Guidelines

June 2021

Research project
« Reduction of the Avian Mortality in operating Windfarms »

Detection-reaction systems in onshore windfarms, a mitigation solution to reduce bird fatalities:

Principles for a relevant assessment of their performances

Alexandre Corbeau[1,2], Sophie Dupont[1], and Aurélien Besnard[1]

[1] Centre d'Ecologie Fonctionnelle et Evolutive, University of Montpellier, CNRS UMR5175, EPHE-PSL University, IRD, University of Paul Valéry Montpellier 3, Montpellier, France

[2] University of Rennes, CNRS, ECOBIO [(Ecosystèmes, biodiversité, évolution)] - UMR 6553, Rennes, France

Table of contents

Preface

This short note has been written as part of the MAPE project (https://mape.cnrs.fr/fr). This collaborative research project aims at a better understanding of the causes and consequences of collisions inducing avian fatalities in operating onshore windfarms, in order to reduce these fatalities. This work focuses only on bird fatalities (i.e., it does not consider the bats fatalities) that occur during the operational phase (i.e., not those that happen during the construction phase of the windfarm). It does not consider the indirect impacts either (see below).

This document is based on a critical analysis of all international scientific publications listed at the end of the current document, as well as on the review of 26 unpublished study reports (mostly confidential) of the systems (including seven conducted in France). It also relies on information gathered through the numerous email exchanges or interviews of the different actors of the wind energy sector that we conducted. Notably, we interviewed three wind operators, two turbine manufacturers and three Environmental Impact Assessment companies. We organised several meetings with representatives of the French government, members of research institutes such as the National Museum of Natural History team (MNHN, in Paris) working on the impact of wind energy on bats, one biodiversity policy officer from KNE (Kompetenzzentrum Naturschutz und Energiewende) and four research officers from France Énergie Marine. We also individually interviewed the six detection-reaction systems' suppliers already installed in France (or that will soon be installed) to learn more about their technologies, their technical performances and their limits. At the date of the publication of this report, five of these discussions were conducted by videoconference and one through email exchanges.

The main information contained in this document was presented and discussed at the MAPE Steering Committee and at a seminar bringing together the 90 partner structures of the MAPE project in March 2021. Finally, this document was also reviewed and commented by the members of the MAPE Work Package 4 technical committee: M. Cellier (EDF-RE), J. Champagnon (Tour du Valat), C. Chuzeville (Valeco), G. Dangoisse (Boralex), T. Disca (Sintec-Ing/Biotope), N. Saulnier (LPO 34), M. Thauront (UPGE/Ecosphère) & T. Vasseur (RES).

Furthermore, at the time we wrote these lines, no offshore wind turbine is operating in France. This note then exclusively focuses on French onshore windfarms. Because the issues of bird fatalities and the wind turbine models are largely similar across the world, the information and principles provided in this document are applicable to all windfarms worldwide. In theory, these recommendations are also valid for offshore wind turbines as they operate on the same principles as onshore turbines. However, in practice, offshore wind turbines seem to be more difficult to stop quickly, as they are larger, more powerful and subjected to stronger winds than onshore ones.

It is important to note that this work focuses on rapidly evolving technologies. Many new companies are also investing into this market. Therefore, it is possible that, by the time you read this, other devices than those listed below will be available. Many R&D tests are also currently being carried out in different countries. It is likely that new information on the performances of these devices will be published after the publication of this short note. We thus encourage readers to consult any new document, if available, in relation to this note.

Finally, we would like to point out that some of the information described in this document are extracted from reports that are subject to confidentiality agreements. Because of their importance in the part that aimed at describing current practices, these elements are anonymised and reported without specific reference.

1. Introduction

The use of renewable energies is the preferred method used by the French Government to undergo an energy transition that consumes less fossil fuel (https://www.gouvernement.fr/action/la-transition-energetique-pour-la-croissance-verte) in order to fight against the global climate change. In this context, windfarms as well as photovoltaic panel farms are booming. Their number has significantly increased in France in recent years. In 2020, there were 8,500 wind turbines on the French Territory, producing 17.5 MW. The French Multiannual Energy Programming Act (PPE 2019-2023) plans to double this production capacity by 2024. At the worldwide scale, 651 GW were produced by wind turbines at January 1st 2020, mainly by China and the United States (Global Wind Energy Council 2020).

However, this transition to renewable energy, and in particular to wind power, has consequences for the environment and particularly for biodiversity (Katzner et al. 2019). The main taxonomic groups negatively impacted by these infrastructures are birds and bats (Román et al. 2020; Thaxter et al. 2017). It is therefore necessary to identify and understand these impacts in order to avoid, reduce or compensate them as much as possible, in accordance with national and European regulations.

According to the available scientific literature, there are two types of impacts of windfarms on biodiversity:

- Firstly, some impacts are indirect. They occurred through the habitat loss both during the construction of the windfarm and during its operational phase. Indeed, it has been demonstrated that resident and breeding animal populations avoid the infrastructure area because it produces several types of disturbances (Powlesland 2009). For example, studies highlighted a reduction of space used by bats within 500 metres of wind turbines in a hedgerow landscape. This avoidance is even detectable up to one kilometre from the wind turbine mast for some species (Barré et al. 2018). This behaviour would be induced by the movement and noise produced by the rotor. Similarly, studies conducted on bird species found that ambient noise and the projection of the moving shadow on the ground induce a strong repulsion of some birds even if the strength of the effect is very species-dependent. It is particularly strong on passerines (Zwart et al. 2016; Marques et al. 2020). Other taxonomic groups may also be affected by the presence of operating windfarms in their habitat. For instance, wind turbine vibrations seem to have a negative impact on the abundance of ground fauna over distances ranging from 50 to 200 m (Velilla et al. 2021).

- The second impact type described in the literature is direct. It corresponds to fatalities due to a collision with the wind turbines (with the mast and rotor blades, Barrios & Rodríguez 2004; Drewitt & Langston 2006, 2008; Powlesland 2009). Bats, and certainly small passerines, are not only victims of collision but also die from barotrauma. These are induced by local atmosphere depressions created by the movements of the blade that cause the implosion of animals' internal organs (Rollins et al. 2012). All these forms of fatalities can have significant negative consequences on the dynamics of the impacted populations (Carrete et al. 2009; Frick 2017).

In France, the only global study available in the literature estimates that from 0.3 to 18.3 birds die from collisions with wind turbines, for each wind turbine and each year (7 individuals on average - however, this figure should be considered carefully as this estimation was calculated on a limited number of windfarms). This represents just over one fatality every 10 minutes and nearly 60,000 deaths *per* year in France (LPO 2017). Among these fatalities, 81% concern individuals of protected species. In the United States, a literature review, published in 2013 and based on data collected on about fifty American windfarms, estimated that fatality rate was approximately 5.25 ± 2.10 collisions *per* year and *per* wind turbine (close to values observed in France). This represents an annual mortality of 234,000 ± 94,000 birds for the 44,577 local operating wind turbines (Loss 2013). However, very few studies provide a robust estimate of the collisions with wind turbines.

This is notably due to the fact that a small number of carcasses is found in the field, that very large surface areas must be covered to look for all of the carcasses, that too few prospections are conducted and because of the rapid disappearance of carcasses, particularly of small animals (Péron et al. 2013; Bernardino et al. 2018: Dominguez del Valle et al. 2020). Therefore, the published numbers are often underestimations of current fatalities. Moreover, the consequences of these fatalities in terms of population dynamics are species-dependent (Drewit & Langston 2006; Schaub 2012; Bellebaum et al. 2013). Then, general figures have little ecological values (see the short-note of the MAPE research project WP2, Chambert & Besnard 2021).

According to French and European legislation, it is mandatory to avoid, reduce and/or compensate for any destruction of protected species (the ERC sequence, French Environmental Code 2021). Here, we will only focus on **the direct impact, i.e., bird fatality**. Currently, the implementation of mitigation measures in operating windfarms is required when mortality of protected birds is suspected during the impact assessment studies conducted prior to the construction approval (even if it is not yet quantified) or if fatalities are observed during the operational phase. The two main mitigation solutions currently used to reduce these fatalities in operating windfarms are (i) generic curtailment during avian sensitive periods of the year (i.e., breeding or migration periods) or during farming operations which may attract birds or during particular weather conditions (notably for bats, see Arnett & May 2016; Richardson et al. 2021 for example), (ii) the installation of a detection-reaction system on/near of operating turbines; this device emits visual or auditive signals to scare birds approaching the rotor or sends order to shutdown the turbines.

These detection-reaction systems are seen as a means to reduce mortality not to avoid them entirely. In France, these devices would only be used to reduce the fatalities of emblematic avian bird species, i.e., mainly large soaring species (raptors, storks and cranes) and other species subject to a National Action Plan and regularly affected by collisions (kestrel, bustards, etc.).

Despite the installation of such detection-reaction systems in windfarms, fatalities from collisions are still observed in some equipped windfarms. This persistence of such fatalities raises the question of the efficiency of these devices in terms of mortality reduction. Yet, no global and precise study has been carried out to assess the performance and the efficiency of these detection-reaction systems to date. Few evaluations are available in the literature. They were conducted by the system suppliers themselves, by Environmental Impact Assessment companies commissioned by windfarms' operators or system suppliers, or, in some cases, by NGOs or government agencies (see publicly available studies such as May et al. 2012; Aschwanden et al. 2015; Hanagasioglu et al. 2015; Terrill et al. 2018; McClure et al. 2018, 2021). No clear conclusion about detection-reaction systems' performances could however be drawn from these reports. Indeed, they are based on a wide variety of experimental design, which, due to their heterogeneity, do not provide comparable results. Furthermore, these tests are mainly conducted under optimal detection conditions (see for example McClure et al. 2018) and often with small sample sizes (associated uncertainties are also rarely quantified and presented in the consulted reports). Sometimes, the protocol conducted is not relevant (the recorded variables are not consistent with the functioning principles of the system, the evaluation only focuses on a part of the operating steps, the number of replications is limited, some inappropriate statistical analysis methods are used, etc.). In most of these reports, the protocols used to evaluate the performances of the systems are not described or not described precisely enough (statistical method, sample size, uncertainties, repeatability of measurements, etc.) to assess their robustness.

In the present guidelines, we describe the main principles and recommendations on how conducting robust evaluations of detection-reaction systems regarding **their performance** and not **their efficiency**, as the majority of available literature (however, see McClure et al. 2021, for a robust study of an efficiency measurement). Indeed, their actual efficiency can only be measured through their capacity to actually reduce fatality rates. This requires comparing the number of fatalities occurring before *vs* after the installation of the systems as well as in equipped sites *vs* control sites (Before-After Control-Impact, BACI - Smith et al. 1993).

Despite the importance of the efficiency assessment, this parameter has not been studied here for two main reasons:

- There is an ethical issue with such study. To measure the efficiency of these systems, it is necessary to compare the fatality rates occurring before *vs* after the installation of the detection-reaction system on a given site as well as *vs* on control sites. This may imply delaying the installation of a detection-reaction system at the test sites and allowing mortality to continue at control unequipped windfarms, for some years (e.g., three years for the study described in McClure et al. 2021).
- Fatalities estimates are associated to low statistical power. To assess the differences in fatality rates before *vs* after the installation of these systems, it is necessary to precisely estimate these fatalities. Several studies have highlighted the difficulties in obtaining accurate estimations of fatalities due to the several source of biases that need to be considered, such as the probability of carcasses detection by human observers or the rate of carcass disappearance (Péron et al. 2013; Bernardino et al. 2018; Kleyheeg-Hartman et al. 2018; Dominguez del Valle et al. 2020). In addition, because the frequency of field visits is generally low, field prospection usually leads to a small number of detected carcasses. Finally, fatalities of emblematic species' individuals are often rare and one-off events. Altogether, these limits result in very unprecise fatality estimates, which make particularly difficult to (statistically) show a significant difference before *vs* after the installation of detection-reaction systems, even when such a difference exists.

Box 1 – A move towards an evaluation of the efficiency of detection-reaction systems?

The videos/pictures saved by detection-reaction systems already installed in windfarms can be used to detect and quantify bird collisions with wind turbines. By analysing these recordings, it could also be possible to determine the part of these fatalities which seem to have been avoided by the operating detection-reaction system. However, two limits are immediately highlighted: the large amount of data to be processed and the non-exhaustiveness of the detected collisions. Specifically, some mortalities could be more easily identified than others. Notably, if they occur when a bird was detected by the detection-reaction system while the device has not reacted well enough to prevent this collision. On the contrary, quantifying the collisions that occur when the systems did not detect the bird can be more challenging and time-consuming. However, the improvement of image analysis systems, notably the increasing use of artificial intelligence, offers an interesting perspective for conducting such evaluations in the future.

New laser technologies for automatic mortality detection, such as B-Finder (Poznań®, Poland), could also allow to record all fatalities (through the detection of falling bodies of birds or chiropterans) on a windfarm. However, once again, the performance of such technologies needs to be assessed.

Finally, the pooling of all mortality monitoring data, at the national level, in the soon available DEPOBIO database may also permit to evaluate the efficiency of these devices but the high heterogeneity of technologies and the rapid evolution of these systems may limit this possibility.

In the present document, we first describe the principles of these detection-reaction systems functioning, as well as the different technologies currently used in detection-reaction systems available on the market. Then, we detail the variables that may influence the detection-reaction systems' performances. Finally, we present the different steps that should compose the protocols to take into account all of these variables in order to rigorously assess the detection-reaction system performances.

2. The detection-reaction systems

The detection-reaction systems are evolving rapidly. Improvements in technologies (surveillance cameras, computer hardware, etc.), but also in information processing algorithms, make them more and more efficient and more and more affordable. Four different technologies exist, and some more may emerge in the near future. Yet all these technologies rely on four main operating similar stages.

We exclude from the entire report the ornithological human sentinels that are used in few windfarms (not in France), but the main principles detailed below are directly transferable/applicable to them.

2.1. Principles and operations

The operation of detection-reaction systems is organised around four main stages:

- **Definition of a list of species to target**
  Currently, this list is defined in prefectorial decrees. According to information provided by the DREALs, these choices are largely relied on societal choices and notably the specific mortality/collision observed in specific windfarm, the 'ecological' sensitivity of the target species and their size (related to their potential detectability by the systems). Hence, these choices are not strictly based on legislative criteria (a large majority of the species that are subject to collisions with wind turbines are protected with equivalent protection status but not all are equally targeted in the prefectorial decrees) nor on purely scientific ones (see the state-of-the-art report produced within the Work Package 2 of the MAPE project dealing with the impact of fatalities on population dynamics, Chambert & Besnard 2021).

- **Definition of the risk area.**
  This area is a sphere (with the rotor at its centre, Figure 1) around the wind turbine in which the target species are considered at risk of collision. The diameter of this risk area depends on the speed flight of the selected target species as well as on the characteristics of the wind turbines, which notably affect the time they need to be stopped (see the short-note from the Work Package 3 of the MAPE project which aims at characterising the distribution of avian flight speeds, Fluhr & Duriez 2021).

Figure 1: Schematic representation of the risk area around a wind turbine

- **Detection/classification of target species by the detection-reaction system when they are in this zone considered at risk.**

- **Reaction of the system** when it detects/classifies as “at risk of collision” a bird from a target species from its trajectory in the area considered at risk.

These four stages could be translated into four operating main phases for the detection-reaction systems to evaluate. These four phases, i.e., functioning, detection, classification, and reaction, are common to all the technologies and the different detection-reaction systems. It is the right implementation of all of them which ensures the operating devices to be effective in reducing the fatalities of target species.

2.1.1. Functioning

We define the functioning of detection-reaction systems through its temporal and spatial coverage. Temporal coverage is the percentage of time during which the system is operational. It can be expressed as a percentage of time *per* day, month, or year. Spatial coverage is the effective percentage of space included in the risk area that is effectively covered by the system. It depends on blind spots, potential blind angles as well as on the maximum detection distance (specific to each detection-reaction system).

2.1.2. Detection

In this guideline, detection corresponds to the fact that the system “visualises” a potential object of interest. Several techniques for detecting flying objects are available and they greatly differ between detection-reaction systems. For radar, targets are detected by using echoes. For systems based on optical cameras, these objects are pixels on images.

2.1.3. Classification

The classification phase includes all the steps involved in processing the information acquired/collected on the mobile target from its detection by the system (size, speed, etc.) to the decision to trigger a reaction or not. It involves computer algorithms which are of different types, depending on the detection-reaction system (simple programming, filters, artificial intelligence, etc.). This process is generally considered as “industrial secrets” for most of the systems and the details of their functioning is generally not publicly available Consequently, it is hardly possible to determine a list of precise criteria that eventually led to the decision. It is also difficult for artificial intelligence algorithms for which the criteria used by the algorithms are not known even by the supplier of the system.

It can be difficult, if not impossible, to separately evaluate detection and classification steps as these two phases are strongly nested. Indeed, detection-reaction systems continuously detect and classify the flying objects in their surrounding environments to quickly eliminate any ‘non-target’ object.

2.1.4. Reaction

Reaction is defined as the system response following the detection and classification of a target bird considered as at risk of collision. Detection-reaction system usually triggers, in such situation, two types of responses that may be combined or not, depending on the device: (i) triggers an acoustic scaring signal by the emission of various sounds (numerous possibilities according to the operators' needs, depending on the target species and the proximity of the windfarm to human settlements or not, etc.) or (ii) triggers a shutdown of the wind turbine through an order transmitted to the SCADA of the turbine (i.e., the wind turbine management automaton). Note that some systems (not yet installed in France) also use active visual scaring signals (light signals).

The efficiency of acoustic or visual scaring measures (i.e., one of the possible device's reactions) is not addressed in this short note. Here, we only addressed criteria for estimating the duration needed for both the system and the turbine to induce a turbine shutdown after the bird is classified as "at risk".

2.2. The four main families of detection-reaction systems

In this section, we have grouped all known detection-reaction systems into four different classes, depending on the technology they rely on. This classification also includes systems still under development. The popularisation of these technologies, as well as the emergence of new devices on the market, will quickly make this list obsolete. Nevertheless, these four main families are large and should be relevant for all current but also future systems.

Unresponsive detection systems (usually used to monitor bird migration etc.) are not included in our list because they are not a mitigation measure, nor are the 'human bird watchers' because they are not currently used in France.

2.2.1. 2D optics

The 2D optic systems use optical cameras. Some suppliers couple them with thermal cameras or with infrared illumination to monitor the turbine environment during the night. However, these last two technologies are currently rarely used, as they induce a significant increase in device cost.

In these 2D optic systems, detection and classification are achieved by the analysis of the pixel changes in the recorded images. In general, the system detects changes in pixels contrast between successive images and classifies in real time whether the spotted object is relevant or not, according to its size and/or size and location changes on the image. To do so, both manually programmed algorithms or artificial intelligence algorithms ('Machine Learning' or 'Deep Learning') are used, depending on the device.

2.2.2. 3D optics

The 3D optic devices also use optical cameras. Here, the used technology allows a more accurate assessment of the distance between the system and the detected object by using trajectometry, compared to 2D optic systems. The direction of the target is then determined through this trajectometry, which ensures a finer analysis of the need to trigger a reaction or not.

At the date of this report publication, the only system based on this technology (i.e., Identiflight® USA) performs a species-specific identification of the targets using an artificial intelligence algorithm. It is today only calibrated for a few species (Bald eagles, White-tailed eagles, Golden eagles or Red kites; McClure et al. 2018, 2021). The number of species that it can identify is however likely to grow over time as this system will probably be deployed for other species.

2.2.3. Radar

Radar technology has been used more and more for ornithology studies for several years, particularly to count and map bird tracks (Larkin et al. 1979; Diehl et al. 2003). It is based on the reflection of radar waves by the surrounding objects (notably birds). The echoes of these encountered objects are picked up by the radar and recorded after eliminating parasite echoes. Radar can usually classify the encountered birds into size groups (Harmata et al. 1999) but not yet at the species level.

Compared to optical devices, these systems have a greater detection range but may have a poorer short-distance coverage.

2.2.4. A combination of different technologies

The combination of the different technologies described previously in a unique device is increasingly suggested as a promising tool but is not yet available on the market, at the time we wrote this report. Specifically, the current prototypes combine a long-range radar technology with a short-range optical camera. They then take advantages of these two technologies (detection distance *vs* species identification) and overcome their respective limitations. Another system under development (i.e., EchoTrack®, Canada) combines radar technology and microphones to record and monitor bird calls around turbines. However, we were not able to access the first tests carried out on these devices.

2.2.5. List of suppliers

Below, we present a list of detection-reaction systems suppliers currently available on the market in France in the first half of 2021 (Table 1). They are classified according to the family of technology they use.

Table 1 – List of detection-reaction systems suppliers available in France in May 2021.

Family of technologies	Product name	Company (Country)	Operationality	French windfarms equipped	Other countries using this system
2D camera	BirdSentinel/Safe Wind	Biodiv-Wind (France)	Yes (several versions)	43	Europe
2D camera	DTBird	DTBird (Spain)	Yes (several versions)	23	Europe, USA, Asia
2D camera	Bioseco	BIOSECO (Poland)	Yes	1	Poland, Germany
2D camera	ProBird	Sens of Life (France)	Yes	~50	Europe
2D camera	BirdRecorder	ZSW (Germany)	Under development	0	Germany (test)
2D camera	BirdVision	BirdVision (Germany)	Under development	0	Germany (test)
2D camera	Eagle removal minimisation project	Oregon State University (USA)	Under development	0	USA (test)
3D camera	IdentiFlight	Boulder Imaging (USA)	Yes	1	Europe, USA
Radar	RobinRadar MAX	Robin Radar System (the Netherland)	Yes	0	Germany, the Netherlands (test)
Radar	3D FlightTrack	Diadès Marine (France)	Yes	2	NA
Radar	BirdTrack	Strix (Portugal)	Yes	0	Portugal
Radar	BirdScan MS1	Swiss Birdradar (Switzerland)	Under development	0	Germany (test)
Radar + micro	EchoTrack Radar-Acoustic SurveillanMultiradarce System	EchoTrack (Canada)	Under development	0	South Africa (test)
Radar + Camera	Laufer Wind	Renewable Energy (USA)	Under development	0	USA (test)
Radar + Camera	MUSE	DHI (Denmark)	Under development	0	Denmark (test)

3. Evaluating the performances of detection-reaction systems

In this section, we first introduce the statistical concepts that need to be understood and mobilised for the successful implementation of the protocols to test the performances of detection-reaction devices and for the correct interpretation of the results of these tests. In a second part, we define and describe the parameters which are important to estimate for qualifying/quantifying the performances of detection-reaction systems. Finally, we list the factors potentially affecting these performances and show why it is important to take all these parameters and variables into account when testing these systems, using a few examples from some reports we consulted.

3.1. An attention to statistical reliability is needed

3.1.1. Standardisation and repeatability of tests

To compare studies and associated device performances, a common and standardised protocol is required.

The Competence Centre for Nature Conservation and Ecological Transition in Germany (KNE) has already published a guide which outlined the most important principles to follow when setting up an assessment protocol of detection-reaction system performances (KNE 2019). Yet, the guidelines described in this report seem to not be easily universally applied for all types of detection-reaction systems available on the market. In addition, this report does not deal with the statistical analyses needed in these tests.

<u>Example 1:</u>

One source of bias we observed in a number of reports is the change of human observers or of used equipment (drones, binoculars, rangefinder, etc.) from day-to-day of the same study. These modifications may induce bias in the detection/classification probability of the reference system due to the differences in detection/classification probability from one observer or equipment to another. To limit this heterogeneity, the tests should be standardised as much as possible. Any modification in the protocol should be reported and must be considered in the statistical analyses.

<u>What should be found in the protocols and/or test results:</u>

In final reports, it is necessary to find a precise description of the achieved protocols. Sample size, identity, and fieldwork investment of each human observer as well as the material used during tests should be systematically reported.

3.1.2. Defining the parameters to estimate

Evaluating performance involves the estimation of some parameters: i.e., detection/classification probability, average detection distance, etc. It implies that protocols allow the measurement of some variables, i.e., quantifiable measures conducted on a clearly defined entity (called statistical units or statistical individuals).

In most field studies in ecology, two types of variables are recorded:

- The first one is the **variable to be explained** (sometimes also called “response variable”). This is the focal variable of the study which will be used to concretely quantify the detection-reaction device performances. It can be the capacity of a system to detect or not a bird/a track before a certain distance or the distance at which a bird trajectory is detected for the first time by the system for example. Through our qualitative analysis of the available literature, we noticed that these variables are not always explicitly described in the final reports (see below). Their formalisation is however absolutely necessary as they are the basis for statistical analyses.

- The second type of variables that can be recorded is the **explanatory variables** (sometimes also called “influencing variables”)**.** These variables may influence the variable to be explained. Regarding detection-reaction system performances, such a variable can be for instance the distance between the target object and the device, the bird species, the luminosity, etc.

Several explanatory variables (distance, species, weather conditions, etc.) can be jointly considered when testing the performances of a device. However, each performance is estimated using a unique variable to be explained. For example, a performance to estimate can be the monthly device functioning percentage of time. A second one may be the probability of successful bird detection/classification.

<u>Example 2:</u>

In some study reports that we consulted, birds’ trajectories are frequently used as raw data to evaluate the performance of the detection phase. However, a trajectory is an imprecise unit that cannot be explicitly used in statistical analyses of performance tests. Yet, some variables can be derived from these flight tracks such as the detection or not before a certain distance or the average distance of first detection. These last two variables can be easily analysed with statistical methods.

<u>What should be found in the protocols and/or test results:</u>

The set of parameters to be estimated as well as the corresponding variable to measure (one for each performance to evaluate) and the explanatory variables must be clearly defined, and their quantification should be precisely described. In addition, the estimation method (statistical method) of these parameters (e.g., generalised linear model) should be clearly stated.

3.1.3. Sample size and statistical uncertainty

Defining a relevant/sufficient sample size is one of the main difficulties in the elaboration of robust protocols. Indeed, the uncertainty around the variables to estimate is directly related to the sample size of the analysed dataset (number of times these response variables have been measured). There is a negative mathematical relationship between the precision of an estimate and the sample size used for that estimate. More precisely, the larger the sample size, the smaller the uncertainty is and the closer the values of parameters to be estimated are to the (unknown) real value. A small sample size is always associated with a larger uncertainty in the estimate and then in a lower reliability of the evaluated performance than when using a large sample size. Of course, high precision implies high sampling effort and thus high (field) costs.

Note that the calculation of the uncertainty should be systematically reported in the test results. Indeed, without this information, the estimates of the performance parameters are unusable. Yet, our review of study reports highlighted that these uncertainties in estimates were almost never reported.

Example 3:

In the example 2 (detailed above), several detection data (i.e., part of a trajectory in a given space and time) are required to estimate the associated detection probability. This performance is expressed as a mean probability with its standard error. When a study report claims that a detection-reaction system can detect 80% of the targets within 150 metres, it is impossible to know from this single figure (i.e., without uncertainty and sample size) whether this estimate is reliable or not. This performance estimates could have been derived from a study based on 5 or 500 bird tracks and thus associated to very different confident intervals. In these two extreme situations, statistics allow us to conclude that the true (unknown) detection probability is included in the following 95% confident interval: [28.3%; 99.5%] or [76.2%; 83.4%] respectively (a 95% confidence interval means that the real value has 95% chance of being in this interval). This example illustrates the strong link between sample size and accuracy (the estimation based on 500 tracks is ten times more accurate than the one based on 5 tracks).

This should be reported in the protocols and/or test results:

When providing values for the estimated parameters, it is essential to specify both the sample size measured and the associated uncertainty (through confidence interval or standard error for instance). This enables all readers to assess the robustness of the conclusions of the study.

3.1.4. Field data collection by human observers

In most of the study reports we read, the number of detections/classifications events recorded by the detection-reaction device is compared to the data collected by one human observer. However, it is well known that human visual capacities vary from one observer to another as well as over time (notably due to fatigue). In addition, these visual capacities decrease with distance between the observer and the object to detect (Rosenstock et al. 2020). Such a potential detection decrease with distance could strongly impacts the estimation of the detection/classification capacities of a detection-reaction system. Nowadays, few performance assessment reports explicitly model these human biases while they must be considered and reported when using this experimental approach.

Example 4:

We read in some performance study reports that detection-reaction systems usually have better detection capacities than human observers, whatever distance. However, the absolute detection performance of the detection-reaction device could not be obtained through a single comparison of the relative data collected from these two 'observers' systems (i.e., the device and the human observer). The estimation of this absolute value (i.e., without any bias) requires to explicitly model the detection probabilities. The following paragraphs illustrate this point.

Here, we consider a situation in which the human observer and the detection-reaction system have an 80% and 90% detection probability respectively (i.e., a difference of 10%). The 'naive' comparison of the number of detected tracks results in a slightly overestimated detection probability of 92% for the detection-reaction device (Table 2).

Table 2 – Case study: estimating the detection probability of a detection-reaction system (90%) thanks to a human observer (detection probability = 80%) based on 100 real tracks near a wind turbine. The blue table reports the actual values of detection capacities for the human observer and the detection-reaction system. The green one presents the estimate of detection probability obtained by a naive comparison of the number of tracks detected by the observer and the detection-reaction system.

100 tracks	Detection probability	Number of detected tracks
Human observer	0.8	80
Detection-reaction system	0.9	90
Both		72
Detected by the system but NOT by the human observer		18
Detected by the observer but NOT by the system		8
Number of analysed tracks	98	
Estimated detection probability y of the system	0.92	
Bias in the estimated detection probability	0.020	

In this second case, the actual detection rates for the human observer and the detection-reaction system are respectively 30% and 40% (i.e., still a difference of 10%). Here, the 'naive' calculation of the detection probability of the detection-reaction system returns an estimate of 72.4%, which is a very large overestimation of the actual value (Table 3)

Table 3 - Case study: estimating the detection probability of a detection-reaction system (40%) thanks to a human observer (detection probability = 30%) based on 100 real tracks near a wind turbine. The blue table reports the actual values of detection capacities for the human observer and the detection-reaction system. The green one presents the estimate of detection probability obtained by a naive comparison of the number of tracks detected by the observer and the detection-reaction system.

100 tracks	Detection rate	Number of detected tracks
Human observer	0.3	30
Detection-reaction system	0.4	40
Both		12
Detected by the system but NOT by the human observer		28
Detected by the observer but NOT by the system		18
Number of analysed tracks	58	
Estimated detection probability y of the system	0.69	
Bias in the estimated detection probability	0.724	

This should be reflected in the protocols and/or test results:

If human observers are used as a reference to evaluate the performance of a detection-reaction device, it is essential to individually identify those that are involved in each test (who can change from one study to another and from one field day to another) as well as their ornithological skills (training, experience in counting and monitoring target species). This allows the evaluation and modelling of the detection and the classification biases of each observer regarding all the influencing variables (distance, visibility, species, etc.). These measurements are included in the statistical models to estimate unbiased devices performance.

Importantly, the use of double counting, with two experienced human observers, is a good way to reduce and easily model human biases in detection probabilities ('double observers' method).

3.2. The functioning step

- Parameters to be estimated:
  - Temporal coverage: is the system always active? if not, under what conditions would it be active?
  - Spatial coverage: does the system cover the entire risk area defined around the wind turbines? Does the system consider all potential angles of bird arrival including birds arriving vertically? Does the system consider species-specific distances of arrival depending on the target species (see Work Package 3 of the MAPE project, Fluhr & Duriez 2021)?

- Influencing variables:
  - The operationality of the equipment and connections can impact this step: the reliability of the system components themselves, but also the reliability of power supply, the quality of the internal network in the windfarm as well as potentially the internet network.
  - Time of day: the activation of the systems during the day or night depends on the ecology of the target species. Importantly, the circadian rhythm of the target species may vary over the annual cycle: breeding, migrating, or wintering. Specifically, numerous scientific studies have reported that diurnal birds are also active at night, notably during their migration phase (Brewster 1886; Alerstam 2009; García-Jiménez et al. 2020). Yet, these variations of the daily pattern of activity are quite rare in large diurnal soaring birds, which are currently the most targeted species for the implementation of detection-reaction systems in operating windfarms in France.
  - Weather conditions: contrary to preconceived ideas, numerous studies have highlighted that, birds are active and fly in all types of weather conditions, including when winds are strong (Krüger & Garthe 2001). Therefore, the systems should work as soon as the weather conditions are favourable for wind turbines to operate. This includes periods of strong wind (that may be associated with vibrations of the system support), extreme positive and negative temperatures (risk of overheating or freezing of the system) and harsh weather (snow, rain, fog, etc. which may reduce the detection/classification capacity of the sensors).

- Some thinking on the content of the evaluations:

We have been told that detection-reaction systems may sometimes be out of service. This has been detected through abnormal results obtained during field performance tests or after a technical examination following an unusual mortality in an equipped windfarm. It is therefore important, and necessary, to measure this step of functioning of the installed devices. An accurate record of spatial and temporal coverage, through tests of visibility from a reference image or from control points in the field, both at the time of their installation and repeatedly over time would allow to continuously verify the stability of the functioning of the device.

3.3. Detection

- Parameters to be estimated:

Here, the variable to be estimated is the probability to detect ‘at-risk’ trajectories. Replicas are compulsory to express this detection probability as an average with its associated standard error.

We could determine based on this estimate (Table 4):

- The rate of true positives, which is the reference value for measuring the detection capacity of the system regarding actual target objects in the environment (detection probability).
- The rate of false negatives (calculation is: 1 – detection probability). This rate must be as low as possible, as it corresponds to cases in which the system does not detect certain birds at risk.
- The number of false positives. This number should also be as low as possible to limit production loss. Indeed, it represents cases in which the system orders to shutdown the turbine while there was no bird ‘at-risk’ of collision in the area.

Table 4 - Confusion matrix for the detection of one ‘at-risk’ trajectories

	Detection	No detection
Presence of target species	True positive	False negative
No target species	False positive	True negative

- <u>Influencing variables and their measurements:</u>

  - Species of the target bird: the species strongly influence the detection capacity of the device, particularly through their sizes. Large species are generally detectable from further away than small ones. Therefore, the performance assessment tests should consider a range of species sizes to include all target species, from the largest to the smallest one (box 2).

  - Distance between the detection-reaction system and the target bird: a minimum distance of detection must be defined according to the species specifically targeted in each windfarm. This distance is related to the flight speed of the target species (see Fluhr & Duriez 2021 and KNE 2019). There is probably a strong negative correlation between the detection probability of a bird by the device and the distance between them. Then, statistical analyses should always consider the parameter to be estimated as a function of the distance between the device and the target bird. For 2D systems which do not accurately measure this distance, distance classes could be used (of 100 metres width for example, from 0 to 1,000 metres).

  - Altitude: It has been observed that some target species achieved descending vertical flights from the top of the turbine. Others performed ascending vertical flights, i.e., from the foot of the turbine to high elevations. Therefore, detection-reaction systems should detect at a sufficient distance above and below the turbines to efficiently reduce collisions for these species (see Fluhr & Duriez 2021).

  - Azimuth: Birds can approach the wind turbine from any direction. The detection-reaction system must perform equally well at 360° horizontally (i.e., the numerous cameras used to cover the different angles should have the same characteristics and work correctly whatever the weather conditions).

  - Background: According to detection-reaction systems' suppliers, a homogenous blue sky results in sharp contrasts between bird and background sky; It allows good detection capacities of the devices. Objects moving on a plain ground (with no intrinsic movement) would also be detected with a higher probability than if the background is made of moving plant/cloud/sea. Consideration of this influencing factor when modelling the detection probability of the device is necessary. The interference made by moving background is also important to consider for systems using radar technology (notably from the ground vegetation).

  - Time of day, season, and the bird trajectory in relation to the sun position: sunsets and sunrises can create strong backlighting effects in optical systems. Additionally, a target coming straight from the sun would be much more difficult to detect by the devices. Conducting the tests at different hours of the day will allow taking into account the different orientations of the sun and bird when estimating the detection probability.

  - Weather conditions: bad weather conditions (fog, rain, snow, hail, etc.) reduce the detection capacities of the detection-reaction systems through a decrease of the surrounding environment visibility and contrast. Measuring the effect of this influencing factor is important as bad weather conditions could represent a significant part of the operating time for some windfarms (depending on their geographical area). Then, it is crucial to conduct performance tests under all weather conditions and not only in ideal conditions (i.e., sun at the zenith, good weather, etc.).

Box 2 - How to test the range of sizes of potential target species?

It could be difficult to conduct robust performance assessment tests with a sufficient sample size for all target species. However, it is possible to group species according to their size and then to reduce the number of tested species:

- 'Large bird species', birds with a wingspan of more than two metres: Griffon, Black and Bearded vultures, Golden and White-tailed eagles, White and Black storks, Common crane, pelicans, etc.
- 'Medium bird species', birds with a wingspan of one to two metres: Egyptian vulture, Short-toed, Bonelli's and Booted eagle, Osprey, Red and Black kites, Common and European honey buzzard, Northern goshawk, Marsh, Montague's and Northern harriers, geeses, cormorants, herons, flamingos, gulls, etc.
- 'Small bird species', birds with a wingspan of 40 centimetres to one metre: Black-winged kite, Eurasian sparrowhawk, European roller, ducks falcons, pigeons, etc.

Note that these three categories have been defined on the basis of the current detection performance of detection-reaction systems operating in windfarms. Their detection capacities are still low for birds with a wingspan of less than 40 centimetres. As technology evolves, it will be interesting to create new categories for these smaller species in the future protocols.

Falconry birds may be used to increase the sample size when observations of wild birds did not allow collecting enough tracks/data.

- <u>Some thinking on the content of the evaluations:</u>

The detection probabilities, determined for each category of the influencing variables described above, should be listed in a standardised performance table. This unique document (*per* detection-reaction system) will allow an easy performance comparison between devices available on the market. Therefore, it will help operators to choose the most relevant detection-reaction system for their windfarms (according to their topography, geography, target species etc.).

3.4. Classification

The assessment of the classification and the detection phases are similar. In addition, the variables that affect their estimates are also similar. Then, a joint evaluation could be undertaken for these two steps.

- Parameters to be estimated:

Here, we aim to model/evaluate the probability of correct classification by the detection-reaction system. This variable is expressed as an average associated with its appropriate uncertainty. It then requires several replicates to obtain a robust estimate.

We could determine based on this estimate (Table 5):

- The rate of true positives, which is the reference value for determining whether a detection-reaction system classifies efficiently or not a detected target bird as ‘at risk’ (probability of proper classification).
- The rate of false negatives (calculated with the following formula: 1 - probability of proper classification). This number must be as low as possible, as it corresponds to cases in which the system does not trigger a reaction despite the presence of a target species ‘at-risk’.
- The number of false positives. This number should be as low as possible to limit unintentional shutdowns when there is no ‘at-risk’ situation.

Table 5 - Confusion matrix for the classification of one ‘at-risk’ trajectory

	Correct classification	Wrong classification
Target species	True positive	False negative
No target species	False positive	True negative

- Influencing variables and their measurements:

Influencing variables are identical than for the detection step. Please see 3.3 for details about these factors.

- Some thinking on the content of the evaluations:

Real birds must be used to estimate the probability of proper classification. Indeed, drones are not always classified as target species by some devices (notably those based on Artificial Intelligence) due to their behaviours and silhouettes which differ from birds.

This performance assessment of classification step could be done either by a human observer (who identifies bird species directly on the field or on pictures recorded by the system), or by using a known target species (falconry birds) around the detection-reaction to provoke classification events.

The probabilities of detection and proper classification should be reported in the same performance table to allow a full and standardised assessment.

3.5. Reaction

- Parameters to be estimated:

  - The system responsiveness: measurement of the reaction time of the system. This parameter is important to determine the appropriate width of risk areas (also depending on the flight speed of the target species, see Work Package 3 of the MAPE project).

  - The consistency in response: verifying whether there is always an appropriate reaction from the turbine when the detection-reaction system sends an order. Only shutdown orders are considered here as the visual and acoustic scaring are triggering independently from the SCADA.

- Influencing factors:

  - The stability of the connection: as for the functioning phase (see part 3.2), the reliability of the internal network of the windfarm as well as the reliability of the external one are important to consider. More precisely, a poor connection can induce no or extended reaction times.

  - The consideration of system shutdown orders by the SCADA: The SCADA is differently managed according to the turbine manufacturer, the operator, and the windfarm configuration. Therefore, it has been noted duration variations in the receipt/consideration/implementation of system orders by the wind turbine through the SCADA.

  - The status of the wind turbine: it seems that some wind turbines do not take into account new shutdown orders when restarting after a first shutdown order.

- Some thinking on the content of the evaluations:

According to detection-reaction systems suppliers that we met, all reaction orders are systematically recorded and saved by the device. The associated rotor speed could also be recorded and saved by the detection-reaction systems and is systematically recorded by the SCADA. Therefore, it is necessary to combine data from the device and the SCADA in order to verify whether a reaction has been correctly implemented and to measure the associated reaction time.

By reporting this data in the performance grid, the reaction uniformity between devices could be evaluated.

The assessment of the system reaction step can be done regularly in an operating windfarm. Indeed, this does not require any additional manipulation of the system or the wind turbine.

4. Conclusion

This guideline report aimed to describe the ins and outs associated with the use of the different detection-reaction systems and related technologies. This document is intended for anyone interested in performance assessment of detection-reaction systems, i.e., people in charge of developing protocols, applying protocols in the field or in charge of verifying the quality of the evaluations carried out.

The heterogeneity of the technologies used by detection-reaction systems and the numerous factors influencing the four operating phases of these devices make the evaluation of their performances quite complex. However, this evaluation is crucial. First, it is necessary to verify their ability to reduce bird fatalities. Second, it is a relevant way for operators to obtain robust criteria to choose the most suitable system for their windfarms.

In the framework of the MAPE project, we will propose a complete, robust, and universal performance assessment protocol for all detection-reaction systems to provide standardised and windfarm-specific performance grids.

5. Acknowledgements

We are grateful to all the stakeholders who participated to the interviews that led to this document.
We would also like to thank all members of the MAPE project research team (CEFE-CNRS) as well as its management team (MSH SUD): C. Blary, T. Chambert, O. Duriez, J. Fluhr & M. Vieira Pak.

6. References

Alerstam T (2009). Flight by night or day? Optimal daily timing of bird migration. *Journal of Theoretical Biology*, 258(4):530-536.

Arnett EB & May RF (2016). Mitigating wind energy impacts on wildlife: approaches for multiple taxa. *Human – Wildlife Interactions*, 10(1):5.

Aschwanden J, Wanner S & Liechti F (2015). Investigation on the effectivity of bat and bird detection at a wind turbine: Final report bird detection. *Schweizerische Vogelwarte, Sempach, Schweiz*.

Barré K, Le Viol I, Bas Y, Julliard R & Kerbiriou C (2018). Estimating habitat loss due to wind turbine avoidance by bats: Implications for European siting guidance. *Biological Conservation,* 226:205–214.

Barrios L & Rodríguez A (2004). Behavioural and environmental correlates of soaring-bird mortality at on-shore wind turbines: Bird mortality at wind power plants. *Journal of Applied Ecology,* 41:72–81.

Bellebaum J, Korner-Nievergelt F, Dürr T & Mammen U (2013). Wind turbine fatalities approach a level of concern in a raptor population. *Journal for Nature Conservation,* 21:394–400.

Bernardino J, Bevanger K, Barrientos R, Dwyer JF, Marques AT, Martins RC, Shaw JM, Silva JP & Moreira F (2018). Bird collisions with power lines: State of the art and priority areas for research. *Biological Conservation,* 222:1–13.

Brewster W (1886). Bird migration. Memoirs Nuttall Ornithological Club 1, Nuttall 498 Ornithological Club, Cambridge, Massachusetts.

Carrete M, Sánchez-Zapata JA, Benítez JR, Lobón M & Donázar JA (2009). Large scale risk-assessment of wind-farms on population viability of a globally endangered long-lived raptor. *Biological Conservation,* 142(12):2954-2961.

Chambert T & Besnard A (2021). Note de synthèse : Évaluer l'impact démographique des collisions aviaires avec les éoliennes : Synthèse des connaissances et recommandations méthodologiques.

Diehl RH, Larkin RP & Black JE (2003). Radar observations of bird migration over the Great Lakes. *The Auk,* 120(2):278-290.

Dominguez del Valle J, Cervantes Peralta F & Jaquero Arjona MI (2020). Factors affecting carcass detection at windfarms using dogs and human searchers. *Journal of Applied Ecology,* 57:1926–1935.

Drewitt AL & Langston RHW (2006). Assessing the impacts of windfarms on birds. *Ibis,* 148:29-42.

Drewitt AL & Langston RHW (2008). Collision effects of wind-power generators and other obstacles on birds. *Annals of the New York Academy of Sciences* 1134:233–266.

Fluhr J & Duriez O (2021). Note de synthèse : Déterminer les distances de détection minimales des oiseaux pour réduire les risques de collision avec les installations éoliennes : Synthèse des connaissances relatives au vol et aux vitesses de vol des oiseaux.

Frick WF (2017). Fatalities at wind turbines may threaten population viability of a migratory bat. *Biological Conservation,* 209:172-177.

García-Jiménez R, Martínez-González JM, Oliva-Vidal P, Piqué J, Sesé JA & Margalida A (2020). Nocturnal flights by Bearded Vultures -*Gypaetus barbatus*- detected for the first-time using GPS and accelerometer data. *Bird Study,* 67:135–141.

Global Wind Energy, Council (2021). Gwec - Global wind report 2021.

Hanagasioglu M, Aschwanden J, Bontadina F & De la Puente Nilsson M (2015). Investigation of the effectiveness of bat and bird detection of the DTBat and DTBird systems at Calandawind turbine. Untersuchung zur Effektivität der Fledermaus-und Vogeldetektion des bei Windturbinen mit DTBird System, *Swiss Federal Office of Energy (SFOE), Research Program Wind Energy*.

Harmata AR, Podruzny KM, Zelenak JR & Morrison ML (1999). Using marine surveillance radar to study bird movements and impact assessment. *Wildlife Society Bulletin,* 27:44–52

Katzner N, Diffendorfer JE, Duerr AE, Campbell CJ, Leslie D, Vander Zanden HB, Yee JL, Sur M, Huso M, Braham MA, Morrison ML, Loss SR, Poessel SA, Conkling TJ & Miller T (2019). Wind energy: An ecological challenge. *Science,* 366:1206–1207.

Kleyheeg-Hartman JC, Krijgsveld KL, Collier MP, Poot MJM, Boon AR, Troost TA & Dirksen S (2018). Predicting bird collisions with wind turbines. Comparison of the new empirical Flux Collision Model with the SOSS Band model. *Ecological Modelling,* 387:144–153.

KNE (2019). Anforderungsprofil, "Anforderungen an eine fachlich valide Erprobung von technischen Systemen zur bedarfsgerechten Betriebsregulierung von Windenergieanlagen".

Krüger T & Garthe S (2001). Flight altitudes of coastal birds in relation to wind direction and speed. *Atlantic Seabirds,* 3(4):203-216.

Larkin RP, Griffin DR, Torre-Bueno JR & Teal J (1979). Radar observations of bird migration over the western North Atlantic Ocean. *Behavioral Ecology and Sociobiology,* 4(3):225-264.

Loss SR (2013). Estimates of bird collision mortality at wind facilities in the contiguous United States. *Biological Conservation,* 168:201-209.

LPO (2017). Le parc éolien français et ses impacts sur l'avifaune.

Marques AT, Santos CD, Hanssen F, Muñoz A, Onrubia A, Wikelski M, Moreira F, Palmeirim JM & Silva JP (2020). Wind turbines cause functional habitat loss for migratory soaring birds. *Journal of Animal Ecology,* 89:93–103.

May RF, Hamre Ø, Vang R & Nygård T (2012). Evaluation of the DTBird video-system at the Smøla wind-power plant. Detection capabilities for capturing near-turbine avian behaviour. *NINA rapport.*

McClure CJW, Martison L & Allison TD (2018). Automated monitoring for birds in flight: Proof of concept with eagles at a wind power facility. *Biological Conservation,* 224:26-33.

McClure CJW, Rolek BW, Dunn L, McCabe JD, Martinson L & Katzner T (2021). Eagle fatalities are reduced by automated curtailment of wind turbines. *Journal of Applied Ecology*, 58:446–452.

Péron G, Hines JE, Nichols JD, Kendall WL, Peters KA & Mizrahi DS (2013). Estimation of bird and bat mortality at wind-power farms with superpopulation models. *Journal of Applied Ecology,* 50:902–911.

Powlesland RG (2009). Impacts of windfarms on birds: a review. *Science for conservation,* 289.

Richardson SM, Lintott PR, Hosken DJ, Economou T & Mathews F (2021). Peaks in bat activity at turbines and the implications for mitigating the impact of wind energy developments on bats. *Scientific Reports,* 11(1):1-6.

Rollins KE, Meyerholz DK, Johnson GD, Capparella AP & Loew SS (2012). A forensic investigation into the etiology of bat mortality at a windfarm: barotrauma or traumatic injury? *Veterinary pathology,* 49(2):362-371.

Román PR, Salinas CO & Araújo BM (2020). Assessing the effect of windfarms in fauna with a mathematical model. *Scientific Reports,* 10(1):1-11.

Schaub M (2012). Spatial distribution of wind turbines is crucial for the survival of red kite populations. *Biological Conservation,* 155:111–118.

Smith EP, Orvos DR & Cairns Jr J (1993). Impact assessment using the before-after-control-impact (BACI) model: concerns and comments. *Canadian Journal of Fisheries and Aquatic Sciences,* 50(3):627-637.

Terrill S, Howell J, Smith J, Zirpoli J, Wolf K, Lindke K & Watt S (2018). Evaluating a commercial-ready technology for raptor detection and deterrence at a wind energy facility in California. Report by H.T. Harvey & Associates; for American Wind Wildlife Institute (AWWI).

Thaxter CB, Buchanan GM, Carr J, Butchart SHM, Newbold T, Green RE, Tobias JA, Foden WB, O'Brien S & Pearce-Higgins JW (2017). Bird and bat species' global vulnerability to collision mortality at windfarms revealed through a trait-based assessment*. Proceedings of the Royal Society B: Biological Sciences,* 284 (1862), 20170829.

Velilla E, Collinson E, Bellato L, Berg MP & Halfwerk W (2021). Vibrational noise from wind energy-turbines negatively impacts earthworm abundance. *Oikos,* 08166.

Zwart MC, Dunn JC, McGowan PJK & Whittingham MJ (2016). Windfarm noise suppresses territorial defense behavior in a songbird. *Behavioral Ecology,* 27(1):101–108.