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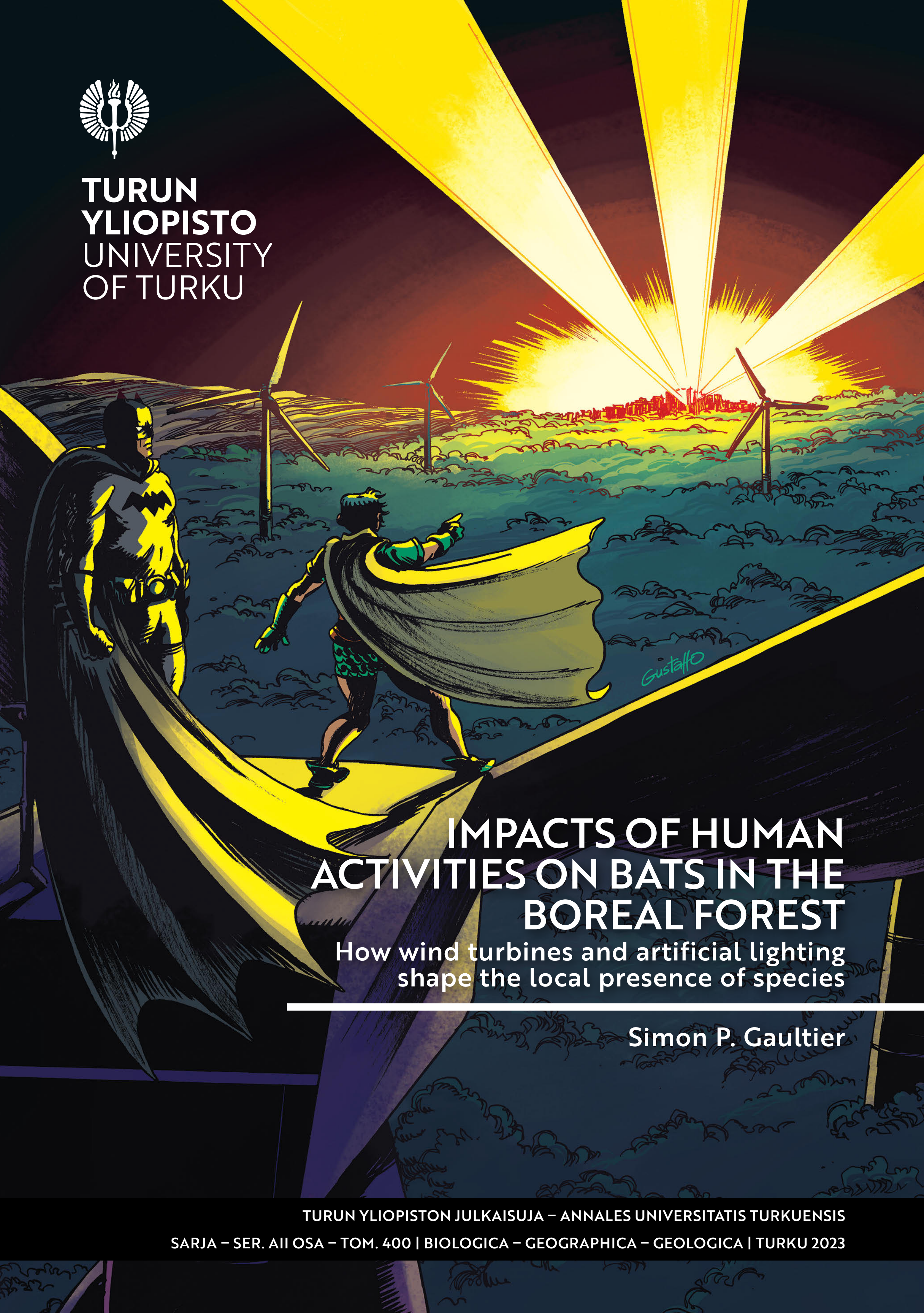

IMPACTS OF HUMAN ACTIVITIES ON BATS IN THE BOREAL FOREST

How wind turbines and artificial lighting shape the local presence of species

Simon P. Gaultier

TURUN YLIOPISTON JULKAISUJA – ANNALES UNIVERSITATIS TURKUENSIS
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“Odi panem quid meliora! It doesn’t mean anything but it does wrap it up nicely.”

- Kaamelott

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ABSTRACT

Human activities can negatively impact biodiversity, including bats, leading to excessive mortality, population declines and potentially species extinction. Amongst these threats, wind power and light pollution are both known to affect bats when foraging, commuting, or roosting. This can have consequences on species presence at a local scale, but when cumulative impacts from all wind turbines and artificial lighting sources, consequences are greater on species' survival.

As the dominating boreal forest is of great importance for Finnish bats, especially during the summer and its permanent twilight, I investigated how wind turbines and artificial lighting could affect the presence and activity of bats in this habitat. This choice was motivated by the vast proportion of wind turbines being built there at the moment, and the general increase in the use of artificial lighting at night. The final reason is that there is no data on the impacts of artificial lighting and wind power on bats in the country.

I monitored bat acoustic activity at several wind farms located in forest and observed that the presence of bats increased when getting away from wind turbines, for both *Eptesicus nilssonii* and *Myotis spp.* The range of this repelling effect was estimated at 800 m for the former species, and more than 1,000 m for the latter. This avoidance of wind turbines and their surroundings could mean a loss of commuting and foraging habitats for bats. The reasons behind this phenomenon are not understood but could be explained by the changes in landscape consequent of the construction of turbines in the forest, or the consequences of these changes on insects.

Regarding light pollution, I set up flood lights in the forest and recorded bat activity to assess the effect on *E. nilssonii* and *Myotis spp.* The response of the latter was negative towards flood lights, with significantly lower presence at lit sites than dark sites. The observed response of *E. nilssonii* was also negative, but not significantly, and could be explained by the absence of UV emission by the flood lights, that would fail to attract insects.

In this thesis, I showed that wind power and light pollution have negative impacts on the presence of bats in Finland. At a local scale, the existence of wind turbines or artificial lighting will shape the presence of *E. nilssonii* and *Myotis spp.* When looking at the cumulative impacts of all wind turbines and artificial lighting in Finland, but also other sources of disturbance such as roads or power lines, we could see a considerable part of the country's total area being affected, i.e., being avoided by bats. Therefore, I recommend better consideration of bats in wind power projects and in the use of artificial lighting. More globally, I recommend that the actual impacts of wind power on bats – including fatalities - in the country to be assessed, and the use of artificial lighting to be reevaluated, as renewable energy and energy sobriety are both key components for our transition to sustainability.

KEYWORDS: bats, avoidance, wind power, wind turbine, light pollution, artificial lighting, boreal forest, Finland

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TIIVISTELMÄ

Ihmistoiminnalla voi olla haitallinen vaikutus monimuotoisuuteen, kuten lepakoihin, ja se voi johtaa lisääntyneeseen kuolleisuuteen, eliöiden kantojen pienenemiseen ja mahdollisesti lajien sukupuuttoon. Esimerkiksi tuulivoiman tuotannolla ja keinotekoisella valolla tiedetään olevan vaikutusta lepakoiden saalistamiseen, liikkumiseen ja päiväpiilojen käyttöön. Tällä voi olla vaikutusta lepakoiden esiintymiseen paikallisella tasolla, mutta kokonaisvaikutukset voivat uhata koko lajin olemassaoloa.

Boreaalinen metsä vallitsevana luontotyyppinä on lepakoille erittäin tärkeä, erityisesti kesällä valon määrän lisääntyessä, ja tästä syystä tutkin miten tuulivoimatuotanto ja keinotekoinen valo vaikuttavat lepakoihin metsissä. Valintaani vaikuttivat tämänhetkinen tuulivoimarakentamisen lisääntyminen, sekä yleisesti lisääntynyt keinotekoisen valon määrä. Tärkeimpänä syynä on kuitenkin se, että tuulivoiman ja keinotekoisen valon vaikutuksista lepakoihin ei ole maassamme tutkittua tietoa.

Havainnoin lepakoiden ääniaktiivisuutta useilla metsäisillä tuulivoima-alueilla ja huomasin pohjanlepakon (*Eptesicus nilssonii*) sekä siippalajien (*Myotis spp.*) aktiivisuus lisääntyi etäännyttäessä tuulivoimaloista. Tämä karkotusvaikutus näkyi pohjanlepakolla 800 metrin päähän, ja siipoilla vielä yli kilometrin etäisyydellä. Tämä tuulivoimaloiden ja niiden välittömän ympäristön välttely voi johtaa lepakoiden muutto- ja saalistusalueiden vähentymiseen. Ilmiön syyt eivät ole tiedossa, mutta sitä voidaan selittää tuulivoiman rakentamisesta johtuvissa muutoksissa metsämaisemassa, tai näiden muutosten vaikutuksesta lepakoihin.

Valosaasteen vaikutusten tutkimiseksi asetin valonlähteitä metsään, ja äänitin lepakoiden aktiivisuutta selvittääkseni valon vaikutuksia pohjanlepakkoon ja siippoihin. Siippojen vaste valon määrän lisääntymiseen oli negatiivinen, ja niitä esiintyi tilastollisesti merkitsevästi vähemmän valoisilla kuin pimeillä kohteilla. Myös pohjanlepakon vaste oli negatiivinen, mutta ei tilastollisesti merkitsevä, kuten voi olettaa, koska keinotekoinen valonlähde ei sisältänyt UV-valoa eikä näin ollen houkutellut hyönteisiä tutkimuspaikalle.

Väitöskirjassani osoitin, että sekä tuulivoimatuotannolla että valosaasteella on negatiivinen vaikutus lepakoiden esiintymiseen Suomessa. Paikallisella tasolla tuulivoimaloiden tai keinovalon läsnäolo muuttaa pohjanlepakon ja siippojen esiintymistä alueella. Kaikkien tuulivoimaloiden ja keinovalon kokonaisvaikutusta tarkasteltaessa, sekä laskettaessa mukaan vielä voimalinjojen ja tieverkoston vaikutukset, voidaan arvioida merkittävän osa Suomen pinta-alasta olevan häiriön kohteena ja näin ollen karkottavan lepakoita. Tästä syystä suosittelen parempaa lepakoiden huomioonottamista tuulivoimaprojekteissa ja keinotekoisen valon käytössä. Laajemmin tarkasteltuna suosittelen että tuulivoiman todelliset vaikutukset lepakoihin, kuten suorat törmäämiskuolemat, tutkittaisiin Suomessa huolellisesti, sekä keinotekoisen valon käyttöä arvioitaisiin uudelleen, sillä uusiutuva energia ja energiatuotannon läpinäkyvyys ovat molemmat avainroolissa kestävän kehityksen siirtymässä.

ASIASANAT: lepakot, tuulivoima, keinovalo, valosaaste

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RESUME

Les activités humaines peuvent avoir des impacts négatifs sur la biodiversité, notamment sur les chiroptères, en provoquant une surmortalité, un déclin des populations, voire des extinctions d'espèces. Parmi ces menaces, l'éolien et la pollution lumineuse ont le potentiel d'affecter les chiroptères lors de leurs déplacements, en chasse ou au gîte. Ceci peut se répercuter sur la présence des espèces à l'échelle locale, mais les impacts cumulés de nombreuses éoliennes ou sources de lumière artificielle peuvent avoir des conséquences décuplées sur la survie des espèces.

Milieu prédominant de la Finlande, la forêt boréale est d'une grande importance pour les chauves-souris du pays, notamment durant l'été où le crépuscule est permanent. J'ai donc étudié comment les éoliennes et l'éclairage artificiel pouvaient affecter la présence et l'activité des chiroptères spécifiquement dans cet habitat. Ce choix fut motivé par la propension des développeurs à construire des éoliennes en forêt, ainsi que par l'augmentation globale de l'utilisation de l'éclairage artificiel durant la nuit. La raison finale derrière ce choix est l'absence de données sur les impacts de l'éclairage artificiel et de l'éolien sur les chiroptères en Finlande.

J'ai suivi l'activité acoustique chiroptérologique autour de plusieurs parcs éoliens situés en forêt et observé que la présence des chauves-souris augmentait avec la distance aux éoliennes, à la fois pour la sérotine de Nilsson (*Eptesicus nilssonii*) et les murins (*Myotis spp.*). La portée de cet effet répulsif a été estimée à 800 m pour la première espèce, et plus de 1 000 mètres pour les murins. L'évitement des éoliennes et de leurs alentours équivaudrait à une perte de corridors de déplacement et de zones de chasse pour les chauves-souris. Les causes de ce phénomène ne sont pas entièrement connues, mais seraient liées aux changements paysagers induits par la construction d'un parc éolien en forêt, ou aux conséquences de ces changements pour les insectes.

Pour étudier les effets de la pollution lumineuse sur *E. nilssonii* et *Myotis spp.*, j'ai installé des projecteurs en forêt avant d'enregistrer leur activité acoustique. Les murins montrent une réponse négative à la lumière, avec une présence significativement plus basse sur les sites éclairés que sur les sites gardés dans l'obscurité. La réponse d'*E. nilssonii* est aussi négative, mais pas significativement, et pourrait être expliquée par les projecteurs qui n'émettent pas d'UV, et n'attirent donc pas les insectes.

Dans cette thèse, j'ai montré que l'éolien et la pollution lumineuse ont des impacts négatifs sur la présence des chauves-souris en Finlande. A l'échelle locale, la présence d'éoliennes ou de sources de lumière artificielle détermine la présence d'*E. nilssonii* et *Myotis spp*. En considérant les impacts cumulés de toutes les éoliennes et sources de lumière en Finlande, ainsi que d'autres sources de perturbation telles que les routes ou lignes électriques, nous pourrions voir une part conséquente du pays être affectée, c'est-à-dire évitée par les chiroptères. Par conséquent, je recommande d'améliorer la prise en compte des chiroptères dans les projets éoliens et dans l'utilisation de l'éclairage artificiel. Plus généralement, et parce que les énergies renouvelables et la sobriété énergétique sont des composantes clefs de notre transition énergétique et écologique, je recommande qu'en Finlande, les impacts de l'éolien sur les chiroptères, notamment la mortalité, soit réellement évalués, et l'usage de l'éclairage artificiel réexaminé.

MOTS-CLES: chiroptères, évitement, projet éolien, éolienne, pollution lumineuse, lumière artificielle, forêt boréale, Finlande

Table of Contents

Abbreviations

ALAN	Artificial Lighting At Night
UV	Ultraviolet

List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I **Gaultier S. P.**, Blomberg A. S., Ijäs A., Vasko V., Vesterinen E. J., Brommer J. E. & Lilley T. M. (2020). Bats and wind farms: The role and importance of the Baltic Sea countries in the European context of power transition and biodiversity conservation. Environmental Science & Technology, 54(17), 10385–10398. https://doi.org/ 10.1021/acs.est.0c00070

II **Gaultier S.P.**, Lilley T.M., Vesterinen E.J. & Brommer J.E. (2023). The presence of wind turbines repels bats in boreal forests. Landscape and Urban Planning 231 – 104636. https://doi.org/10.1016/j.landurbplan.2022.104636

III **Gaultier S.P.**, Brommer J.E., Vesterinen E.J. & Lilley T.M. Species-specific response of bats to artificial light in boreal woodlands. Manuscript

1 Introduction

1.1 Anthropogenic threats on bats

Bats worldwide face threats caused by anthropogenic activities that put pressure on populations and will potentially lead to species extinction in the near future. Among these threats can be found logging, agriculture, energy production, pollution, etc., and of course, climate change (Frick et al., 2019; Voigt & Kingston, 2016). These threats usually translate to bats in direct excessive mortality, or habitat degradation that will hamper their foraging and roosting possibilities, meaning decreased chances for survival that will lead to indirect excessive mortality (Frick et al., 2019; Voigt & Kingston, 2016).

Among these threats, I chose to focus on wind power and light pollution. The former because of its importance in the energetic transition to renewable energy while having significant impacts on bats – among others (Dai et al., 2015; Saidur et al., 2011). Thus, it is a really hot topic in many countries, for researchers as well as in politics, but in Finland the focus has been more on other taxa (Balotari-Chiebao et al., 2018; 2023). The latter because, once again, it has not been a topic of interest for research and politics in Finland, while impacts are real and solutions exist (Voigt & Kingston, 2016).

Conservation efforts linked to the impacts of wind power and light pollution then promise to be often a source of conflicts as stakeholders (citizens, scientists, industrialists, public authorities and policy makers) obviously have different agendas. In the case of wind power, it is the so-called "green-green dilemma", where energetic transition is often opposed to biodiversity conservation (Barré et al., 2022a; Kati et al., 2021; van Rooij et al., 2022). Meanwhile, the reduction of artificial lighting has social, health, economic and environmental benefits all at the same time (Cupertino et al., 2022; Hölker et al., 2010; Rodrigo-Comino et al., 2021).

1.1.1 Wind power

Wind power is playing a substantial role in the transition to clean energy production in many countries (Ember, 2021). Being a renewable source, the exploitation of wind does not generate pollution (Edenhofer et al., 2012). Unfortunately, developing and operating wind farms can still have negative impacts on landscape, human health, environment or biodiversity, and thereby lead to lower social acceptance of wind turbines or damages to fauna and flora (Buchmayr et al., 2022; Dai et al., 2015; Saidur et al., 2011).

The impact of wind power on bats have been known for decades. Fatalities were first reported in 1972 and have since been intensively studied. Affected species, seasonal peaks and the influence of weather conditions on bat fatalities have been largely described, at least for Europe and North America (Hein & Schirmacher, 2016; Rydell et al., 2010a). Bats are also affected by habitat destruction during the construction of wind farms, with the potential loss of important features for roosting, commuting, or foraging, such as wetlands or hedgerows (Reusch et al., 2022).

Knowing all the characteristics of these impacts have since led national and international organisations to propose guidelines and measures on how to correctly plan wind power projects in order to avoid or minimise impacts on bats (Rodrigues et al., 2015). Such mitigation measures include avoiding construction close to known bat roosts or other important features and installing curtailment on wind turbines to decrease the risk of fatalities, or designing wind farms with an intent to reduce their footprint on habitats (Gartman et al., 2016a, 2016b). These measures are far from being completely respected by wind power developers, even in developed countries (Barré et al., 2022a; Voigt et al., 2022). Most of all, these measures are not always enough to mitigate impacts of wind farms on bats, because the mortality is still taking place and very difficult to offset (Hayes et al., 2019; Rodrigues et al., 2015; Voigt et al., 2015), especially when cumulative impacts of several wind farms are considered at a larger, landscape scale (Roscioni et al., 2013).

1.1.2 Light pollution

Another threat currently faced by bats is light pollution, i.e., “the inappropriate or excessive use of artificial light” (Cupertino et al., 2022). Being essentially nocturnal animals, bats can be affected by artificial light at night (ALAN) in multiple ways, directly or indirectly (Rowse et al., 2015). Some species, such as *Rhinolophus hipposideros*, have been observed actively avoiding lit areas, a disturbance affecting their commuting or foraging (Luo et al., 2021; Stone et al., 2009). Meanwhile, other species, such as *Pipistrellus pipistrellus* in Western Europe (Blake et al., 1994), or

E. nilssonii in Sweden (Rydell, 1991; 1992a), thrive under street lighting, exploiting the abundance of insects attracted there by lights. The presence of artificial lighting has also been shown to delay and slow roost emergence for most species, and therefore could have consequences on the life expectancy of individuals or the presence of entire colonies (Boldogh et al., 2007; Downs et al., 2003; Rydell et al., 2017a; Voigt et al., 2018; Zeale et al., 2016). Consequently, the roles that bats play in ecosystems as pollinators or pest controllers, could be undermined by the presence of ALAN (Lewanzik & Voigt, 2014).

Therefore, controlling and reducing the use of artificial light is key to bat conservation not only in urban areas where ALAN is the most present, but it is also of concern in more natural areas (Barré et al., 2022b; Lacoeuilhe et al., 2014).

1.2 Finland as a study area

The European boreal biogeographic region is a part of Europe located in the north-east of the continent, and comprising Estonia, Latvia and Lithuania, as well as most of Finland and Sweden, and portions of Norway and Russia (fig. 1). The region is defined by its climate, with shorter summer, less light, lower temperatures and precipitation, and a longer snow cover than the rest of Europe (Cloudsley-Thompson 1975; Sundseth, 2009). It is mostly covered by forest (60 % of the total area of the region) or wetlands (8 % on average in the countries of the region), but in Finland, woodlands and wetlands cover about 72 % and 15 % of the country's total area, respectively (Corine Land Cover data).

All the characteristics of this biogeographic region also influence animal communities and their ecology, including bats (Rydell, 1992b; Rydell et al. 2017b; Siivonen & Wermundsen, 2008a; Wermundsen & Siivonen, 2008). It also means that interactions between bats and wind turbines or ALAN may differ, with impacts varying in nature or intensity.

Figure 1. The European boreal biogeographic region (light grey area). The main migration flyways of bats are represented by black arrows. The dashed arrow indicates uncertainty about the use of the flyway. As an example, current (dark grey triangles) and future (light grey triangles) wind farm projects in Finland are presented.

1.2.1 Wind power

Maybe the most important part of the boreal region regarding wind power and bats, is the Baltic Sea. Strong winds there have attracted most of the Finnish wind farms along the western coastline (fig. 1). While the development really started 10 years ago only, with 59 turbines and 171 MW built that year, last year (2022) saw a huge leap with more 400 new turbines built for 2238 MW of power. It brought the total number of turbines in Finland around 1,281, for a total power of 5,248 MW, but there are already 339 more turbines that will be built in 2023 and 2024, and 4573 more are under review for authorisation, for an estimated total power of 33,330.8 MW (Etha Wind, 2022).

These numbers indicate that wind power is not anecdotal in Finland anymore, and consequently, neither are its impacts on bats, and therefore should be considered more seriously. Moreover, and because of the Finnish landscape, most turbines are built in forests (Asko Ijäs, personal communication, 30/03/2022). Such a decision goes against the EUROBATS recommendation (Rodrigues et al., 2015) but is explained by other constraints, such as staying away from populated areas, which are mostly located in open areas (Corine Land Cover data). Therefore, forests are considered the best choice for the construction of wind farms, without considering bat communities present there. All bat species present in Finland use forest to different extents for their foraging or roosting needs (Siivonen & Wermundsen, 2008a; Vasko et al., 2020; Wermundsen & Siivonen, 2008). In addition, because of the permanent twilight of Finnish summer, most bats spend more time in the forest to enjoy the darker environment provided by the trees (Rydell, 1992b; Vasko et al., 2020). In consequence, the construction of wind turbines in forests is sure to have impacts on bats at some stage of the project, either during the building or the operating phase.

1.2.2 Artificial lighting

Similar to other industrialised countries, Finland's use of lighting has greatly increased in recent decades, particularly for roads and outdoor lighting (Adato, 2013; Finnish Transport Agency, 2012). And as for other industrialised countries, it is expected that the use of ALAN in Finland would have impacts on the environment – and bats. There is currently no data on the effects of light pollution on health and environment specifically for Finland. In addition, these effects are poorly known from the general public in the country (Lyytimäki & Rinne, 2013).

As the impacts of ALAN on European bat species is usually known thanks to studies from other countries, the responses of Finnish bats to ALAN are not totally unknown. However, being located at high latitudes influences seasonal variation of night length and darkness in the country. During the winter, nights are long and entirely dark, but they get shorter and lighter when approaching the summer solstice. Even in southern Finland, summer nights usually resemble permanent twilight rather than a completely dark night. These differences are known to affect bats in the country and at similar latitudes, notably with a switch from open to more secluded habitats during the summer (Rydell, 1992b; Vasko et al., 2020). It is believed this response is associated with an increased risk of predation related to the absence of darkness in open areas (Rydell, 1992b). It could also be linked to the response of their prey to this change in night darkness. For instance, *E. nilssonii* has been observed foraging around street lights during Spring and Autumn, but is absent between May and July. This could be explained by lights becoming less attractive at this time of the year, because of a lack of contrast with the background scenery (Rydell, 1992a).

Therefore, secluded habitats such as forests act as "dark shelters" essential for Finnish bats during the summer. However, it is not clear how bats respond to ALAN in these "shelters" during the summer. Would *E. nilssonii* avoid light in these conditions, because of the predation risk? Or would it be foraging around lights that would attract a lot of insects?

1.3 The aims of the thesis

The main aim of this thesis was to investigate how human activities could affect the presence of bats in boreal forests. I focused on wind power and ALAN because both are known to impact bats at several scales, but there was no data on these impacts in Finland until now. I also focused on forests as my study areas, as it is at the same time the dominant landscape in the country, the preferred choice for wind power development, and vital habitats for all bat species.

As wind farms and artificial lighting are multiplying in the country, it is important that research and relevant authorities do not overlook these impacts, especially when already-existent solutions could be employed almost straight away. In order to get a better grasp on the situation in the boreal region and Europe more globally, I started my thesis with a bibliographic review on the impacts of wind power on bats (chapter I), a review that allowed me to define possible further research for my thesis. Consequently, I chose to study the avoidance effect of wind farms by bats in the boreal forest, as this impact has been completely ignored in the region until now (chapter II). Lastly, I concentrated on light pollution, using a field experiment to see how artificial lighting affects bats in the forest (chapter III).

I. Assess the knowledge on wind power and bats in the European boreal biogeographic region and the rest of Europe, in order to identify the lacks and needs on the topic;

II. Investigate the avoidance effect in Finland, through the monitoring of bat acoustic activity at wind farms, and propose ideas and recommendations to better understand and mitigate this impact;

III. Examine the impacts of ALAN on bats during the boreal summer, using floodlights set in the forest. Bats switch to secluded habitats in order to avoid the summer permanent twilight and could react differently to light there.

2 Materials and Methods

2.1 Data Collection

2.1.1 Literature review (I)

Chapter I of this thesis describes the current knowledge on the impacts of wind power on bats in Europe globally and in the European boreal biogeographic region more specifically. Scientific literature and reports on impacts and how to mitigate them were collected from scientific journals, books and organisation websites, then reviewed. I compared the situation in the boreal region (including Finland, Sweden, Russia and the Baltic States) with the rest of Europe. Needs for further research, regulation and cooperation were also assessed, based on gaps in current knowledge and legislation, and on opinion articles, but also after exchanges with several stakeholders (researchers, wind power representatives).

2.1.2 Responses to wind turbines (II)

2.1.2.1 Study sites

Data were collected at seven wind farms located on the western coast of Finland, in the regions of Ostrobothnia, Satakunta and South Ostrobothnia (fig. 2) All wind farms consisted of 5 to 34 wind turbines (mean = 15) with a mean height of 206 m at the highest tip of the pale (standard deviation = 4.4 m), and a mean rotor diameter of 136 m (standard deviation = 11.2 m). The distance from the wind farms to the coastline was between 2 and 18 km, with an average distance of 10 km (standard deviation = 6.2 km). I decided to include canopy cover in the analysis, using three classes: [x > 95 %], [95 %>x > 50 %] and [x < 50 %] where x is the percentage of area covered by tree canopy, regardless of their species, in a 150-m radius around the sampling point. In our study area, forest patches were of a similar age (mean = 49.33 years old, standard deviation = 12.32) and similar composition (deciduous tree cover mean = 9.95 %, standard deviation = 7.85 %), which is representative of the forests of Finland and the rest of the boreal region (Luke, 2017), therefore I did not include these two parameters in our analysis.

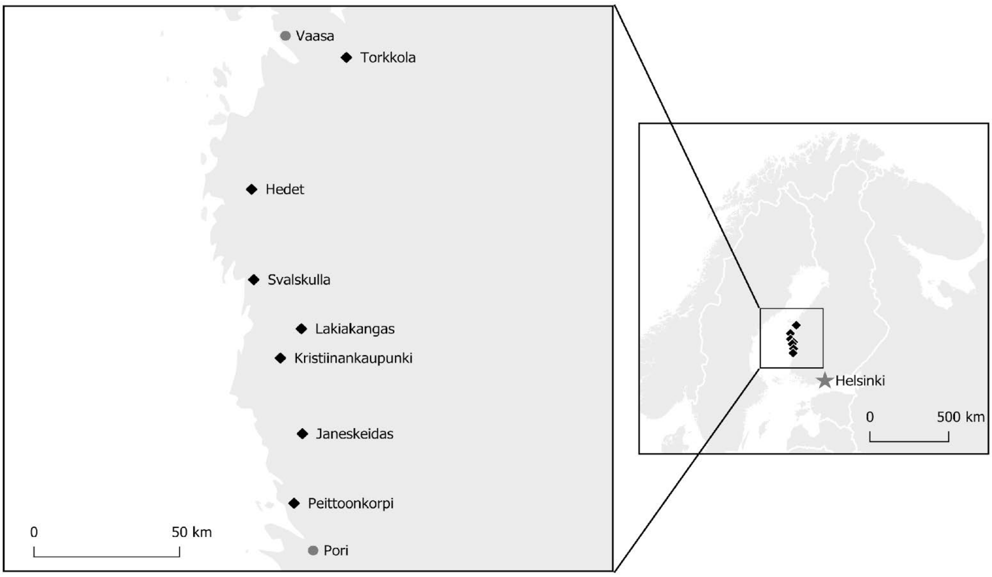

Figure 2. Localisation of the seven study sites (black diamonds) and their position in relation to close major cities (grey dots) and the capital (grey star).

2.1.2.2 Sampling design

We studied bat activity along forest edges or forest roads, with a distance gradient of 0 to 1,000 m from the nearest wind turbine. These features are important to bats as commuting routes, and a higher number of bat species are likely to be found using these habitats for foraging with both close-space and open space habitats present (Vasko et al., 2020). Moreover, wind farm construction contributes to the creation of some of these open areas in forests when roads and pads are cleared for the turbines. We sampled six distances (0, 200, 400, 600, 800 and 1,000 m) to the nearest turbine in duplicate at each wind farm, adding up to 12 sampling points for each wind farm, and adding up to 84 points in total. We recorded bat acoustic calls at all 84 points every night, starting June 1st, 2020 and ending between September 10th and 20th, 2020, depending on the recorder (16 weeks). Sampling commenced 30 min after sunset and was concluded 30 min before sunrise, with 5 min recording periods alternating with 10 min of sleep. The length of night varies considerably in Northern Europe, shifting from lasting twilight in June (mean = 5.42 h) to full nights towards the end of our sampling period (mean = 11 h) in September. We used AudioMoth recorders (Open Acoustic Devices, version 1.1) at every sampling point. Each recorder was strapped on to a tree along an edge, at around 2 m from the ground, with the microphone facing an open area (road, path or clearing).

2.1.3 Responses to artificial lighting at night (III)

I chose eight sites in the Turku area, all located in woodlands, and where the presence of bats was expected (fig. 3). Woodlands were chosen for their importance for bats during the boreal summer (Rydell et al., 1992b; Vasko et al., 2020). Under the term of woodlands, are grouped any type of habitats dominated by trees, such as mixed and coniferous forests, riparian vegetation, or small patches of woods. For each site, I set up a flood light along a woodland path or road, attached to a tree at around 2 m height and aiming at an approximative angle of 45° upwards. All lights had the same characteristics: they were LED white lights with a luminous flux of 4,000 lumens and a colour temperature of 4,000 K, no UV emission and only a small blue component.

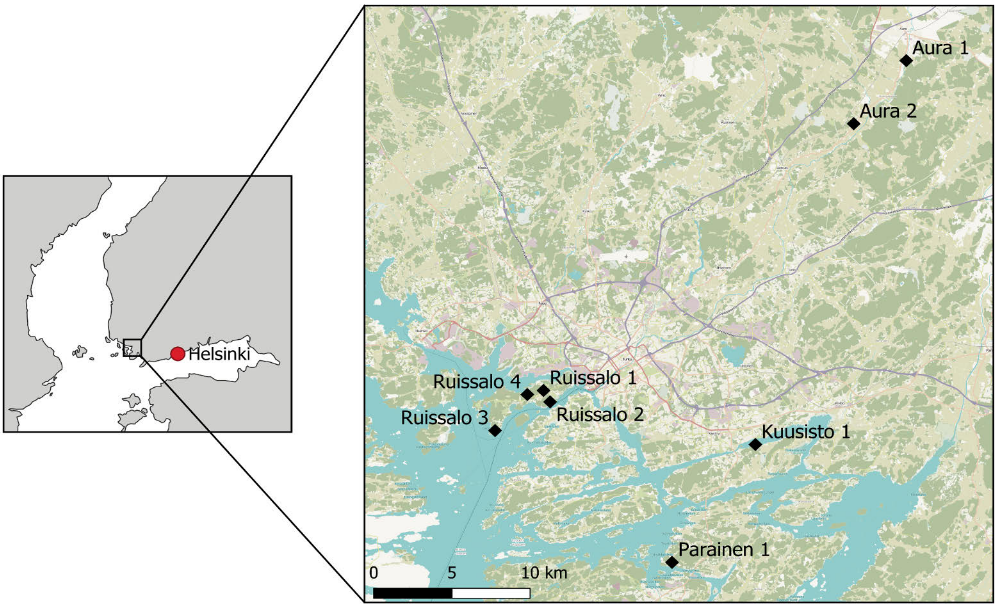

Figure 3. Location of our eight sites (black diamonds) and their position in relation to the capital (red dot).

With every light I set up a AudioMoth recorder (Open Acoustic Devices, version 1.1) also attached to a tree at about the same height, with the microphone directed towards the road. A second recorder was set similarly but several hundred metres away from the first one and acted as a control, with no artificial light there.

The experiment started on June 21st and lasted 10 weeks until August 30th. During the first week, four lights were turned on while the other four were off. Every week, lights that were on were then turned off, and the other way around. Therefore, every week there were always four sites with a light on, and four with a light off. Timers were set each week in order to automatically turn on the lights between sunset and sunrise.

We studied bat acoustic activity at each site: sampling started 30 min after sunset and was halted 30 min before sunrise, with 5 min recording periods alternating with 5 min of sleep. The length of night fluctuates significantly in Finland, shifting from lasting twilight in June (mean = 5 h) to full nights by the end of our experiment in August (mean = 10 h).

2.2 Bat call analysis (II, III)

I used Kaleidoscope (Wildlife Acoustics) for automated identification of bat calls, before proceeding to manual verification of the identifications. Signal detection parameters were the following: frequency range between 8 and 120 kHz, detected pulse length between 2 and 500 ms, with a minimum number of pulses of 2 and a call sequence maximum length of 5 s. A sample of *E. nilssonii* calls was manually checked to assert the reliability of the auto-identification. Thus, we decided to validate all *E. nilssonii* calls with a confidence value superior to 0.2 provided by the software, and discarded the rest. Because the software is not reliable with the identification of species of the *Myotis* genus, and furthermore, the manual identification of their calls is complex, we decided to pool and analyse all *Myotis* calls as a group. Calls of other species identified by Kaleidoscope (i.e., *Pipistrellus nathusii*) were manually checked.

2.3 Statistical analyses (II, III)

The estimation of bat abundance is not possible with acoustic monitoring. Therefore, we opted to assess bat activity in both studies using the positive minute as our unit of measure (Vasko et al., 2020). Here, each minute with at least one bat call is assigned as “positive” for bat activity. Then we pooled positive minutes per week because of the expected temporal variations in bat activity in the boreal zone, something that would be more visible with such pooling.

2.3.1 Response to wind turbines (II)

We analysed the number of positive minutes during one week as a response variable with two separate analyses. These analyses were run independently for *E. nilssonii* and calls of *Myotis spp.*, the two most common taxa at our sites. We did not have enough calls from other species to run the models. First, we analysed whether there were calls recorded (presence) or not (absence) per site in a mixed model with binomial errors. Second, we analysed the number of positive minutes per recorder in a mixed model testing for the fit of the following distributions: (1) negative binomial, (2) zero-inflated negative binomial; (3) Poisson; (4) zero-inflated Poisson. Using the R package glmmTMB (version 1.1.4; Brooks et al., 2017), we compared the models with the chosen distributions using Akaike Information Criterion (AIC) and degrees of freedom (DF), using the distribution fitting our data the best.

The ID of Audiomoth recorders and the ID of wind parks were assigned as random effects in all models. Fixed effects were (1) recording time per recorder and per week (in minutes, with or without bat calls in it) standardised to a zero-mean (2) distance of the recorded calls to the wind turbine as a factor; (3) canopy cover as a factor with three classes and (4) week of the recording coded as a factor (1 to 16). The models were implemented in glmmTMB (Bolker et al., 2009; Brooks et al., 2017) in R 4.1.2 (R Core Team, 2021). The intercept of the models reflects the expectation at a distance of zero metre (i.e., at the base of the wind turbine) in canopy cover [95 %>x > 50 %] reflecting the opening in the forest due to the presence of a turbine, for the average recording time. The models statistically take into account differences due to recording time (reflecting night length), habitat, seasonality (fixed effect: week) while the random effects take into account the non-independence of observations from the same recorder and from the same wind park. Hence, our primary interest is whether the models' estimates for the different classes of distance from the wind turbine (200 m, 400 m, 600 m, 800 m, 1,000 m) significantly differ from the expected value at the wind-turbine (distance = 0 m; the intercept). The significance of these contrasts was tested using a Z-test of the model estimates.

2.3.2 Response to artificial lighting (III)

We assessed the presence and absence of bats at each site based on recorded calls, for one species and one group of species: *E. nilssonii* and *Myotis spp.* We did not record other species. The analysis was done using the R package glmmTMB (version 1.1.4; Brooks et al., 2017) to run a mixed model with binomial errors in R 4.2.2 (R Core Team, 2022). The intercept of the model reflects the expectation at the control sampling point.

The ID of AudioMoth recorders was assigned as a random effect in our model. Fixed effects were (1) treatment at the sampling point (experimental or control), (2) weeks of the recording coded as a continuous variable, (3) the species (*E. nilssonii* or *Myotis spp.*), (4) the interaction between treatment and species, (5) the interaction between treatment and weeks and (6) the recording time per recorder and per week (in minutes) standardised to a zero-mean. The model statistically takes into account differences due to total recording time (reflecting night length), and seasonality (fixed effect: week) while the random effects take into account the non-independence of observations from the same recorder. Hence, our primary interest is whether the model's estimates for the experimental points significantly differ from the expected value at the control points (light = always off; the intercept). Significance of these contrasts were tested using a Z-test of the model estimates.

2.4 Habitat loss due to the presence of wind turbines (II)

I estimated the area avoided by bats per turbine, and for all current and planned wind power projects in Finland up to June 2022. Information on wind farms in the country is publicly available on the website of the Finnish Wind Power Association. I used the observed range of avoidance (800 m for *E. nilssonii*, 1,000 m for *Myotis spp.*; fig. 4) to determine the area avoided around each turbine by each species or group of species. Then, I calculated the proportion of area impacted by the presence of turbines in Finland, for all current and planned turbines.

3 Results and Discussion

3.1 Wind power and bats in the Baltic Sea region: the example of Finland (I)

3.1.1 Impacts of wind power on bats

Data about fatalities in the Baltic Sea region is mainly coming from two sources: post-construction monitoring reports and scientific studies. The monitoring reports are describing results of carcass searches and bat acoustic activity monitoring in wind farms. In Europe, among other missions, the EUROBATS organisation compiles all the reports available to establish observed and estimated bat fatalities (UNEP/EUROBATS, 2019). Thanks to this, there are records of bat fatalities in Estonia, Finland, Latvia, and Sweden. This means that wind farms in these countries have an impact on bats. The current numbers of collisions cannot, however, be compared to Central Europe because only a limited number of carcass searches have so far been conducted in the Baltic Sea region.

Post-construction monitoring related to bats is not mandatory in Finland and is not often required by the environmental authorities. Nevertheless, some have already been conducted for research purposes or on behalf of the energy companies (Aminoff, 2014; EUROBATS, 2018). This led to the discovery of six *E. nilssonii* in 2012, but since then no additional mortalities have been reported according to EUROBATS (UNEP/EUROBATS, 2019). This most likely reflects the lack of monitoring effort.

In addition to post-construction monitoring studies, only three scientific studies have been conducted on the impacts of wind farms on bats. In addition to finding two dead bats, the main conclusion of the first study was that EUROBATS guidelines could not be used in Finland due to the vastly differing conditions, such as a tall and dense vegetation cover around turbines, and therefore specific guidelines should be developed; however, this has not been the case up until now (Aminoff, 2014). The second study assessed the presence of bats at rotor height in southern Finland, including the migratory species *P. nathusii* and the resident *E. nilssonii* (Blomberg, 2016). The third research focused on migration of *P. nathusii* along the Finnish western coastline, arguing that its aggregating presence during the migration period would clash with future establishment of wind turbines in the region, while sedentary species *E. nilssonii* should be taken into account for inland projects (Ijäs et al., 2017).

The issue of habitat loss has not been studied in Finland so far, and the avoidance effect is the topic of the second chapter of this thesis.

3.1.2 Mitigation use in Finnish wind power projects

There is currently no published study in peer-reviewed journals focusing on mitigation methods used for wind farms in the Baltic Sea region, despite the probable use of several methods. Information from other sources, such as EUROBATS or national wind power associations, is still rather scarce. In Finland, and despite consideration of bats in wind power projects, there is no national guideline on mitigation for bats (EUROBATS, 2018). Use of mitigation techniques, such as blade feathering or increased cut-in speed, has not been reported. In Finland, macro- and micro-siting are common practices, with the avoidance of nature reserves as an example. However, decisions are rarely based only on the presence of bats in the vicinity of the wind farm. In addition, there is no guideline to help developers with siting in the country.

3.1.3 Topics in need of attention

Considering that there is almost no data on the actual impacts of wind power on bats in Finland, the extent of topics in need of attention is quite large. It reflects a lack of interest and incentives on wind power and bats from research, planners and authorities, and consequently a lack of means.

First of all, we are lacking basic knowledge on bats in Finland about their distribution (Kotila et al., 2023; Tidenberg et al., 2019), but also their preferences in terms of roosting (Siivonen & Wermundsen, 2008b), commuting, foraging (Vasko et al., 2020), diet (Vesterinen et al., 2018). Most of all, we do not know much about migratory bats and the flyways that exist in the country. The main migratory species passing by Finland is *P. nathusii*, and there are clues indicating that it uses the coastline for its migration, but more is needed, especially for mitigation purposes (Ijäs et al., 2017; Rydell et al., 2014).

Another subject of interest is the presence of bats in woodlands, an essential topic for Finland as more than 70 % of the country's area is made of forests, and these habitats are also the first choice of wind power developers to build wind turbines. Because of this, and the importance of forests for Finnish bats (Vasko et al., 2020), the impacts of wind turbine presence in forests should be investigated in more detail: collisions, habitat loss, attraction, avoidance, etc. (Rydell et al., 2017b).

Bat surveys in Finland are also to be improved, not being extensive enough during the pre-construction step of wind power projects. They usually lack long term monitoring but also survey at rotor height (Ijäs, personal communication, 2019). This deficiency could be due to the belief that the impacts of wind power on bats are supposedly low in the country, despite the actual impacts not being known.

However, as the quality and utility of pre-construction surveys is challenged worldwide, the question of how to correctly assess impacts in Finland is difficult to answer, mostly because of the important changes that the construction of a wind farm causes on the landscape and the habitats (Rodrigues et al., 2015). These changes are reflected in the presence and activity of bats at the wind farm and around (Kirkpatrick and al., 2017). Therefore, it seems impossible to assess the impacts of a wind farm before its actual construction.

Meanwhile, the utility of post-construction surveys is clearer, and their use in Finland is deeply needed (Aminoff, 2014; Ijäs, personal communication, 2019). Fatality estimation at current wind farms, as well as monitoring of bat activity at rotor height, are the first and most important step to an actual assessment of the impacts of wind power in Finland. They would provide data on which species are killed and how many individuals, at what time of the year and in which part of Finland. However, fatality estimation is costly in terms of money and time, and the recommended protocols are not necessarily adapted for wind farms in forest.

Based on the situation in the rest of Europe, recommendations are to base the impact assessment of wind power projects for bats on both pre- and post-construction surveys (Lintott et al., 2016; Rydell et al., 2017b). Pre-construction investigation could determine the feasibility of a project at the chosen site, to avoid costly post-construction mitigation measures for example. After construction, surveys of fatalities and activity would assess the actual impacts and allow the implementation or adjustment of mitigation if needed (Lintott et al., 2016; Mascarenhas et al., 2018).

Surrounding this research and data needs, there is a need to improve the availability of results to stakeholders (researchers, wind power companies, public authorities) at local, national and European levels. The impact of wind power on bats is an issue without borders: bats of the same species can cross Europe and are prone to mortality anywhere between Finland and Spain due to the same structures. Sharing the knowledge would profit both research and wind power development. But in order to do so, surveying methods must be standardised for Europe, by using the recommendations of EUROBATS for instance (Rodrigues et al., 2015).

Lastly, all these needs in terms of research, data sharing or improvement of surveys must be led by the authorities and the policy makers. Regulations and legislation on the topic must be created or improved in Finland. We cannot count on the sole willingness of wind power companies to do more than required by law in terms of surveys and mitigation, especially when it costs money. The conservation of biodiversity is usually not a good incentive for them.

3.2 The presence of wind turbines repels bats in boreal forests (II)

Using presence/absence data, our results indicated significant differences in species presence at differing distances from wind turbines (fig. 4). For *E. nilssonii*, presence at 600, 800 and 1.000 m was significantly higher than presence at 0 m from wind turbines (fig. 4). Presence of *Myotis spp.* was significantly higher at 800 and 1.000 m from wind turbines (fig. 4).

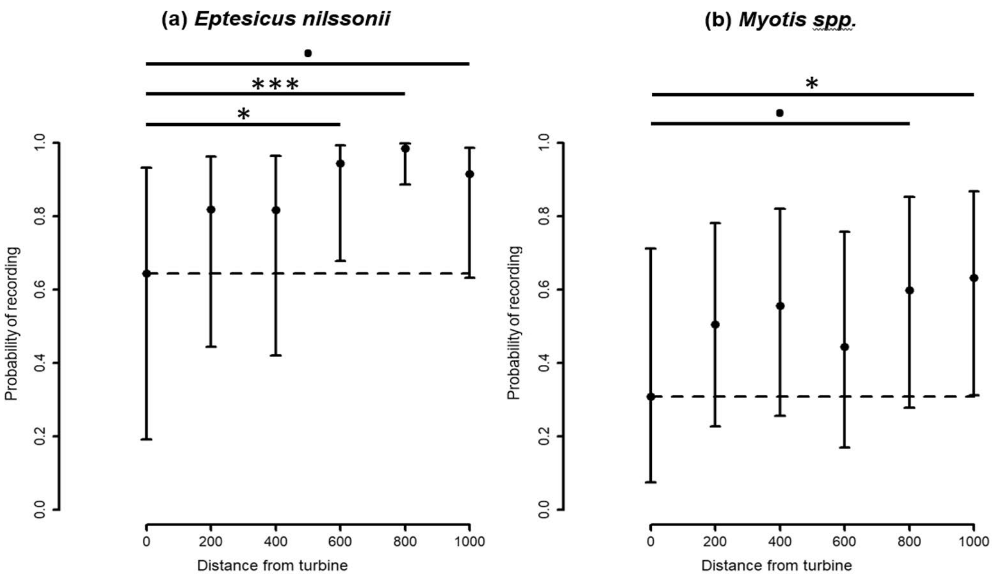

Figure 4. The expected probability to record one or more echolocation pulses per week as a function of the distance from the wind turbine.

Using activity minutes (i.e., the quantitative number of positive minutes), only activity at 800 m was significantly higher than activity at 0 m in *E. nilssonii*. Activity of *Myotis spp.* did not differ from the intercept at any distance from wind turbines.

These results indicate that the presence of wind turbines have a repelling effect on bats within a range of at least several hundred metres around each turbine. This could have ecological consequences for bats, primarily the loss of the habitats located both on their territory and near wind turbines (Rybicki and Hanski, 2013). Narrow- and edge-space foraging species - and even open-space foragers during specific periods of the year (Flaquer et al., 2009) - are strongly dependent on habitats such as forests and wetlands, or wooded linear networks for their commuting and feeding (Davidson-Watts et al., 2006; Entwistle et al., 1996; Rudolph et al., 2009), and can have small home-range, especially at high latitudes. Making these habitats and landscape features unavailable or degraded in quality, would impair the ability of these bats to easily forage in these habitats, or to fly between their roost and feeding territories through these affected areas.

When considering cumulative impacts, regions where the density of wind turbines is high, like the western coast of Finland, will have extensive areas of degraded habitats for bats. The results of our models allowed us to estimate the cumulative area lost due to the presence of wind turbines in Finland, reaching 4,38 % and 6,85 % of the total area of Finland for *E. nilssonii* and *Myotis spp.*, respectively, for all projects publicly ongoing as of June 2022. This estimation of avoided area indicates that a relatively small area of Finland is impacted by wind turbines. We however postulate that the cumulative area is an underestimation and that many more projects are surely planned for the future. Therefore, the proportional area of Finland impacted will greatly increase in the years to come.

Investigation on the causative mechanisms contributing to the avoidance effect is direly needed. Two possible “main” causes are that bats are either avoiding wind turbines themselves, or are avoiding the area surrounding the turbines.

Regarding the former, several hypotheses have been proposed, including the noise and lighting from wind turbines (Barré et al., 2018). However, both have uncertain effects on bats, and the range of their potential disturbance is clearly inferior to the observed range of avoidance in our study or others (Barré et al., 2018; 2021; Guest et al., 2022; Katinas et al., 2016; Zeale et al., 2018).

The second main cause behind this avoidance effect, that bats are avoiding the area surrounding wind turbines, could be explained by the changes in habitats caused by the construction of the wind turbines. It is particularly true in the context of wind farms located in woodlands (like in our study), because the establishment of turbines in this habitat entails cutting large portions of forests for turbine pads, or the roads connecting them. This has consequences for the multiplication of open areas in a landscape usually more closed, an opening that is unfavourable to certain species like *Myotis spp.* and would explain why they are avoiding the area around wind turbines (Vasko et al., 2020).

We also suggest that these changes in habitat created by the construction of wind turbines in forests could also deter insects in the area, therefore indicating that turbines can either attract (Jansson et al., 2020; Rydell et al., 2010b; Voigt, 2021) or repel insects, depending on the scale, habitat and species, similarly to what Leroux et al. (2022) observed with bats.

Besides ecological consequences for bats in the long-term, our results add proof towards the necessary improvement in consideration and protection of bats in the context of wind power development not only in boreal Europe, but also across the whole continent, starting with wind power planning (Barré et al., 2018). However, wind farm siting in Finland is complex, because of the land cover (mostly woodlands and wetlands), and the concentration of populated areas in open lands (Corine Land Cover data). Therefore, the current preferred implementation of wind farms is in woodlands (Asko Ijäs, personal communication, March 30, 2022), despite guidelines not recommending this (Rodrigues et al., 2015).

This placement of wind turbines at a landscape-scale is also an argument in favour of improving the quality of impact assessment for bats in wind power projects in Finland. If wind turbines are to be built in woodlands, it must, at a bare minimum, be confirmed the site is not an important area for bats, through thorough site-specific surveys for bat activity and roosting.

Above all, implementing wind turbines outside woodlands should always be preferred when possible and considered synonymous with lower impacts on bats. If not, other mitigation solutions can be used. Depending on the actual cause of avoidance of wind farms, either curtailment or compensation should be used. Shutting down turbines when bat activity is high would also decrease collision risks (Behr et al., 2017; Gartman et al., 2016b; Ijäs et al., 2017), whereas compensation would increase the quality of habitats away from wind farms. However, compensation is hard to implement and its efficiency questionable, while not preventing the original impacts. Therefore, I recommend careful planning and siting of wind farms as the best way to mitigate its impacts on bats.

3.3 Species-specific response of bats to artificial lighting in boreal forests (III)

E. nilssonii was the most recorded species at our sites, with 1,202 minutes of activity (2,0 % of total recording time), with most activity at control sites (878 minutes, 73 % of the species' activity). *Myotis spp.* were recorded during 872 minutes (1.5 % of total recording time), with 679 minutes at our control sites (77.9 % of the species' activity). These results are not surprising as in the country, the *Myotis* genus comprises five species strongly associated with forest habitats, at least partially in the case of *Myotis daubentonii* (Tidenberg, 2019; Vasko et al., 2020). For *E. nilssonii*, the permanent twilight around midsummer drives the species to switch to forests, although it can be seen in more open habitats during the rest of its active period (Rydell, 1991).

At our control sites, activity of *E. nilssonii* peaked around mid-July to continuously decrease afterwards, a pattern slightly different than what has been observed previously, where the species' activity in forests peaked one month earlier, around midsummer (Rydell et al., 1991; Vasko et al., 2020).

When looking at the presence of our species at the sites, we can see that they are more present at the control than at the experimental sites (fig. 5), although without seeing any significant difference in our models (Table 1).

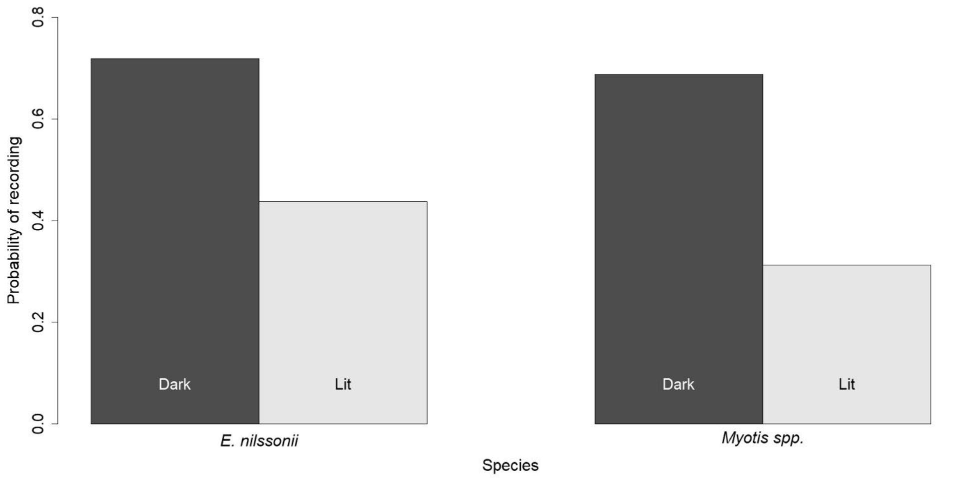

Figure 5. Probability per week of recording *E. nilssonii* and *Myotis spp*. at control (Dark) and experimental (Lit) sites.

Table 1. Results of a mixed model with binomial errors on the presence (one or more calls) or absence (no call) per week of *E. nilssonii* and *Myotis spp*. Intercept represents the presence of *Myotis spp*. at the control sites. A "***" symbol means a p value between 0 and 0.001, "**" for a value between 0.001 and 0.01, "*" for a value between 0.01 and 0.05, "." for a value between 0.05 and 0.1, " " for a value between 0.1 and 1.

Variable	Estimate	S.E.	Z	P	
(Intercept)	2.586	1.144	2.260	0.024	*
Treatment: lit	-2.882	1.511	-1.907	0.05657	.
Species: *E. nilssonii*	-0.270	0.737	-0.367	0.714	
Treatment: lit x Species: *E. nilssonii*	-0.562	0.986	-0.570	0.56882	
Week	-0.145-	0.071	-2.049	0.040	*
Treatment: lit x Week	0.134	0.088	1.524	0.127	
Total recorded time	0.001	0.000	1.949	0.051	.

Our results show that *Myotis spp.* presence at our lit sites is significantly lower than at our control sites (table 1), a result supported by the literature on the topic: most *Myotis* are slow-flying aerial hawkers that avoid illuminated areas for the most part, probably because of a higher risk of predation there (Rydell, 1992a; 1992b; Stone et al., 2009; 2015). Only red light has shown minimal impact on *Myotis spp.* activity, but it is rarely used for outdoor lighting (Spoelstra et al., 2017).

The presence of *E. nilssonii* also appears to be lower at our lit sites (fig. 5), but without any significant difference in our model (table 1). This indicates that the species does not seem to be drawn in by our lights, probably because of their incapability to attract insects. In situations where UV is emitted by lights, *E. nilssonii* seems more active at these lights than in dark areas, even during the summer (Valanne, 2022). Therefore, the response of this species to ALAN in boreal woodlands seems to be more dependent on the type of light (and the quantity of insect attracted) and less on the season. Our results, as well as those of Valanne (2022), confirm Rydell's hypothesis (1991) that *E. nilssonii* does not forage around street lights in open areas during the summer because they do not attract enough insects during the time of the shortest nights. However, the species keeps foraging around UV-emitting lights when they are located in woodlands, most likely because a bright light in a dark area is more attractive to insects (Valanne, 2022).

Based on the literature and our results, we recommend reevaluating the need for ALAN in woodlands, in urban and non-urban areas of Finland. Light pollution is to be considered in the same way as roads (Claireau et al., 2019), power lines (Froidevaux et al., 2023) or wind turbines (Leroux et al., 2022) in its capacity to disrupt bat commuting or foraging, either by repelling or attracting them. Impacts on bats differ but are negative in both cases: attraction can cause fatalities, while avoidance can lead to habitat loss (Azam et al., 2018; Barré et al., 2018; Leroux et al., 2022). As a priority, the use of ALAN should be avoided to a great extent, and at least reduced and controlled when its presence has to be maintained, in order to provide as many dark areas for bats across the landscape and through the night as possible.

The lucifugous *Myotis spp.* would be the first species to benefit from a decrease in the use of ALAN in woodland habitats, in both urban and non-urban areas, and this during their whole activity period (from April to October approximately) in Finland. Most of them are woodland specialists that spend most of their time in this type of habitats, but *M. daubentonii* also switches to forests and more wooded wetlands around midsummer, so an absence of ALAN there would also profit this species (Vasko et al., 2020). Decreasing the presence of ALAN would facilitate the commuting of *Myotis spp.* in the landscape, guaranteeing them dark corridors to fly and reach foraging grounds. Decreasing ALAN would also ameliorate the foraging of *Myotis* by increasing the quantity and quality of foraging areas, but also by decreasing the vacuum cleaner effect, i.e., the attraction of *Myotis* prey to illuminated areas and their depletion in dark areas (Eisenbeis, 2006).

It is currently uncertain whether *E. nilssonii* would benefit from a decrease in ALAN. Certainly, less blue- or UV-emitting lights would diminish the accumulation of insects there, and consequently could decrease the foraging success of *E. nilssonii* individuals who could not take advantage of this profitable and predictable source of prey anymore (Lewanzik & Voigt, 2017; Rydell et al., 2020). Previous study showed this happening to *P. pipistrellus* when LEDs replaced high-pressure mercury vapour in street lights (Lewanzik & Voigt, 2017). If not able to adapt quickly to this change, populations of street-lighting foragers could suffer from it (Lewanzik & Voigt, 2017; Rydell et al., 2020). But in the long term, they could profit from the resurgence of insect populations provoked by disappearance of attractive lights (Lewanzik & Voigt, 2017).

When ALAN is required, multiple solutions exist to limit its impacts on biodiversity, such as adjusting the beam to reduce light trespass, or using motion sensors and timers to decrease the time where light is uselessly on (Voigt et al., 2018). As evoked above, another possibility is to change the type of light to ones that do not emit UV or blue light, to limit the attraction of insects, and therefore bats, but also the impacts on humans (Cupertino et al., 2022; Donners et al., 2018; Stone et al., 2015; Voigt et al., 2018).

We believe that the absence of significant response of *E. nilssonii* to ALAN during our experiment could be attributed to our limited dataset, and not necessarily reflects the actual response. This limitation also prevented us from analysing the effect of ALAN on bat activity levels. Our confined dataset is the result of technical problems with our AudioMoth recorders, most notably dying batteries and issues with the protective cases, but also bad choices regarding our sampling sites. Presence of bats beforehand was confirmed only at a few of these sites (in Aura notably), while presence in others was only "expected" because of the general area being favourable to bats (Ruissalo sites). There is incertitude about the response of *E. nilssonii* to lights without UV, as there is nothing in the literature about it. Rydell et al. (2020) show a decline in *E. nilssonii* activity around street lights after the lights become less attractive to insects, but they do not say whether activity of *E. nilssonii* at these lights is more or less than in dark areas at the same time. Fully understanding the response of the species to ALAN in Finland would require the monitoring of activity at both dark and illuminated areas in different landscapes, with different types of lights and during its full activity period.

We did not record other species during our experiment, but data on their responses to ALAN exist in the literature (Barré et al., 2021; 2022; Spoelstra et al., 2017; Stone et al., 2015). For example, *Plecotus auritus* is a common species in Finland and like *Myotis*, is intolerant to ALAN (Spoelstra et al., 2017; Barré et al., 2021; 2022). However, because the species has low-amplitude echolocation calls, it is very much underrepresented in acoustic data and cannot be assessed for the question in hand (Barataud, 2015). Nevertheless, it is another species that should be taken into account in the same way when assessing ALAN.

4 Conclusions

4.1 Key findings

Wind power has become central in many countries' plans for energetic transition and reduction of carbon emission. However, it also has negative impacts on the environment and biodiversity, such as bats.

In the European boreal biogeographic region, Finland included, the number of wind power projects has been increasing significantly these recent years, mostly in forests. At the same time, impacts on bats and appropriate mitigation solutions have been overlooked in the region, and more particularly in Finland where no data on the actual impacts of wind power on bats exist, no mitigation is used, and no effort to fix these two issues, despite having the tools to do so.

For instance, the avoidance effect that wind turbines can have on bats is a topic we barely have a grasp on in Europe, but a topic that has not been studied at all in the boreal region. Through the monitoring of bat acoustic activity at wind farms located in forests, I studied how bats responded to the presence of wind turbines through most of their active season. Both target species, the northern bat *E. nilssonii*, and the *Myotis* group of species, showed higher presence starting 600 m and 800 m from wind turbines, respectively.

The reasons behind this avoidance could be the openings in habitats caused by the construction of wind turbines (roads, pads), but also the impacts on abundance and local distribution of bat prey of these openings. Other possible sources are the light and noise emitted by turbines, and the turbulence and wake surrounding them.

Another source of disturbance and habitat loss for bats is light pollution. Response of bats to artificial lighting at light is species-specific, with some being lucifugous (*Myotis spp.*) and other exploiting insect-attractive lighting for easy foraging (*E. nilssonii*). In Finland where the length and darkness of night vary a lot through the year, bats have been adapting their habitat selection accordingly.

Therefore, I studied how bats would respond to the presence of artificial lighting during the summer and in a secluded habitat (forest). *Myotis spp.* avoided lit sites as expected while northern bats also showed a non-significant preference for unlit sites that could be attributed to the lights not being attractive for insects.

The results of both studies indicate similar consequences for bats: they lose commuting and foraging habitats due to wind turbines or ALAN. When adding together all wind turbines built or planned for the future in Finland, the percentage of Finland's total area being impacted and potentially avoided by bats reaches several percent. The habitat loss due to light pollution, but also roads, power lines, open fields, forest clearcuttings, etc., should be added to this estimate.

Based on these results, I recommend improving the consideration of bats – and biodiversity – in wind power projects and the use of ALAN, but also in any kind of habitat-altering projects. Bats are an essential part of the ecosystem, playing a role in reducing the abundance of silvicultural pests, for instance. Reducing our use of ALAN is easy and not only benefits bats, but also humans, directly and indirectly. Regarding wind power projects, more efforts should be granted to pre-construction surveys to avoid any area of importance for bats.

4.2 Recommendations

4.2.1 Wind power

These recommendations are based on the results of this thesis and literature are just the first steps for a good comprehension of the topic in Finland. First thing to do is to obtain fatality estimation and patterns for Finland. This data would help get a good overview of the situation in the country, and from that, further research and work on regulation could be steered in the right direction.

1. **Fatality estimation** of current wind farms in Finland. Using trained dogs as a priority, carcass searches should be done in a sample of wind farms through Finland, in different habitats and locations. Search efficiency and scavenger removal rates must be measured too.
2. Bat **monitoring at wind farms**, at ground and rotor height.
3. **Increase the length and frequency of bat surveys** during pre-construction impact assessment. It should include (rotor) height monitoring and long-term surveys (several weeks/months).
4. Identification of the **migration period and flyways** in Finland to identify the riskiest locations.

4.2.2 Artificial lighting at night

These recommendations are mostly based on literature, and can be applied to Finland as bats' responses to ALAN there are overall similar to the rest of Europe.

Recommendations basically stand in assessing the actual need of each existing light, asking why, when, where and how:

1. **Why**: Is this light actually required? Can you turn it down? Lit roads aren't safer than dark roads. Lit areas in town give a false sense of security.
2. **When**: does this light need to be turned on all the time? Can you use a motion sensor and timer to reduce the actual use of the light without reducing its efficiency for people?
3. **Where**: does this light need to illuminate all this area? Can you use shielding or reduce the light height to avoid spilling and only illuminate the needed area (a path or road for example)?
4. **How**: does this light need to be that bright and use that colour? Can you turn down the intensity or use less intense light, and can you switch to lights that don't emit UV or blue light (harmful for both humans and biodiversity)?

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