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Review of Bat Fatality Mitigation Studies and Recommendations for Canada

Canada

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1. Introduction

As nations set their goals towards achieving net-zero in the next few decades, renewable energy production will need to substantially increase. In fact, wind energy capacity is expected to increase by 170-225 GW globally from 2023 to 2028 [1]. With wind being a major component of renewable growth, efforts are required to ensure any negative environmental or ecological impacts of wind turbine expansion is mitigated. One of onshore wind's largest negative impacts is bird and bat fatalities [2]. Bats are significantly more vulnerable to the risks posed by wind turbines than birds. The large and fast moving turbine blades are hard to avoid with a bat's limited eyesight and use of echolocation, compounded with their rapidly dropping population from white-nose syndrome [3]. Multiple strategies exist to reduce these fatalities, with the main options currently available being curtailment, deterrent, and detection.

Over the past years, field studies testing these methods have become more prevalent in an attempt to quantify fatality reduction. Some methods have only been tested a small number of times and require significantly more testing to be considered a valid mitigation option. Past field studies do not adhere to any set standard of quality and it has been observed that there are notable differences between how these studies are set-up, methods are tested, data is collected, and reports are written. Lack of standardization has led to inconsistencies, exclusion of data, and vague reporting. As a means of supporting Canada's responsible deployment of wind energy CanmetENERGY-Ottawa is seeking to investigate the environmental impact of wind turbines on bat populations, the potential mitigation options therein, to develop a higher standard of reporting, and to partake in a field trial to test mitigation strategies. This report contains four sections. Section 2 contains a background review on declining bat populations and correlation to wind turbines, bat behaviours, curtailment strategies, and other mitigation methods such as deterrents and detection. Section 3 summarizes a large set of field studies, discusses trends, and merges results. Section 4 lays out suggestions and guidelines for high-quality field study experiments and reports. Section 5 lists the limitations relating to this study. Section 6 contains concluding remarks as well as potential areas for future work.

2. Background

2.1 Rapidly Declining Bat Populations – White-nose Syndrome and Wind Turbines

White-nose syndrome is a fungal disease that is exotic to North America and since its first observance in 2006, has been estimated to have killed 5.7 million North American bats [3]. Some non-migratory species like the Little brown myotis, northern myotis, and tri-colored have faced population declines of greater than 90% [4]. These species have been listed as "Endangered Species" under Canada's Species at Risk Act since 2014 and are expected to be joined by three of their migratory cousins: the hoary bat, eastern red bat, and silver-haired bat [3, 5].

The exact number of bat fatalities from wind turbines within Canada is extremely hard to estimate, let alone quantify exactly. Very little research has been done on the matter. In 2016, it was estimated that on average, 15.5 bats were being killed per turbine on an annual basis accounting for a total of 47,000 bats per year (using the number of installed turbines in 2013) [6]. Today, with over 7,000 turbines operating in Canada, that fatality estimate would increase to over 110,000 bats a year assuming consistent fatality rates [7]. However, rotor diameters of wind turbines have also increased in size over

the years which could result in even higher numbers than that estimate of 15.5 fatalities per turbine per year [8].

Ontario was, and remains, the leading producer of wind energy within Canada. This means it is the province with the most bat fatalities, accounting for 87% of fatalities due to interactions with wind turbines in 2016 [6]. The exact cause of why bats experience significantly higher fatalities than birds from wind turbines has been hypothesized in many ways some of which blame the attraction to the wind turbine sounds or even the attraction to insects that are themselves attracted to the turbines [9].

Due to the high percentage of fatalities, Ontario has one of the stricter provincial bat fatality policies. The policy states:

> "Where a post-construction monitoring annual report indicates the annual bat mortality threshold of 10 bats/turbine/year has been exceeded, operational monitoring will be implemented across the wind power project (i.e. at all turbines) from sunset to sunrise, from July 15 to September 30. This mitigation will continue for the duration of the project." [10]

This government enforcement should only exist as a last resort as wind farms should be implementing mitigation efforts before this limit is reached assuming bats are known to be within the area. The careful consideration of new site planning and implementation of various mitigation efforts such as curtailment, deterrents, and/or detection for wind farms are crucial to reducing these fatalities and keeping these bats from going extinct.

2.2. Bat Behaviours and Flight Paths

There are two main categories of bats affected by wind turbines: migratory bats and cave bats. Migratory bats (like hoary bats, silver-haired bats, and eastern red bats) are most impacted by wind turbines in North America as they travel to and from their sub-tropic and tropical winter roosts. Many of these bat species fly at altitudes of 120 m which is within the rotor swept area of numerous wind farms [6, 11]. Cave bats (such as little-brown myotis, northern myotis, and tricolored bats), on the other hand, are local and tend to be more active around the summer months. These bats may even travel significant distances to transfer from their summer roosts to winter hibernation sites [6].

Very little is known about the exact flight paths of these migratory species. They may even change on a yearly basis, so it can be difficult to site wind turbines to entirely avoid bat flight paths. However, knowledge of the locations of cave bats and typical roosting spots of migratory bats may be helpful in determining locations for new wind farm development. Some bat behaviours are well known and could be tracked or strategically monitored within a smart curtailment system, which is described in Section 2.3.4. Bats tend to be more active at night between sunset and sunrise, when temperatures are above 5°C, wind speeds are less than 6 m/s, and when there is no precipitation [12]. Bats have also been recorded during temperatures as low as -4°C [13].

2.3. Curtailment Methods

Curtailment, in this context, refers to manually limiting the wind turbine generation, with the intent to lessen the negative impact on bats within the area. There are various curtailment options available, each with varying trade-offs, costs, and complexities. The main disadvantage with curtailment is that it, by its very definition, reduces the amount of electricity generated. These curtailment options are typically only

implemented during known times of high bat activity (sunset to sunrise of certain months). Curtailment options currently available are outlined in Sections 2.3.1 to 2.3.4 below.

2.3.1. Feathering Turbine Blades

Most modern turbines include a pitch control system, which allows the blades to pitch, or rotate, to achieve maximum torque relative to the wind speed and can be seen below in Figure 1. This helps turbines optimize their outputs regardless of the wind speed and smooths power production [14]. When minimal blade rotation is desired, this same system is used to "feather" the turbine blades. By pitching the blades 90° or parallel to the wind, torque is minimized. Blades are still free to rotate, but typically only up to 2 RPMs [11]. Since the likelihood of bats are higher in lower wind speeds [12, 13], turbine blades should be feathered when wind speeds are lower than the cut-in speed, which is the minimum wind speed required for a turbine to produce power. This is a very easy mitigation solution to implement as it is already a feature of most modern turbines and requires no additional installation or maintenance of other systems.
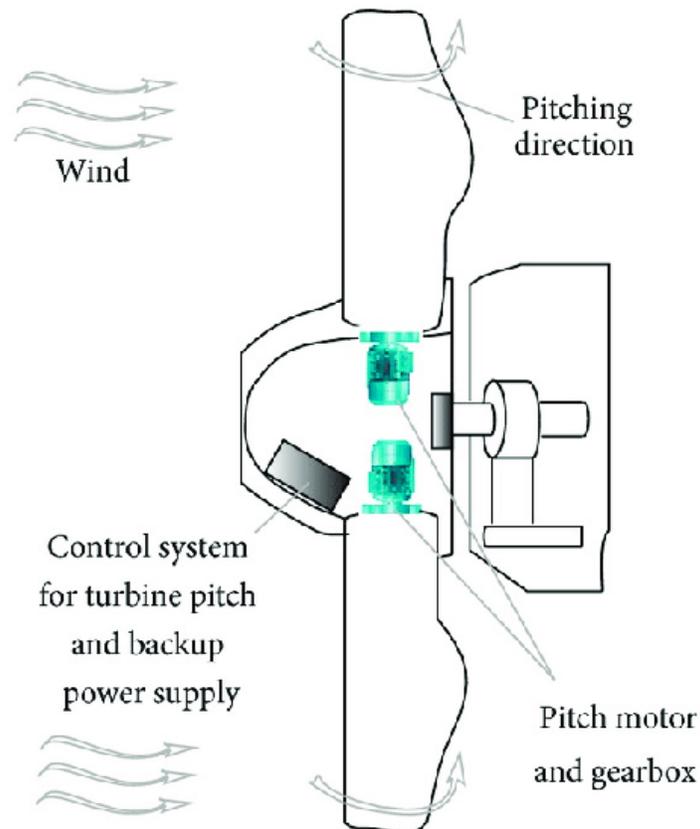
Figure 1 - Wind turbine pitch control system [13].

2.3.2. Raising Cut-in Speeds

Another easy to implement option is to raise the cut-in speed of the turbines. The cut-in speed is the wind speed that is necessary for wind turbines to begin generating electricity. While manufacturer rated cut-in speeds are designed into each turbine, control systems allow these values to be raised to meet the

wind farm's operational needs. In conjunction with the pitch control system, the blades can and should remain feathered up until the desired cut-in speed. This further reduces blade rotation in wind speeds where bats typically fly [12, 13]. It has been estimated that for every 1.0 m/s increase in cut-in speed, there is a 33% fatality reduction [15].

2.3.3. Blanket curtailment
Blanket curtailment raises the cut-in speed to inhibit generation for a defined period of time [16]. This period is typically when bats tend to be more active and the risk of interaction with turbines is higher [12, 13]. In Ontario, this begins on July 15th and continues until September 30th [10], but other regions may experience different active bat months.

2.3.4. Smart curtailment
Smart curtailment refers to any method of curtailment that uses additional information and a decision-making process to determine when to curtail the wind turbines. The advantage of smart curtailment is the ability to both optimize renewable power generation and mitigation of bat fatalities. Smart curtailment can be grouped into two main categories: predictive, where a model that predicts active bat times has been constructed beforehand for the system to follow, or reactive, where the system is actively reacting to oncoming bats in real-time.

Predictive smart curtailment involves creating a model from data gathered from bat activity analyses on a wind farm site. The model will identify times where bats are more active and predict when there is a higher likelihood of bat activity so that curtailment can be implemented accordingly [17]. This type of model may also need to be re-evaluated repeatedly as bat activity changes over the years.

Reactive-based smart curtailment involves the use of live data from detection and monitoring equipment, which are explained in more detail in section 2.5, to make decisions "on the fly". While this optimizes power generation and reduces bat fatalities, the intermittency of when bats are detected and the turbines are curtailed may cause complications in grid management [17].

Costs of smart curtailment are unknown and likely will vary dependent upon how sophisticated the model or monitoring system is. The predictive system does not require advanced monitoring and system integration like the active-based system but may require an extensive bat activity analysis depending on how advanced a predictive model is required [18]. Pairing both types may be favourable for grid management but would likely be much more cost intensive.

2.4. Deterrent Methods
Deterrents for bats exist in many different forms: acoustic, surface coatings, lighting, and even electromagnetic radiation [11]. In general, these technologies are still in their early stages as only a handful of field study reports have been published. Regardless, as bat mitigation regulations have gotten stricter, the adoption of these technologies has increased in recent years as indicated by the increased number of field studies testing these technologies.

2.4.1. Acoustic deterrents
Acoustic deterrents are designed to protect bats from wind turbines by emitting high-frequency sounds (typically ranging from 12.5 – 112.5 kHz), that impede prey detection and flight orientation [19]. One

advantage of this method is its compatibility with other deterrent techniques to further reduce bat fatalities. However, there are disadvantages, such as the limited data on its long-term effectiveness and the potential need for continuous operation, which can result in increased energy consumption. The effectiveness varies depending on the device, bat species, and environmental conditions. The exact effective range of these devices are hard to estimate since different species of bats react to different frequencies in different ways and since lower frequencies travel farther than higher frequencies. For example, 20 kHz may travel as far as 80m, but a 50 kHz may only travel 25m and much less for even higher frequencies [20]. This leads to concerns regarding the ever-expanding size of turbine blades and will require innovation on the technology and its placement to remain effective. Success in reducing bat fatalities using acoustic deterrents has been mixed, and testing their effectiveness involves field studies, controlled experiments, and acoustic monitoring. One of the most concerning observations of these deterrents are the increased number of fatalities observed in Eastern Red Bats found in two studies [21].

2.4.2. Surface coatings

Surface coatings, like paint or texture changes on turbine blades, aim to make the blades less appealing to bats or disrupt the airflow that attracts them. Bats are thought to interpret the smooth texture of wind turbines as potential locations for bugs, similar to the appearance of still water. Adding textured surfaces may shift this interpretation, but risk being interpreted as a potential tree roost like the bark of a tree if the texture is too similar [11]. There is limited data on long-term effectiveness and varying efficacy across different bat species and costs will likely vary on the type and amount of coating used. There are also studies that look at how colours attract insects which may lead to attracting bats [22]. Transport Canada currently has regulations that restrict the colours and reflectivity values of surface coatings which may make these options difficult [23]. Other governments have similar regulations within their countries.

2.4.3. Lighting systems

Lighting systems, such as ultraviolet (UV) or visible light deterrents, serve as a visual barrier around turbines to discourage bats. While bats can still see in very dim light, their ability to differentiate a tree and a wind turbine tower is limited. Adding lights to turbines may help bats make this differentiation and avoid them. Using UV lights will avoid lighting up turbines for humans, but allow for bats to see since they can detect the ultraviolet spectrum [24]. These can be integrated into existing turbines with relatively low costs. One study noted about 40% reduced bat activity around 40 m tall windbreakers when UV lighting was used [25]. Transport Canada also has regulations regarding lighting on wind turbines, but UV lights may still help in bat fatality mitigation [23].

2.4.4. Electromagnetic radiation

Electromagnetic radiation, like radio waves or microwave signals, may be able to deter bats by creating an electromagnetic barrier with emitted pulses of around 0.3 µs at strengths greater than 2 V/m [11]. There is limited data on its effectiveness as well as technical and regulatory hurdles but it has been shown to reduce the activity of bats in an area by almost 40% with small and affordable systems [26]. More research also needs to be done in terms of how ethical this mitigation method may be as it may cause increased stress to the bats if exposed for longer periods [11].

2.5. Detection and Monitoring

While detection and monitoring do not dissuade bats from approaching wind turbines like deterrents do, they are still crucial components within the bat mitigation space. These technologies are used to support bat analysis studies and reactive smart curtailment systems. Real-time data is fed into the smart curtailment system, which can make the decision to trigger a curtailment event, thus slowing down the wind turbine blades. This allows bat fatalities to decrease with minimal impact to renewable power going into the grid.

2.5.1. Acoustic Monitoring

Acoustic monitoring, which is typically used when performing pre-construction analysis, uses specialized microphones to detect and records bats' echolocation calls near wind farm sites [11]. This offers non-invasive, real-time insights into species, flight patterns, and collision risks, but has limitations such as the ability to capture calls from all species, filtering out ambient noise, requiring expert interpretation for accurate species identification, and the physics of sound waves interacting with the atmosphere. Bats may also modulate their echolocation calls making it more difficult for these systems to identify exact species or filter out ambient noise [27].

2.5.2. Infrared Cameras

Infrared or thermal imaging cameras work by detecting the electromagnetic waves (infrared radiation or IR) that objects emit. This allows them to capture footage of bats in the night due to the IR they emit [28]. However, this technology falls short in species identification (especially between distinguishing between bats and birds) as well as reduced effectiveness in conditions such as high humidity, rain, clouds, and fog. Recent advancements in the technology like classifying characteristics (size, speed, heat, and flight pattern) and integrating machine learning has been shown to identify bats with a 90% accuracy [11].

2.5.3. Collision Detection Systems

Collision detection systems employ sensors like radar, lidar, video cameras, and accelerometers to detect impacts at wind turbines. These can be utilized in a reactive smart curtailment system to feather blades and increase cut-in speeds if impacts are detected, but these can yield false positives if not correctly tuned [11]. Accelerometer-only systems are unable to track what objects impacted the blades, which is important when attempting to identify bat impacts by species [29]. Very little research regarding systems like this has been reported [11].

2.5.4. Marine Radar

Marine radar systems, traditionally used for tracking ships and vessels, are also capable of detecting bat movements near wind turbines. Their advantage lies in covering extensive areas, thus offering significant data on bat activity patterns. Like other technologies, marine radar falls short in its ability to identify bat species, necessitating supplementary methods for accurate species determination. Marine radar is also often more expensive to operate and process data compared to acoustic or IR monitoring systems [11, 30].

3. Field Study Summary

3.1. Field Tested Mitigation Methods

A total of 51 bat fatality studies consisting of 20 unique wind farms were analyzed to compare experimental designs, procedures, and results. The studies took place in North America between 2006 and 2023. Of the 51 studies, 43 included mitigation efforts while the remaining eight were post-construction monitoring reports with no recorded mitigation. The treatment options observed consisted of deterrents, raising cut-in speed, blade feathering, detection, or some combination thereof. The distribution of the 43 mitigation studies can be seen below in Figure 2.
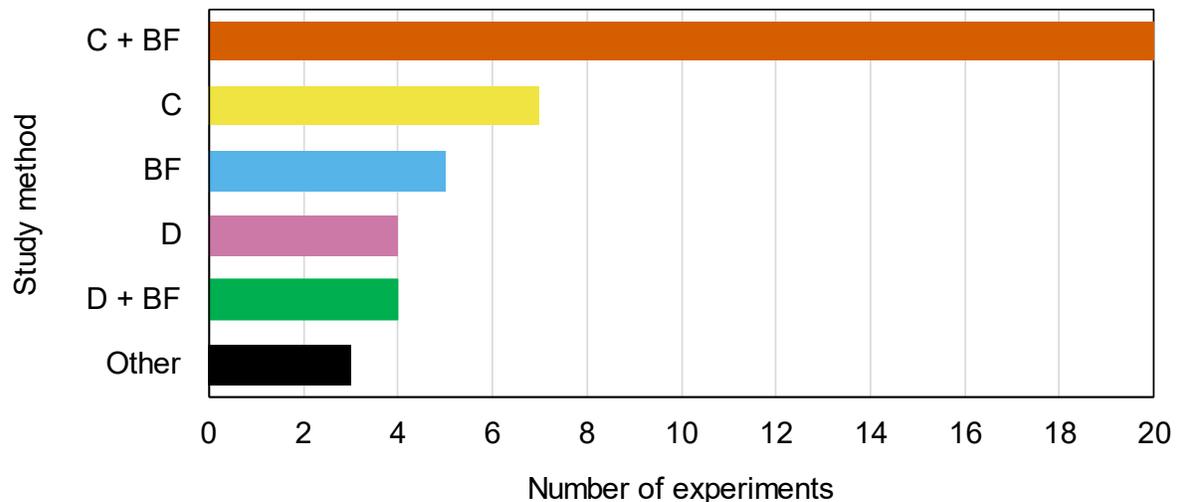
Key:
C = Raising cut-in speed   D = Deterrent   BF = Blade feathering
Other = Other combinations of treatments

Figure 2 – Distribution of the 43 mitigation studies analyzed. The five main study methods include: Rasing cut-in speed plus blade feathering, raising cut-in speed, blade feathering, deterrents, and deterrents plus blade feathering. The "other" category contains the following study methods: detection plus raising cut-in speed and blade feathering, deterrent plus raising cut-in speed, and deterrent plus raising cut-in speed and blade feathering.

Most of these studies used a combination of raising cut-in speed and blade feathering strategies to reduce bat fatalities while deterrent, blade feathering, and raising cut-in speed, on their own, make up the next largest distributions. The "Other" category includes a single detection study paired with both raising cut-in speed and blade feathering as well as three deterrent studies each paired with blade feathering, raising cut-in speed, and both, respectively.

3.2. Field Test Experimental Setups

The above 43 field experiments were analyzed, and their setups and methodologies were compared. Table A.1 in the Appendix lays out the ranges of each of the 43 experimental setups within each treatment category. About 25% of these experiments did not include a control group against which to compare the treatments and 6% made no mention of a control group at all. Some compared against control groups from previous years experiments or monitoring reports, but this is not as accurate as using a control group in the same experiment as bat migratory paths or migration numbers may significantly change from year to year.

Another key proponent of these experimental setups are how the turbines are selected, grouped, or assigned treatments. Most studies used some sort of statistical blocking design. Blocking is a statistical method which utilizes smaller groups (blocks) out of the larger sample to perform experiments with reduced variability [31]. Some studies randomly assigned turbines to treatment or control groups (each turbine is in its own block) while others grouped turbines into blocks and rotated the assignment of the blocks between treatment and control throughout the experiment. A few studies used a more systematic approach and carefully grouped turbines so that each grouping would be equal and representative of the entire wind farm. Others were not specific on how turbines were either grouped or assigned treatments.

3.3. Field Test Results

Results from the 43 mitigation experiments were indicated in various ways. Some listed fatality values as actual counted carcasses, others as estimated results, or just percentages of improvement. Not all experiments had control groups so there was nothing to compare treatment results against in these cases. Of the five main treatment types, a total of 19 experiments provided fatality results of counted carcasses for both control and treatment groups, while five experiments only provided these fatality results as a percentage of the pre-treatment fatality numbers. Figure 3 shows the ranges in percent fatality reduction for each of these five treatment options.
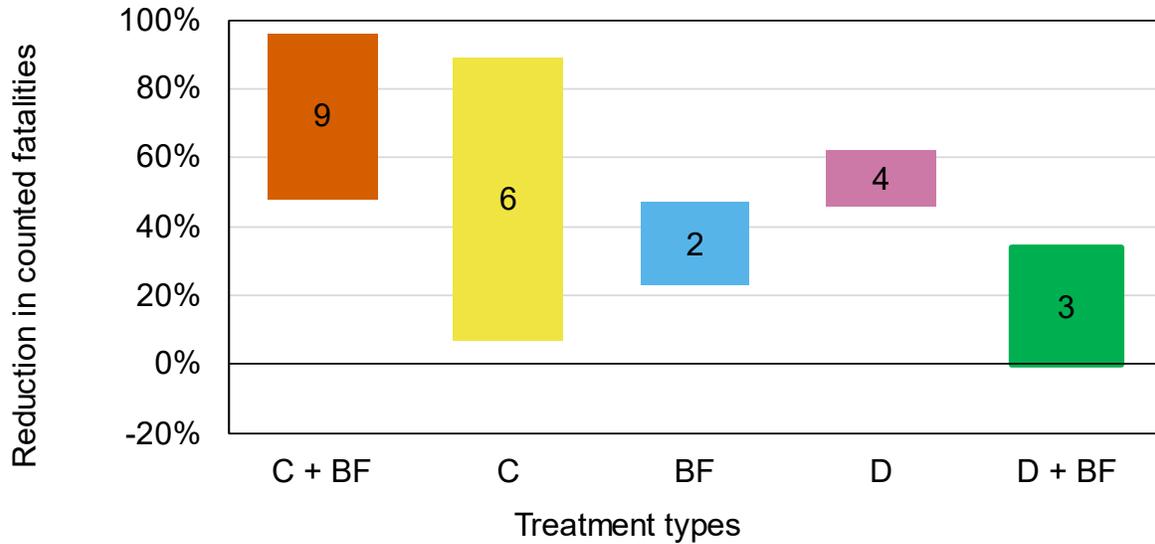
Figure 3 – Percent reduction in counted fatalities from the five main treatment types: Raising cut-in speed plus blade feathering, raising cut-in speed, blade feathering, deterrents, and deterrents plus blade feathering. Numbers indicated within the ranges denote number of experiments the range includes.

The experimental results indicate that raising cut-in speed can be one of the most effective ways of reducing bat fatalities, with this method demonstrating reductions of 7-89% [32, 33, 34, 35]. When blade feathering is also applied, reductions of 48-96% were documented [11, 36, 37]. Blade feathering on its own has shown an effectiveness of reduction from 23-47% [38] while ultrasonic deterrents on their own have shown a reduction range of 46-62% [20, 39]. The combination of compressed air deterrents and blade feathering show reductions of 33%, but may also increase them by 1% [40]. A fourth study with ultrasonic deterrents estimated a range with an increase in fatalities by 36% to a 45% decrease in fatalities [21]. The large variabilities in these values may be attributed to various factors such as specific site location, specific turbine location, change in bat populations or migration patterns, among other reasons. For example, just because deterrents with blade feathering looks worse than using only deterrents, doesn't mean that is true for all locations. Many other variables exist between these experiments such as location, species specific bat activity in the area, geographical features, and more. The three experiments included in the "other" category from Figure 2 were omitted from this graph since their results were only estimates. One, which used deterrents and blade feathering estimated the range of increased fatalities from 0% to 420% (for Eastern Red Bats) [21]. Another experiment which used deterrents and raising cut-in speed resulted in an 69% reduction of bat fatalities [41]. The third study, which was the only study to test detection, reported a reduction of 84% when combined with raising cut-in speed and blade feathering [34].

4. Guidelines and Suggestions for Experimental Designs

While there are many different options for each design aspect within these experiments, there are some that stand out as being designed and executed with greater levels of rigour and scientific integrity compared to others. These principles are highlighted and discussed with the goal of designing future experiments to be more accurate, less biased, and more transparent. The categories discussed include experimental design, testing period, field searches, and reporting habits.

4.1. Experimental Setup

Turbines included in any bat fatality mitigation experiment must be split into a control and treatment group to allow for a more accurate comparison between the chosen treatment(s). Depending on the number of turbines, groups should be kept large enough for an "adequate" sample size. While an exact "adequate" sample size is difficult to quantify, analyzing the mitigation experiments can provide some insight. Out of 43 studies reviewed, only 26 provided the number of turbines used in both control and treatment groups. Sizes of control and treatment groups were not always the same and some experiments neglected to include a control group altogether. Analyzing all groups, a total of 64 control and treatment groups, more than 70% range from 4 to 14 turbines with a median of 8. This is an ideal target group size to start with, but the more turbines included, the more significant the results will be.

Many uncontrollable factors can also affect group sizing such as the wind farm size, number of turbines able to take part in a study (*e.g.* turbines that are functioning and not down for maintenance), cost constraints, *etc.* Both the control and treatment groups should also be equally representative of the wind farm's geography to avoid any turbine biases (*e.g.*, there should be an equal number of turbines in each grouping that is coastal, by hills, by forests, *etc.*). Another way to achieve this is to utilize a complete blocking design such that all the turbines included in the experiment switch between control and treatment(s). This can be done randomly or by previously specified groupings, but each turbine should spend an equal amount of time in each group and there should be an equal amount of treatment and control results. When deterrents are being tested, complete blocking can be costly as every turbine would require the deterrent technology installed to allow treatment rotation among turbines. If possible, extra turbines should be selected and set aside to be swapped into groups in case of unexpected downtime.

4.2. Testing Period

Throughout the year, two major periods are observed with significant increases in bat fatalities: spring and fall, with fall typically resulting in the larger numbers of fatalities. This aligns with the migratory patterns of Canada's migratory bats. In Ontario, bat fatalities were observed from May to October with most occurring in July, August, and September [11]. Testing should be done for this entire six-month period from May to October to account for both cave bats and migratory bats. The exact same tests should be repeated yearly for at least two years, but three would be preferable, to allow for inter-annual variations.

4.3. Field Search Radius

Field searches result in some of the most widely varying aspects of these experiments. This could be due to the significant costs associated with searching, terrain limitations, and other factors. To standardize what search radius should be used regardless of turbine height, the search radii used in each experiment were collected and converted to a "search radius modifier." This modifier is the quotient of the search radius and the maximum turbine height (hub height + blade radius). This allows for a simple multiplication of the search radius modifier and the maximum turbine height to determine an appropriate search radius. For example, a turbine with a hub height of 100 m and a blade radius of 45 m would have a maximum height of 145 m. If the search radius was 90 m, then the search radius modifier would be 0.62. Figure 4 below, shows the distribution of these search radius modifiers for each treatment type. Only 43 of the 51 field studies included turbine height, blade radius, and search radius, all of which are required to calculate the search radius modifier. The range of the 43 search radius modifiers are displayed below in Figure 4 and arranged by treatment type. The values ranged from 0.25 to 0.85, with an average of about 0.5. This is an ideal target for determining the search radius of a future bat fatality field trial. The larger the search radius, the more accurate results may be, but this is all dependent upon project budget and terrain limitations.
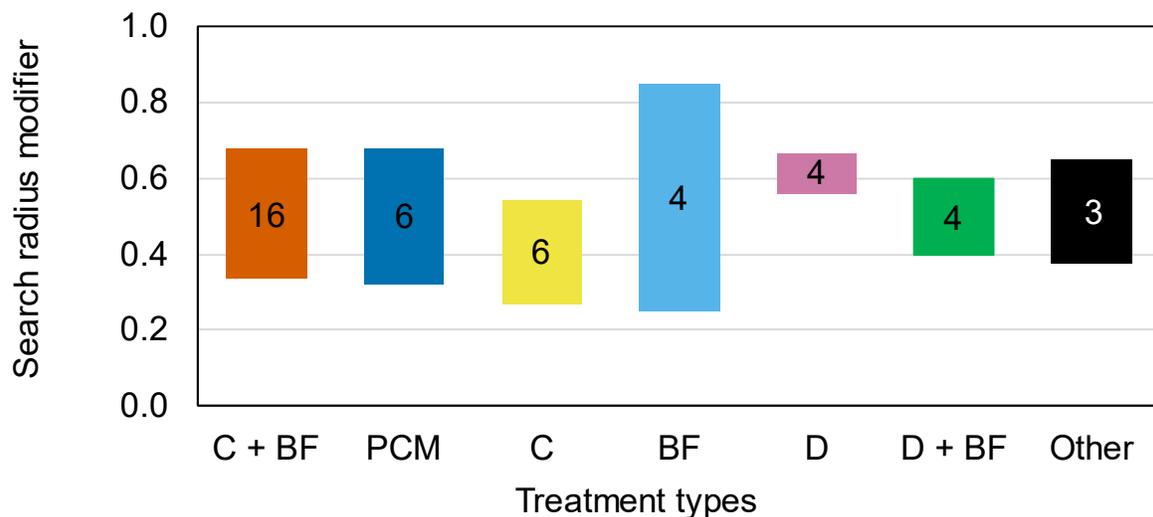
Key:
C = Raising cut-in speed   PCM = Post construction monitoring   D = Deterrent
BF = Blade feathering   Other = Other combinations of treatments

Figure 4 – Search radius modifier observed from 43 field studies and organized by study type. Search radius modifiers ranged from 0.25 to 0.85 with a mean of about 0.5.

While not all reports stated the frequency of searches, the 21 that did indicated search frequencies ranging from daily to weekly. Scavenger trails should be performed to determine how long a carcass can remain on the ground before it is picked up by another animal. This is typically used to set the search frequencies. Additionally, searcher efficiency trials should be done in similar terrains so that any inaccuracies due to the searching group are also corrected [11]. It is recommended that daily search frequencies are to be used for future studies, but depending on project budget and resources the search frequency should be at least weekly with correction factors applied.

4.4. Reporting Habits

Some of these recommendations may not be able to be followed for every situation due to limitations or factors that are outside the control of the experiment. Uncontrollable factors were mentioned in some of the analyzed studies as reasons for why the experiment was setup the way it was. This type of transparency and openness is important within these literatures. The ability to fully understand how each experiment was designed and executed and what issues were involved can significantly help the success of future experiments. Of the 43 experimental studies there were lots of missing information. Some cases were minor such as indicating whether the treatments were only implemented at night or during any specific time frame, and others were very significant like how turbines were selected or if there were control or treatment groupings, etc. The Ontario Ministry of Natural Resources and Forestry recommends experiments and reports be peer reviewed and the results disseminated to the public domain. This also exists as part of their requirements to obtain an overall benefit permit regarding impact on protection of species [42].

5. Limitations

The main limitation encountered within this study was the lack of publicly accessible data and field study reports. Some reports are kept private by wind operators. Even reports that are made public are missing information that could be valuable for analyzing trends or better understanding the overall experiment. While this lack of publicly available information inhibits this type of research, there is some validity to why reports and some information is privatized. Some of the information could be used to fuel public scrutiny on wind farms and their negative impacts on the environment or provide competitors with performance/cost information, which are both something these companies want to avoid. These limitations highlight the need for well-planned, rigorous, transparent studies among the currently available scientific literature.

6. Conclusions and Future Work

Analyzing these 51 studies resulted in a few key findings. Of the 43 experiment-based studies only 26 studies reported fatality reductions from actual counted results. Others either reported estimates of reductions or only provided treatment results with no baseline to compare against. This, along with other various issues such as missing information on turbine specifications, grouping methods, and search parameters, sheds light on major inconsistencies between the qualities of the experiments, data collection, and reporting.

The guidelines and suggestions laid out in Section 4 are by no means enforceable and there will always be exceptions on a case-by-case basis but provide a framework for future studies to anchor themselves to. Ideally, experiments should:

- Utilize both control and treatment groups (targeting 8 turbines per group and including extras to account for unexpected turbine downtime)

- Design both control and treatment groups to be equally inclusive of the wind farm geology and minimize biases (block designs can help)
- Run experiments for the entire period of bat activity (in Ontario, that is May to October)
- Perform study for 2-3 years to capture inter-annual variances
- Run searcher efficiency trials and apply to search results
- Run scavenger removal trails to determine search frequency (remain within daily to weekly)
- Size search radii based on maximum height of the turbine (target radius of half the maximum height)
- Have a clear and transparent report writing process that can easily be replicated
- If possible, submit report to peer-reviewed journal for public access

Future work should continue to support and improve development of an ideal bat mortality field study. Indicators such as number of turbines required for statistically significant results and ideal methods of grouping wind turbines would provide further benefit to this work. More field tests for technologies with little to no recorded experiments are required to increase the statistical significance of the results. Testing technologies that have already been included in multiple experiments should be continued and potentially compared with other and/or newer methods. Additional work should also be done to find commonalities between wind farms with high success rates for certain technologies to predict which technology may best suit any particular wind farm.

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Appendix

A.1. Field Test Setups

Reference	Treatment type(s)	Turbines included	Control turbines	Treatment turbines
[43, 44, 45, 46]	Post-construction monitoring	10	Cut-in speed of 3.0 m/s	N/A
[47]	Post-construction monitoring	28	N/A	N/A
[48]	Post-construction monitoring	183	Blades feathered until cut-in speed of 3.5 m/s	N/A
[49]	Post-construction monitoring	114	Blades feathered until cut-in speed of 3.5 m/s	N/A
[50]	Post-construction monitoring	8	Cut-in speed of 4.0 m/s	N/A
[51]	Curtailment + blade feathering	67	N/A	Blades feathered up to 6.9 m/s from 30 minutes prior to sunset and 15 minutes after sunrise
[21]	Deterrent (ultrasonic) + blade feathering	8	Deterrents off with cut-in speed of 3.5 m/s	Deterrents on with blades feathered up until 3.5 m/s at night
[21]	Curtailment + blade feathering	8	Deterrents off with cut-in speed of 3.5 m/s	Deterrents off with blades feathered up until 5.0 m/s at night
[21]	Deterrent (ultrasonic) + curtailment + blade feathering	8	Deterrents off with cut-in speed of 3.5 m/s	Deterrents on with blades feathered up until 5.0 m/s at night
[41]	Detection + curtailment + blade feathering	20	Cut-in speed of 3.5 m/s	Blades feathered up to 8.0 m/s if a bat call was identified within the last 10 minutes
[36]	Curtailment + blade feathering	8	Cut-in speed of 3.5 m/s	Blades feathered up to 5.0 m/s at night
[36]	Curtailment + blade feathering	8	Cut-in speed of 3.5 m/s	Blades feathered up to 8.0 m/s at night
[47]	Curtailment + blade feathering	14	N/A	Blades feathered (RPM ≤ 2) up to 5.0 m/s at night
[12]	Curtailment + blade feathering	N/A	Cut-in speed of 3.5 m/s	Blades feathered up to 5.5 m/s from sunset to sunrise
[36]	Curtailment	27	Cut-in speed of 3.5 m/s	Cut-in speed of 5.0 m/s
[36]	Curtailment	27	Cut-in speed of 3.5 m/s	Cut-in speed of 6.5 m/s
[52, 53, 54]	Curtailment + blade feathering	118	N/A	Blades feathered up to 5.0 m/s from sunset to sunrise

Reference	Treatment type(s)	Turbines included	Control turbines	Treatment turbines
[55]	Curtailment + blade feathering	75	N/A	Blades feathered up to 5.0 m/s from sunset to sunrise
[56]	Blade feathering	183	N/A	Blades feathered up to 3.5 m/s from sunset to sunrise
[48, 49, 56, 57]	Curtailment + blade feathering	114	N/A	Blades feathered up to 5.0 m/s from sunset to sunrise
[57]	Blade feathering	114	N/A	Blades feathered up to 3.5 m/s from sunset to sunrise
[34]	Curtailment	30	Cut-in speed of 3.0 m/s	Cut-in speed of 5.0 m/s
[39]	Deterrent (ultrasonic)	25	Cut-in speed of 4.0 m/s	Deterrents on with cut-in speed of 4.0 m/s from a half hour before sunset to a half hour after sunrise
[20]	Deterrent (ultrasonic)*	16	Blades feathered up to 3.0 m/s	Deterrents on with blades feathered up to 3.0 m/s at night
[38]	Blade feathering	16	Cut-in speed of 4.0 m/s	Blades feathered up to 4.0 m/s for 5 hours after sunset
[38]	Blade feathering	16	Cut-in speed of 4.0 m/s	Blades feathered up to 4.0 m/s for 5 hours before sunrise
[34]	Deterrent (ultrasonic) + curtailment	30	Cut-in speed of 3.0 m/s	Deterrents on with cut-in speed of 5.0 m/s
[13]	Curtailment*	8	Blades feathered up to 3.0 m/s	Blades feathered up to 5.0 m/s from sunset to sunrise
[13]	Curtailment*	8	Blades feathered up to 3.0 m/s	Blades feathered up to 5.0 m/s for 4 hours after sunset
[11]	Curtailment + blade feathering	N/A	Cut-in speed of 3.5 m/s	Blades feathered up to 4.5 m/s from sunset to sunrise
[33]	Curtailment	16	Cut-in speed of 4.0 m/s	Cut-in speeds of 6.0 m/s when temperatures > 9.5-°C from 30 minutes before sunset to sunrise
[50]	Curtailment	23	Cut-in speed of 4.0 m/s	Cut-in speed of 5.5 m/s (turbines also idle in wind speeds below 4.5 m/s)

Reference	Treatment type(s)	Turbines included	Control turbines	Treatment turbines
[50]	Blade feathering	14	Cut-in speed of 4.0 m/s	Blades feathered up to 4.0 m/s
[11]	Curtailment + blade feathering	N/A	Cut-in speed of 3.5 m/s	Blades feathered up to 5.5 m/s from sunset to sunrise
[11, 37]	Curtailment + blade feathering	N/A	Cut-in speed of 3.2 m/s	Blades feathered up to 4.5 m/s from sunset to sunrise
[11, 37]	Curtailment + blade feathering	N/A	Cut-in speed of 3.2 m/s	Blades feathered up to 5.5 m/s from sunset to sunrise
[40]	Deterrent (compressed air) + blade feathering	16	Blades feathered up to 3.5 m/s	Blades feathered up to 3.5 m/s and deterrents on from 6:00 pm to 6:30 pm
[40]	Deterrent (compressed air) + blade feathering	12	Blades feathered up to 3.5 m/s	Blades feathered up to 3.5 m/s and deterrents pulsing from 6:00 pm to 6:30 pm

*While blade feathering was present, the treatment type was just classified without blade feathering since it was used for both the control and treatment groups.