0.290	0.322	-0.90	0.368
ST04	-0.151	0.330	-0.46	0.647
ST05	0.508	0.316	1.61	0.108
ST06	-0.621	0.358	-1.73	0.083
ST07	-0.239	0.324	-0.74	0.462
Random effect	**Variance**	**St. Dev**		
Nights	6.786	2.605		

3.4.2 Nightly recorded feeding buzzes

Bat foraging activity, measured as number of feeding buzzes, varied between turbine sites (**Figure 14**), and across the monitoring period (**Figure 15**). Similar to the overall bat activity, the number of recorded feeding buzzes peaked between July 18th and August 2nd. Moreover, there was a peak in feeding buzzes in the first days of monitoring, between June 20th and 22nd. Bat foraging activity was highest at turbine ST07 and ST01. There was no recorded bat foraging activity between June 23rd and July 17th, and no recorded activity at turbine ST06 throughout the monitoring period.

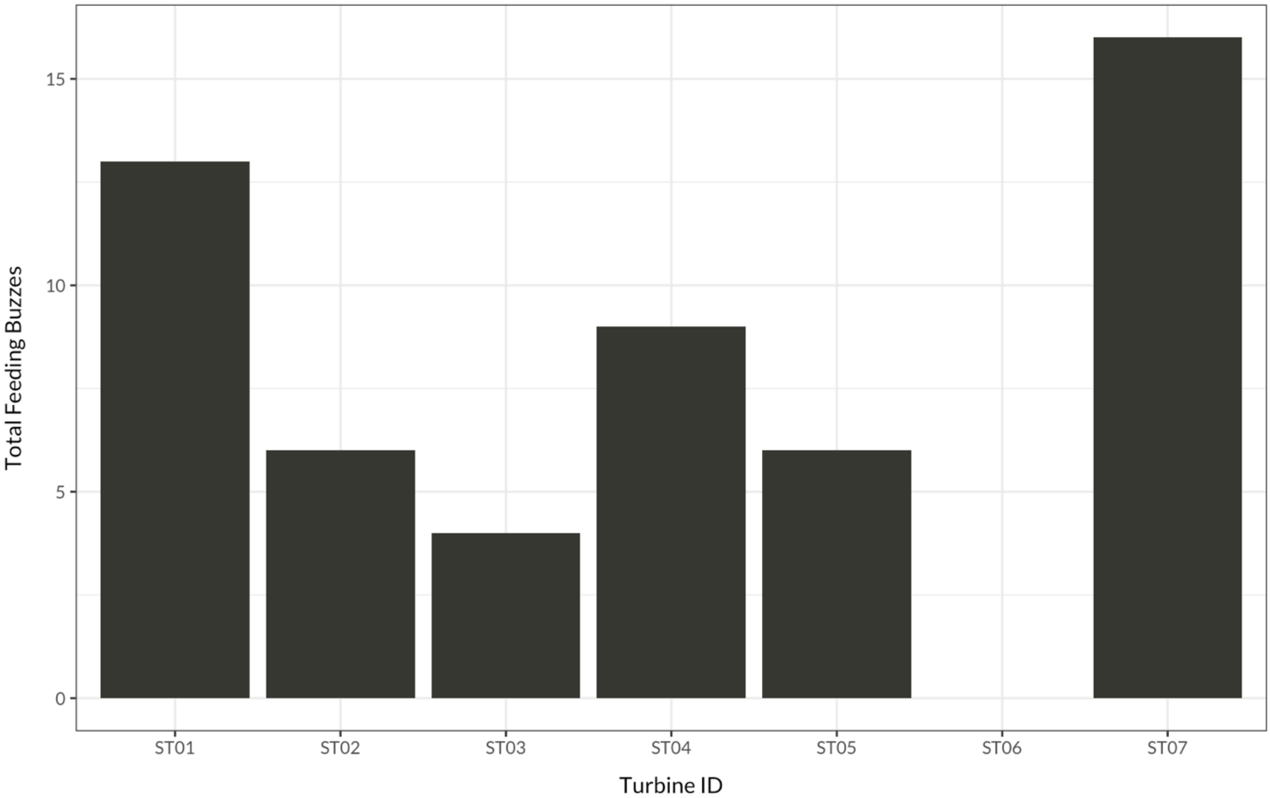

Figure 14. *Total number of recorded feeding buzzes across each turbine during the monitoring period. No feeding buzzes were recorded at turbine ST06. Total number of feeding buzzes recorded across the monitoring period was n=54.*

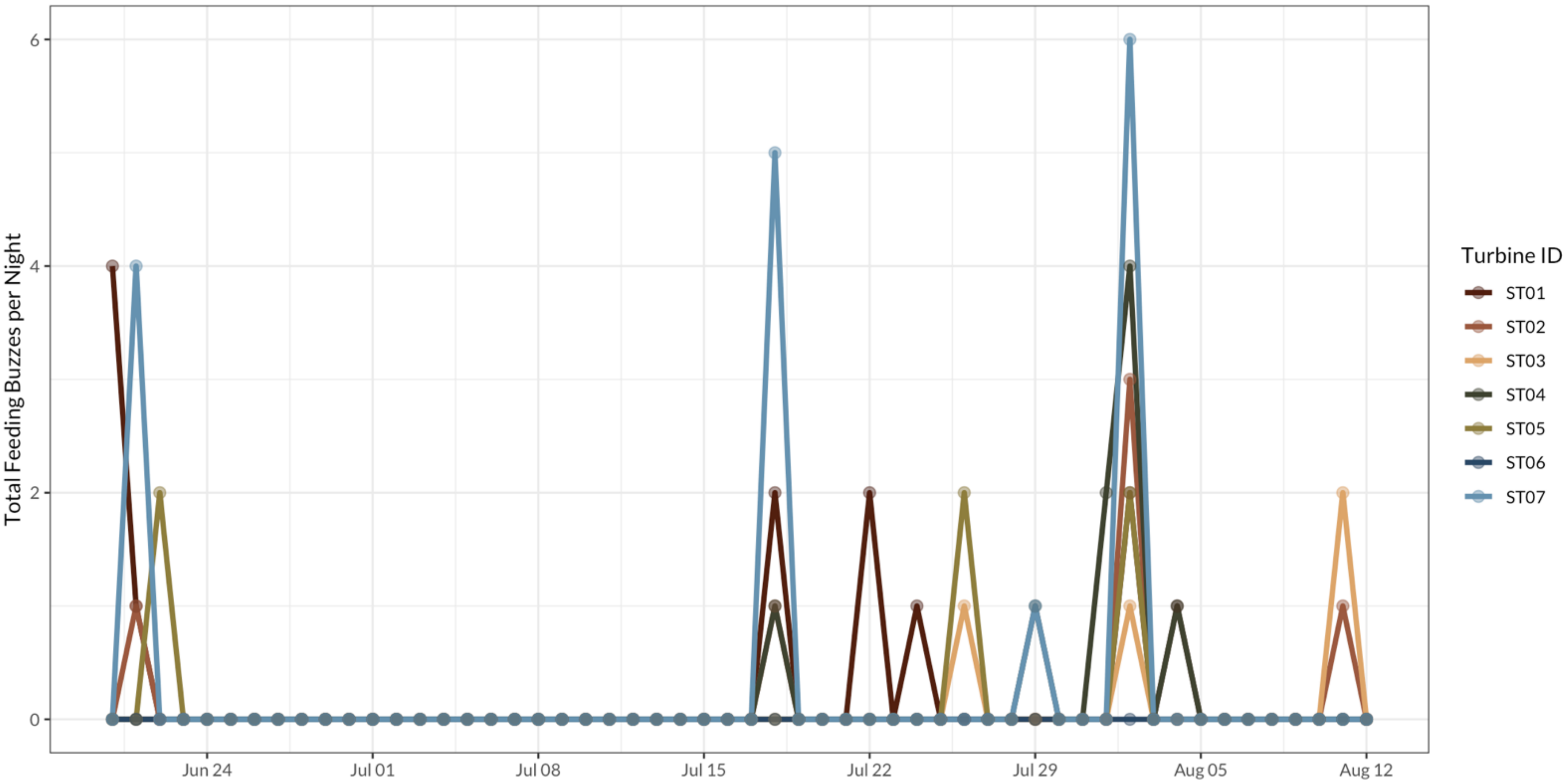

Figure 15. *Nightly feeding buzzes across the eight week monitoring period that started on June 20th and ended on August 12th 2024*

3.5 Relationship between insect abundance and bat activity

There was a weak positive, but not statistically significant ($p=0.784$) relationship between insect abundance ($n=2763$) in sampling period 3 and number of batpasses per night during the same period (**Table 9**). IRR for insect abundance is close to 1, suggesting that the effect of this variable on nightly bat activity is minimal, as seen in **Figure 16**. The random effect of turbine site suggests that there are differences in bat activity across turbine sites.

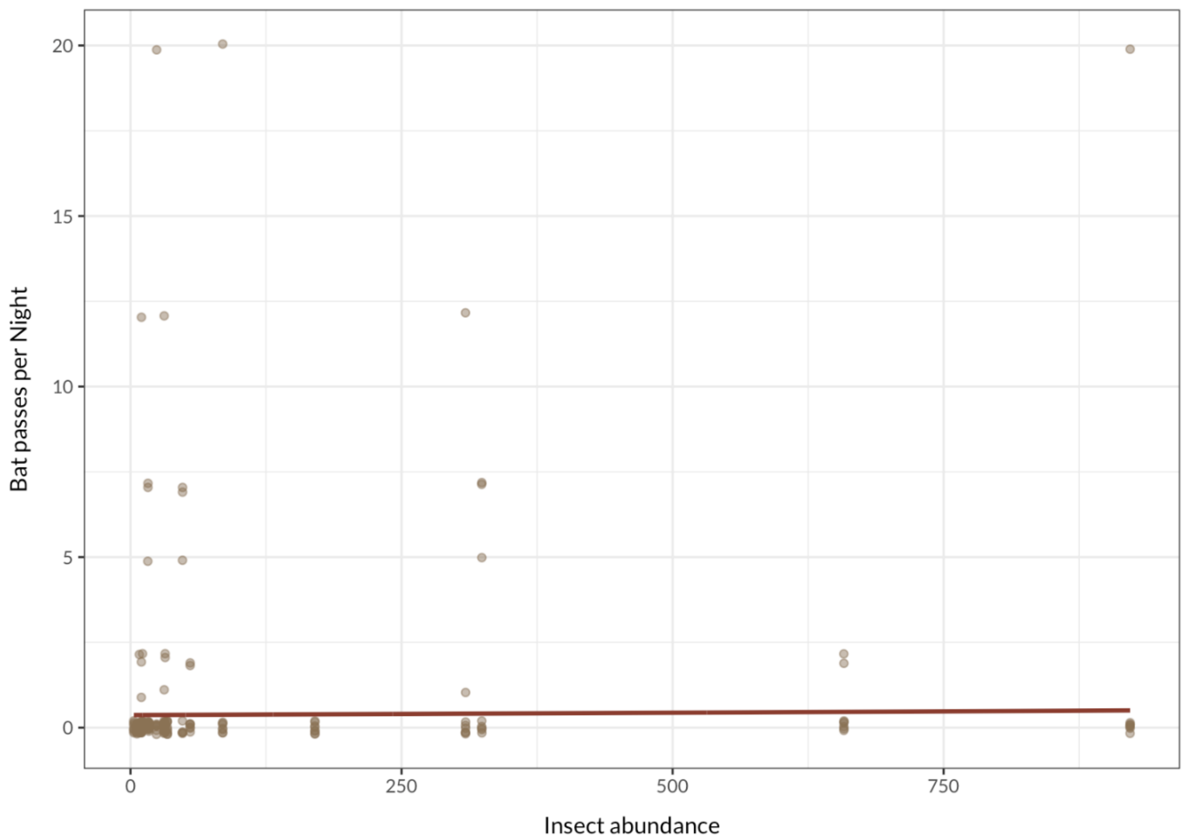

Figure 16. *Predicted relationship between insect abundance and nightly bat activity. Insect size class Extra large is excluded from the prediction model, as the assumption is that only small, medium and large insects are considered favourable prey by bats.*

Table 9. *Output from negative binomial mixed effects model. Analysis of the effect of insect abundance on nightly bat activity during sampling period 3. Turbine site is added as a random effect to account for variation across turbines. IRR is included to facilitate interpretation.*

Variable	**Estimate**	**IRR**	**Std. Error**	**z**	**p**
Fixed effects					
Intercept	-0.99932	0.368	0.88191	-1.133	0.257
Insect abundance	0.00034	1.0003	0.00125	0.274	0.784

Variable	Estimate	IRR	Std. Error	z	p
Random effect	**Variance**		**St. Dev**		
Turbine	3.721		1.929		

4 Discussion

4.1 Key findings

Insect abundance varied considerably between turbine sites in the wind farm. The turbines situated in the south-west of the study area (ST02 and ST04) had the highest insect abundance, while the turbines situated furthest north (ST07) and furthest south (ST01) in the study area had the lowest abundance. Small insects was by far the most abundant size group throughout the wind farm, while extra large insects was the least abundant group across all turbine sites. Moreover, abundance across size groups had a similar distribution to that of the overall insect abundance, with turbines ST02, ST04 and ST05 having the highest abundance of insects across all size groups. Statistical modelling showed that elevation had a small, but significant positive effect on insect abundance, indicating an increase in insect abundance as elevation got higher. In contrast, distance to freshwater had a small, but significant negative effect on insect abundance, indicating that insect abundance decreased with increasing distance to bodies of water. The most abundant insect order found in Stigafjellet was Diptera (79% of collected insects), followed by Hymenoptera (5.4%). Individuals of the orders Coleoptera, Lepidoptera, Hemiptera, Plecoptera and Trichoptera were also identified. I found that order distribution did not significantly vary between turbine sites, but rather within size classes. This was expected, as I identified fewer orders in the large size classes compared to the smaller ones. Looking at bat activity, the overall activity, as well as number of feeding buzzes, peaked towards the end of the summer season, between July 18th and August 2nd. Interestingly, the turbine sites with highest overall bat activity was not the same as the turbines with most recorded feeding buzzes. Lastly, when looking at insect prey of favourable sizes for bats in the study area (small, medium and large), I found a weak positive, but not statistically significant relationship between nightly bat activity and insect abundance.

4.2 Spatial distribution of insect abundance and size groups

Insect abundance was unevenly distributed across Stigafjellet Wind Farm. The two turbines at the northernmost (ST07) and southernmost (ST01) point of the wind farm had the lowest abundance of insects, while the two turbines situated on the southside (ST02 and ST04) of the road going through the wind farm had the highest abundance (see **Ch. 2.1** for overview of turbine configuration in the study area). At turbines ST03, ST05 and ST06, which are all situated on the northside of road, insect abundance was more evenly distributed between the turbines, compared to the four other sites. Although not statistically comparable due to the differences in sampling effort, a similar pattern in spatial distribution of insect abundance was observed in sample 2, but not in sample 1. This could be an indication that turbine sites ST02 and ST04 had certain features that caused more insects to aggregate at these sites, compared to the rest of the turbine sites. Regarding insect size groups, small and medium sized insects were significantly more abundant than large and extra large insects across all turbine sites. All size groups shared the same pattern in abundance distribution across the study area, with the turbines furthest south and north having the lowest abundance, and turbines ST02 and ST04 having the highest abundance. The only exception was size class extra large, which had a higher abundance of insects at ST05 than ST02.

I found that distance to freshwater did have a small, negative effect on insect abundance, supporting my hypothesis. However, elevation had a more pronounced effect on insect abundance, which was unexpected, as the difference in elevation between each turbine was negligible (46 meters from the lowest to highest situated turbine). Although local variations in microclimate, such as distance to freshwater or site elevation, could potentially explain some of the observed differences in insect abundance across the wind farm, there were also some outliers in the dataset that did not fit well with the models. For instance, the turbine site with the highest insect abundance was also the site situated the furthest away from a body of freshwater (560 meters to Kålivatn). Meanwhile, the turbine site with the next to highest insect abundance was also the site located nearest a body of freshwater (100 meters to Kråketjørna). Similarly, the two turbines at the highest and lowest elevation point had the lowest insect abundance. This raises questions about whether these explanatory variables really did influence insect abundance. As the sample size was limited (n=7) due to only using sample 3, it may be strictly coincidental that these variables seem to have some effect on insect abundance. Therefore, in order to better understand the influence of these conditions, a larger dataset would be necessary. Moreover, there are a number of other factors that may influence the abundance of flying insects at the turbine sites, such as variations in vegetation between turbine sites, presence of livestock or wind breaks. Small insects especially, tend to settle in sheltered areas with low wind speeds (Pasek, 1988). Variation in insect abundance across different elevations could thus simply be explaining differences in degrees of landscape openness, or degree of shelter from strong wind. It has been argued that larger insect species have the ability to fly at higher altitudes than smaller insects, as they are better at flying at higher wind speeds (Pasek, 1988). If this is the case, this could also be an explanation for the considerable contrast in observed abundance of larger versus smaller insects at ground level in Stigafjellet.

It is worth noting that a significant limitation in this study is that there was considerable variation in sampling effort across the three insect samplings. This cause for this was that the method was initially only intended to be used to investigate the presence and distribution of insect orders in the wind farm, and not to quantify insect abundance. Consequently, the method for collecting insects from below the turbines was not standardized to begin with, and it only became a substitutional quantification measure when it appeared that the camera trap data would not be usable. In the first sampling, sampling bias in regards to size (i.e., larger individuals were easier to spot and collect) was a considerable factor. Moreover, in the first sampling, insects of the same family that were easily identifiable (e.g., Tabanidae, Syrphidae, or Tipulidae) were only collected once at each of the turbines, as the goal of the collection was only to identify orders and potentially families present in the study area. In the second sampling, there was less of a size bias, and most of the insects that had accumulated in the metal trays below the turbines were collected. However, in this sampling, a portion of the collected insects were likely remaining from the first sampling, and thus still not giving a representative image of the number of insects accumulated since last sampling. The third and last sampling was the most meticulous, and did likely not include many insects from the last sampling. Due to these factors, this sampling was the most reflective of the relative insect abundance at each of the turbines, and were thus chosen for statistical modelling.

4.3 Insect order composition

The identified insect orders in Stigafjellet included seven of the major flying insect orders; Coleoptera, Lepidoptera, Hymenoptera, Diptera, Hemiptera, Plecoptera and Trichoptera. I expected to find insects from most of the major insect orders, as there was both terrestrial and aquatic habitat in proximity to each of the turbines. I did, however, not identify any insects of the orders Orthoptera (crickets and grasshoppers), Neuroptera (net-winged insects) or Odonata (dragonflies and damselflies), which I did expect to find at the study site, as species of these orders has been observed in nearby locations in previous years (Artsdatabanken, 2025).

Existing literature states that there is a lack of knowledge regarding whether some insects are more prone to attraction to wind farms, and if certain taxa are at increased risk of collision with wind turbines (Voigt, 2021). The surveying of insect orders in Stigafjellet does suggest that a wide range of insect orders are present within the wind farm. This may be due to the availability of both aquatic and terrestrial habitat, and possibly due to suitable wind streams. The wind speed attraction hypothesis suggests that migrating insects may congregate in wind farms, as they often seek high, strong winds suitable for long-distance migration, which often coincide with areas with high annual wind speed also suitable for wind power development (Trieb, 2018). These types of winds can often be found in regions with mountain ridges and coast lines (Moe et al., 2024; Trieb, 2018), which does align with the features of Stigafjellet. There are, however, currently no documented migrating insect populations in Norway, and no indication that migrating insects are colliding with turbine blades in Norwegian wind farms (NVE, 2022; Åström & May, 2019). This also seems to be the case for the wind farms operated by Norsk Vind in the Rogaland region, hereunder Stigafjellet, as reported by the operators and maintenance crew. Nevertheless, flying insects did aggregate in the metal trays at the base of the turbines, which was a result of the wind farm infrastructure. This raises the question if studies attempting to quantify insect mortality at wind farms should also include other turbine related mortality in addition to insect collisions with turbine blades.

Although the method used for surveying insect abundance and order distribution in this study did not include sampling of insects at nacelle height, as done in de Jong et al. (2021), the method still provided insight into what insect orders are present in Stigafjellet in a non-invasive way, as the insects were already deceased. Although it remains unlikely that wind farms will significantly affect insect populations on a national scale, the local impact of wind power on local insect populations are potentially notable (Åström & May, 2019). Although there is a lack of knowledge regarding migrating insects in Norway, species of e.g., Diptera and Odonata have been found to travel significant distances at heights that may be in conflict with turbines in England and Lithuania (NVE, 2023). This highlights the need for more knowledge on potential migrating insect populations in Norway. For this purpose, a method where sampling at rotor blade or nacelle height is possible would likely be beneficial in order to realistically sample insects flying at the height where collisions could occur.

4.4 Influence of insect abundance on bat activity

I found that insect abundance had a weak positive, but not statistically significant influence on nightly bat activity between August 4th until 12th, and therefore no support for my hypothesis, which predicted that bat activity would increase as the abundance of insect prey increased. This could suggest that there are other factors influencing bat activity in the wind farm in addition to insect abundance. When looking at the recorded bat activity across turbine sites, and comparing it to the recorded feeding buzzes, this seems to be the case. The turbines with the highest overall bat activity, were not the sites with the highest number of feeding buzzes. This can suggest that bats are not merely in wind farms for feeding purposes. Other suggested factors that may attract bats to wind farms are mating purposes, scent-marking, and attraction to tall structures reminiscent of trees (Guest et al., 2022; Rydell et al., 2010). There was no recorded feeding buzzes at turbine ST06, and there was also overall less bat activity at this turbine site. This also happen to be one of the turbines, along with ST07 and ST01, that had lower insect abundance than the rest of the turbines in the third sampling. Meanwhile, overall bat activity and the number of feeding buzzes were high at ST07 and ST01, despite the fact that insect abundance was lowest at these sites. Thus, there was no clear relationship between variations in insect abundance and bat foraging activity across the turbine sites either.

The lack of a clear relationship between insect abundance and bat activity may be a result of insect abundance having less of an influence of bat activity than hypothesised. At the same time, it is worth questioning whether the insects collected at ground level, below the turbine decks, actually reflects the abundance of available insect prey for bats during night time. As insects were collected at only three occasions, and not daily, it is not possible to quantify the nightly insect abundance and compare it to nightly bat activity. The method could however be tested and further developed in future research, if standardized and carried out daily. As the data did not align temporally, it is not possible to draw conclusions on whether the measured insect abundance had any effect on bat activity. Looking at the trends across the bat monitoring period, turbines ST01, ST04 and ST07 stood out as the sites with most indicated bat foraging activity. Similarly, ST04 was also one of the two turbines with highest insect abundance in the third insect sample. However, ST01 and ST07 were the two turbines with the lowest insect abundance, suggesting that the method for quantifying insect abundance did not reflect the abundance of flying insects available at night time. This was expected, as the initially planned method for quantifying insect abundance were camera traps monitoring insect abundance each night.

4.5 Methods for surveying insect abundance and order distribution in wind farms

Quantifying spatial and temporal trends in insect abundance is a challenging task, especially when using manual trapping techniques (Bjerge et al., 2023). However, the use of camera trapping and automated detection in data analysis is becoming increasingly common in entomological research (Choiński et al., 2023; Gebauer et al., 2024; Sittinger et al., 2024). The method intended for quantifying insect abundance in this study was initially camera trapping (description of method in **Appendix C**). However, as only a limited number of flying insects were detected in the images taken by the camera traps, it was not possible to use this data for quantification purposes. The collected insect were therefore used as an alternative measure of insect abundance between turbine sites, although this resulted in a small data set due to each sample not being truly comparable, as described in **Ch. 4.2.**

The camera traps were tested in a rural agricultural landscape before being deployed in Stigafjellet, in order to test if the setup was functional, and how long the internal batteries would last for. These initial tests were successful, and the pictures taken by the camera traps contained visible flying insects (see **Appendix C, Figure C3**). However, in the wind farm, the camera traps were unable to capture enough flying insects to enable automated analysis of the images. There may be a number of reasons for this, including unfavourable weather conditions resulting in visual clutter (e.g., humidity, precipitation) on the lens, obscuring the view and thus not successfully getting clear pictures. Another plausible cause is that flying insects are too small, or too fast to detect for the camera trap. Insect activity is often ephemeral of nature, and deciding fixed intervals may not only produce a surplus of non-informative data (no detected insects) (Gebauer et al., 2024), but also miss brief swarming events or bypasses. However, we did include two extra camera traps programmed to shoot continuously every five minutes, as opposed to every ten minutes like the rest of the camera traps. This was done to verify that the camera traps operating at ten minute intervals did not miss swarming events or more frequent bypasses. Yet, it is worth noting that the two extra camera traps were set up at ST01 and ST07, which were the two turbines with the lowest insect abundance in sample 3.

A number of studies have already applied a similar camera trapping technique for quantifying insect abundance in various habitats (e.g., Johns, 2021; McKay et al., 2024; Ruczyński et al., 2019; Thomle, 2023) with success. This shows that camera trapping can be an effective method, if the conditions are right. Ideally, camera detection would be automated, and camera traps would only take pictures whenever insects would pass by. However, this may be challenging as insects often are small and move fast, making them hard to detect and separate from the background (Bjerge et al., 2023). As a result, cameras with passive infrared sensors may not be reliable enough in detecting movements of flying insects (Gebauer et al., 2024). The use of entomological lidar has been proposed as another effective method for quantifying insect abundance across large areas (Brydegaard & Jansson, 2019; Chen et al., 2024; Jansson et al., 2020). However, despite the apparent advantages of this type of method, lidar systems are still costly to use, are fairly large, and do require expertise to operate (Wallace et al., 2023). This makes them especially challenging to apply in long-term studies. Consequently, camera trapping may for now remain one of the most cost-effective and applicable entomological surveying methods.

5 Conclusion

Quantifying insect abundance and identifying insect community composition at wind farms remains a challenging task, due to the large temporal and spatial variations in distribution of flying insects. Camera traps are useful tools for gaining insight into temporal fluctuations in insect abundance, but does not provide qualitative data on e.g., insect community structure. The method used in this study, which consisted of collecting naturally accumulated insects from below wind turbine platforms were valuable for gaining insight into the distribution of insect orders present in Stigafjellet, but did however not prove ideal for quantifying insect abundance. This taken into consideration, future studies on insect and bat dynamics in wind farm environments should focus their efforts on further developing and testing different cost-effective and applicable methods for quantifying insect abundance, as well as describing insect community structure and interactions between bats and insects. Increasing available knowledge and empirical data on the use of different entomological surveying techniques in wind farm environments, combined with acoustic bat monitoring, can aid in improving future impact assessments for wind power development. Carefully surveying future wind development sites, especially in regards to insect and bat presence, prior to construction is a crucial step in mitigating negative ecological impacts on local ecosystems and biodiversity. If wind power is to be seen as a truly sustainable source of energy, the ecological aspects must be considered.

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7 Appendix

A. Coordinates and site data for turbines

Table A 1. *Coordinates (latitude and longitude) for each turbine in Stigafjellet, along with turbine site elevation in meters above sea level (masl), and distance to nearest body of freshwater in meters (m).*

Turbine ID	**Latitude**	**Longitude**	**Elevation** (masl)	**Distance to water** (m)	**Name of nearest body of freshwater**
ST-01	58.658207	05.933275	422	450	Kålivatn
ST-02	58.659037	05.939581	414	560	Kålivatn
ST-03	58.663105	05.941779	405	225	Small pond
ST-04	58.662799	05.949979	396	100	Kråketjørna
ST-05	58.665852	05.950931	392	155	Kråketjørna
ST-06	58.667920	05.955730	397	470	Ellivatnet
ST-07	58.669802	05.959903	376	450	Ellivatnet

B. Acoustic bat detector settings

Table B1. *Overview of acoustic detector specifications and settings.*

Detector information	
Recorder	Song meter SM4BAT FS Ultrasonic Recorder from *Wildlife Acoustics*
Microphone	SMM-U2 Ultrasonic Microphone from *Wildlife Acoustics*
Firmware	2.4.1
Time Zone	UTC +2
Recording Schedule	1 hour before sunset until 1 hour after sunrise
Audio settings	
Gain	12 dB
16k High Filter	Off
Sample Rate	256 kHz
Minimum Duration	1.5 milliseconds
Maximum Duration	None
Min. Trigger Frequency	16 kHz
Trigger Level	12 dB
Trigger Window	3 seconds
Max Length	15 seconds
Compression	None

C. Quantifying insect abundance using camera traps

Nine camera traps were deployed at the study site to monitor the abundance of flying nocturnal insects in a non-invasive manner. Camera traps were placed adjacent to the acoustic detector at each of the seven turbine decks, about four meters above ground level (**Figure C1**). An additional camera trap was placed alongside the first at two of the turbines: ST01 and ST07. Each camera trap consisted of 1) a protective 3D-printed transparent hardcover box, 2) a dehumidification bag, 3) one *Ricoh WG-6 Waterproof 20m/65.5ft* camera with firmware version 1.07, an internal battery and a SD-card (ranging from 16-64 GB), 4) a camera holder-box, and 5) a white paper sheet covering the inside of the lid to prevent "greenhouse effect" and overheating of the camera, with holes for lens and flash (**Figure C2**).

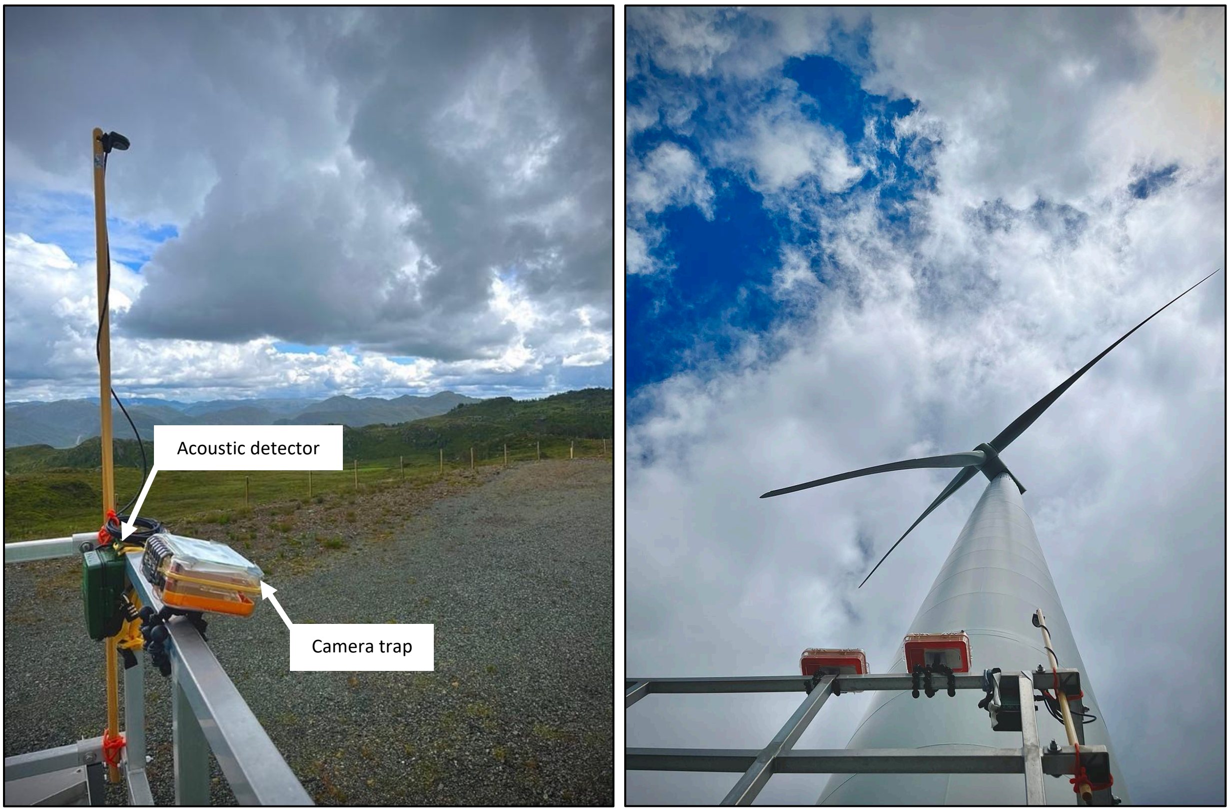

Figure C1. *Camera trap setup at the base of wind turbine. Left: Camera traps were attached to the wind turbine platform railing with a gorilla pod, adjacent to the acoustic detectors, and faced skywards with a slight tilt to prevent rain drops from accumulating in front of the lens. Right: At turbine number 1 and 7, two camera traps recorded at different time intervals; every 10 and 5 minutes. Photos taken by Ylva Heyn Friberg.*

All camera traps were mounted on adjustable Gorillapod tripods and attached to the wind turbine platform railing. Camera traps were positioned with a slight downwards tilt, for rain droplets to run off in case of rainfall. The camera was pointed skyward, to capture pictures of flying insects with a clear background. All seven turbines had one camera trap programmed to take a picture every ten minutes, continuously throughout both day and night, until the internal battery ran out. In addition, the first and last turbine (ST01 and ST07) had one camera trap programmed to take a picture every five minutes, for comparison of battery duration and amount of data collected when image frequency was doubled. All pictures were taken with flash, making insects light up against the backdrop of the sky, in line with the methodology of Ruczynski et al. (2019). A complete overview of the camera settings can be found in **Table C1.**

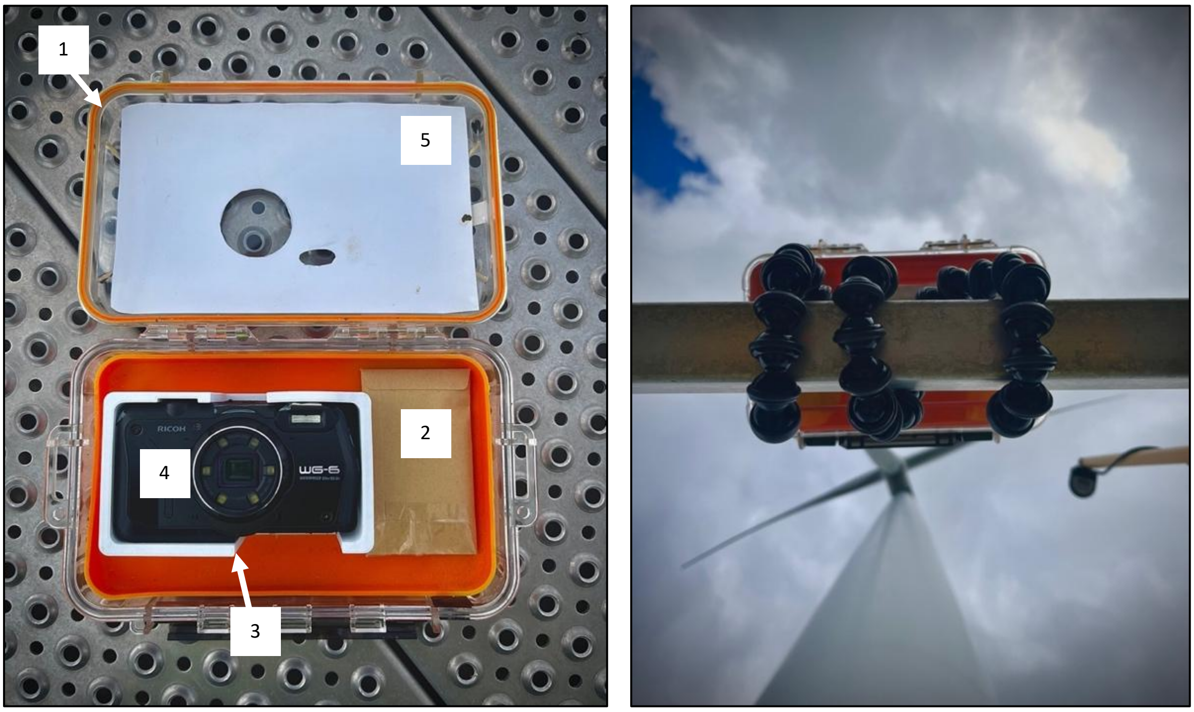

Figure C2. *Left: Camera trap setup consisting of 1) a protective box, 2) moisture absorbing pack with silica beads, 3) camera holder, 4) Ricoh WG-6 camera complete with 65 GB SD-card and internal battery, and 5) a white paper sheet with cut-out holes for lens and flash preventing greenhouse effect and overheating of the camera. Right: Mounted camera trap attached to turbine platform railing, facing skywards. Photos taken by Ylva Heyn Friberg.*

All camera traps were deployed on July 8th and retrieved on August 12th. The majority of the cameras operated all nights during the deployment, 35 nights in total. Maintenance was carried out every four days during the deployment period. The maintenance scheme was dictated by the battery life of the internal batteries, which averaged 3.5 days. Maintenance was carried out in the late afternoon of the fourth day, in order to maximize the amount of night-time the internal batteries would last. This, in most cases, resulted in four nights worth of pictures.

Pictures collected from the camera traps were sent to automatic image analysis performed by Marcin Zagrek. The images were analysed using a deep learning model as described in Choiński et al. (2023). Each image was scanned for small flying objects, as seen in **Figure C3 A**, and the number of objects in each image was recorded. The majority of the images, however, lacked distinguishable objects (as seen in the left picture in **Figure C3 B**).

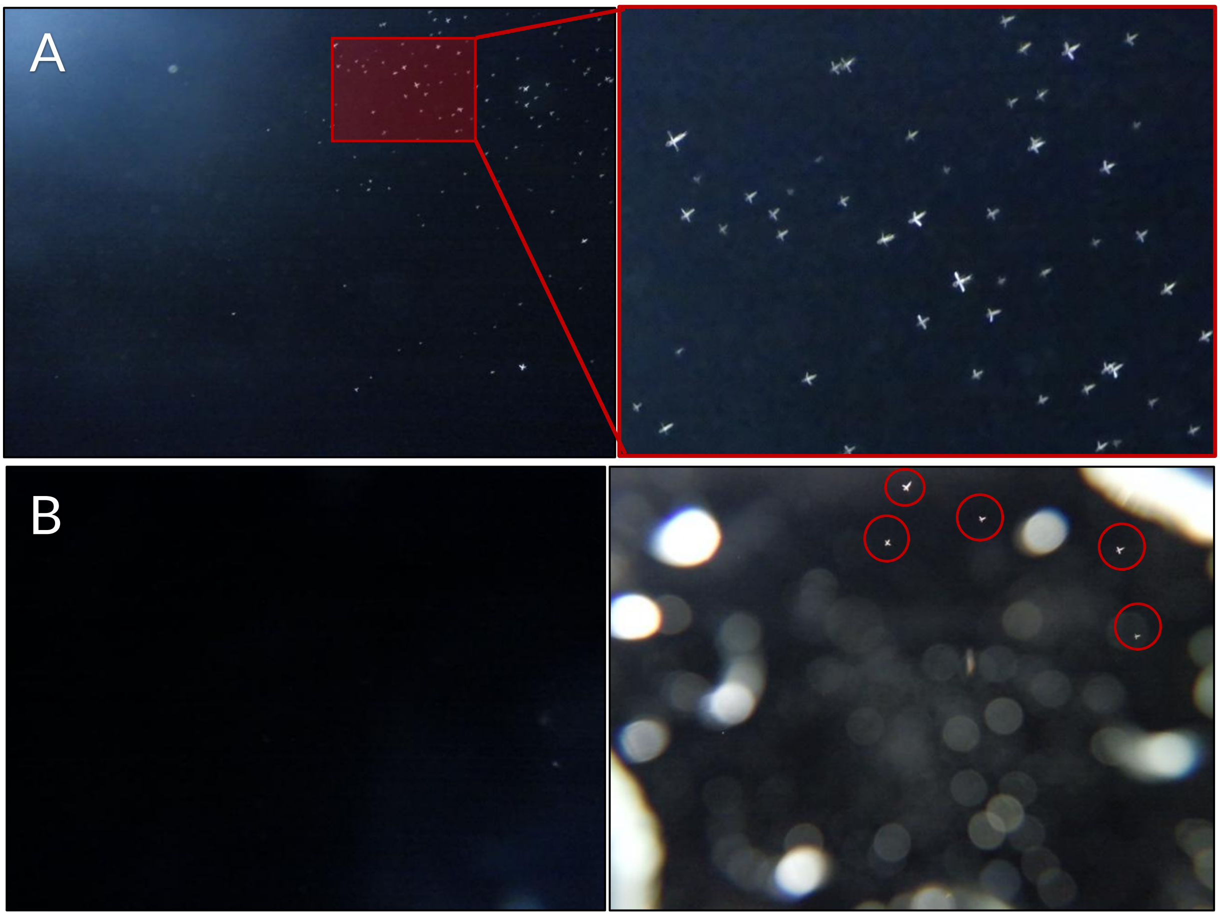

Figure C3. A. *Picture taken with camera trap during testing before deployment in Stigafjellet. Flying insects can be seen as small objects lit up against the sky by the flash.* ***B.*** *Camera trap pictures from Stigafjellet. Left picture without any visible flying insects, and right picture with five visible flying insects marked in red circles, as well as visible rain droplets across the camera lens.*

Table C1. *Overview of camera settings for insect camera traps.*

Camera information	
Model	Ricoh WG-6 waterproof 20m/ 65.5ft
Firmware	Ver. 1.07
Program settings	
Mode	Scene Mode Interval Shooting (SCN)
Shooting Interval	Every 10 minutes; every 5 minutes for extra cameras at ST01 and ST07
Number of Shots	1000
Start Delay	0hr, 0min

Setup settings	
Embed Info	On
Power Saving	5 seconds
Power Button Lamp	Off
Operation Volume	Off
Playback Volume	Off
Sounds	Off
Auto Power Off	Off
Custom settings	
CALS Pixels	L
CALS Quality	*** (3 Stars)
Shooting settings	
Focus	Infinity
AF	Multi
Auto Macro	Off
Focus Assistant	Off
AUTO ISO Range	125-1600
Flash Mode	Off
Face Detection	Off
Blink Detection	Off
Digital Zoom	Off
Quality Level	*** (3 Stars)
Image Tone	Natural

D. Quantifying insect abundance using a sticky trap attached to a balloon

Inspired by the methodology of Winstead et al. (2021), we designed an insect sticky trap attached with a string to a helium balloon. The trap was created using an empty 1.5 L plastic bottle that was covered with sticky coating (Tangle-Trap Sticky Coating by Tanglefoot Company) (**Figure D1**). A lightweight wire mesh shaped to fit the bottle was attached to the bottle neck, in order to prevent larger flying wildlife such as bats or birds from getting stuck to the sticky coating, while still allowing flying insects to get through the holes of the wire mesh. The wire mesh was shaped so it would not get stuck in the glue coating. The trap was intended to be launched in air using a helium balloon, at about six and a half meters above ground, with the intention of capturing flying insects.

The aim of the method was to be able to quantify insect abundance, and identify insect orders present above ground level, in order to get a more realistic impression of relative abundance and order structure of insects during flight, as opposed to only on ground level. However, the method was ultimately not applied to sampling in Stigafjellet due to unsuccessful results (next to no insects captured across both samplings) in the two initial tests of the method in semi-open forest environments, as well as challenging weather conditions within the wind farm.

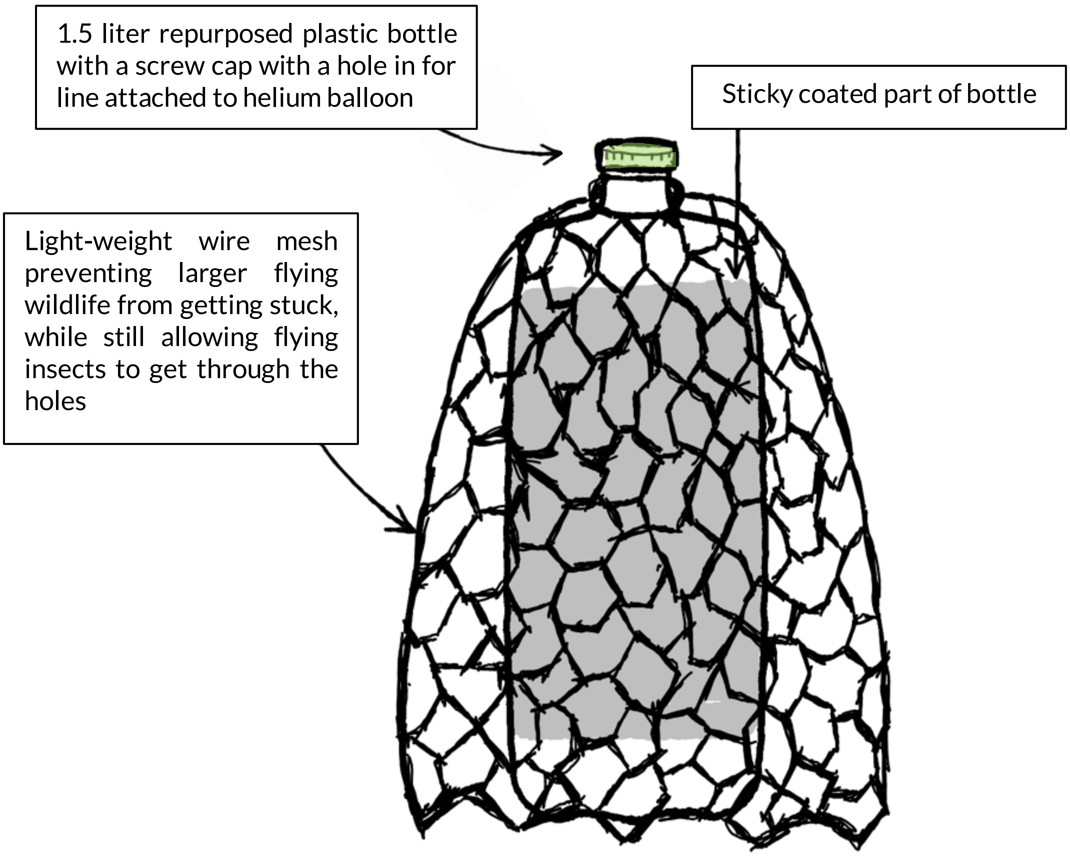

Figure D1. *Illustration of insect sticky trap-bottle design with protective wire mesh attached to the bottle. Illustration made by Ylva Heyn Friberg.*

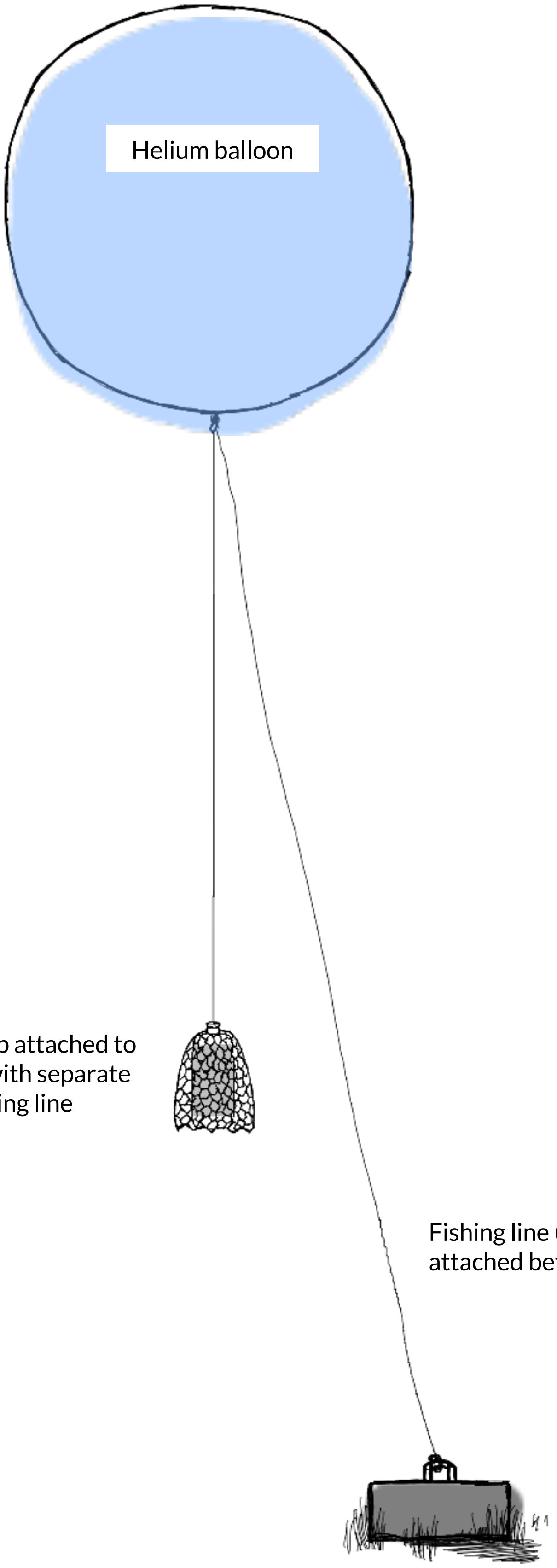

Figure D2. *Illustration of sticky trap set up, with flying helium balloon and ground anchor. Illustration made by Ylva Heyn Friberg.*

E. Insect and bat sampling data

Table E1. *Overview of number of counted insects per turbine site in the three samples collected in Stigafjellet.*

Turbine ID	Sampling 1	Sampling 2	Sampling 3	Total
ST-01	24	72	29	125
ST-02	14	236	1039	1289
ST-03	8	93	356	457
ST-04	18	150	769	937
ST-05	34	124	402	560
ST-06	16	110	224	350
ST-07	9	64	43	116
Total	123	849	2862	3834

Table E2. *Overview of number of counted insects per turbine for each size class in all samples from Stigafjellet combined.*

Turbine ID	Size class 1	Size class 2	Size class 3	Size class 4
ST-01	44	41	28	12
ST-02	1099	114	55	21
ST-03	354	53	18	32
ST-04	729	88	73	47
ST-05	411	73	45	31
ST-06	214	81	36	19
ST-07	68	34	9	5
Total	2919	484	264	167

Table E3. *Overview of number of raw bat recordings per turbine collected from the acoustic detectors in Stigafjellet.*

Turbine ID	n raw recordings
ST-01	2290
ST-02	2129
ST-03	2231
ST-04	881
ST-05	763
ST-06	624
ST-07	976

F. Identified insect orders and families in Stigafjellet

Table F1. *Identified insect orders and families from the samples collected in Stigafjellet.*

Order	Common name	Families
Coleoptera	Beetles	Cantharidae, Cerambycidae, Chrysomelidae, Coccinellidae, Curculionidae, Elateridae, Scarabidae, Scirtidae, Silphidae, Staphylinidae
Diptera	True flies	Calliphoridae, Chironomidae, Culicidae, Empididae, Muscidae, Sepsidae, Simuliidae, Syrphidae, Tabanidae, Tipulidae
Hemiptera	True bugs	Aphididae, Cicadidae, Miridae, Pentatomidae
Hymenoptera	Sawflies, wasps, bees and ants	Apidae (genus *Bombus*), Braconidae, Formicidae, Ichneumonidae, Tenthredinidae, Vespidae
Lepidoptera	Butterflies and moths	Noctuidae
Plecoptera	Stoneflies	
Trichoptera	Caddisflies	
Thysanoptera	Thrips	
Psocoptera	Barklice	

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