Knowledge synthesis

The effectiveness of measures and good practices in place for minimizing the impact of onshore wind power on biodiversity.

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EXECUTIVE SUMMARY

Background

With the current climate crisis, switching to renewable energy sources has become essential to limit greenhouse gas emissions. Onshore wind power, a rapidly growing sector, plays an important part in this transition. However, its rapid development poses a number of environmental issues, including its negative impact on flying species. These impacts include the collision of birds, bats and insects with wind turbines, changes in animal behaviour, and disruption of local ecosystems.

Objectives

The French Foundation for Biodiversity Research (FRB), in collaboration with the Mirova Research Center, conducted a Rapid Review (RR) of the literature to assess the effectiveness of solutions and measures for minimizing the impact of onshore wind power on aerial biodiversity (birds, bats, and insects). The aim was to formulate strategic and operational recommendations based on scientific data, in order to improve existing practices and promote effective solutions to reduce the negative impacts of onshore wind power on wildlife. This publication presents a synthesis of these recommendations, targeting three major audiences: the scientific community, policy makers, and wind power operators. These proposals aim to reconcile the imperatives of the energy transition with the need to conserve biodiversity and flying species in particular.

Methods

A literature review was conducted following the standards and guidelines of the *Collaboration for Environmental Evidence* (the benchmark for evidence syntheses in ecology) for Rapid Reviews. Bibliographic references included scientific (academic literature) and technical articles, as well as reports from databases and specialized websites (grey literature). The collected data were analyzed qualitatively and quantitatively using narrative and statistical approaches to assess the effectiveness of mitigation measures.

Overview of the selected studies and publications

After conducting an objective, standardized and rigourous selection process, 60 relevant documents were retained. We assessed the reliability of the studies: most (83.6 %) were found to be reliable, with a low or moderate risk of error or imprecision. However, around 16.3 % of studies presented a high risk of error.

The selected documents highlighted the following key elements:

- Studies were primarily undertaken in North America (around 70 %) and Western Europe (more than 25%), while other parts of the world were underrepresented.
- Only one document from the list came from France.
- Bats and birds are the most frequently studied taxa, representing 60.6 % and 25.4 % of the bibliographic references, respectively. Insects are clearly underrepresented, being studied in only 5.6 % of the references.
- For bats, the most studied measures were ultrasonic acoustic deterrence and increasing the turbine cut-in speed (the wind speed at which the turbine blades start rotating).
- For birds, the most frequently studied measures involved adjusting turbine curtailment strategies and painting the turbines.
- Most studies were conducted *in situ* on wind farms (72.1 % of the references). *Ex situ* studies, either in a laboratory or in a natural environment without wind turbines, represented 27.9% of the references.
- *In situ* studies focused mainly on two types of results: the activity and mortality of affected species. Mortality is the most frequently reported (68.4 % of case studies).

In general, the measures for mitigating the impact of wind turbine on wildlife included a variety of approaches that were adapted to different contexts. Among these measures were:

- The **prediction of mortality** using models;
- **Micro-siting** and **macro-siting**, which optimize the location of wind turbines;
- Different modes of **curtailment**: increasing the cut-in speed, adjusting blade orientation, shutting down specific turbines, and integrating new technology;
- Different types of **deterrents**: ultrasonic, acoustic + light, mid-frequency acoustic, radar, and UV light;
- Structural modifications, such as **varying the rotor diameter**, applying different **paints,** or applying a **textured coating**;
- Global strategies such as **wind farm repowering** or the **elimination of ecological factors that attract species**;
- Finally, the effect of **aviation warning lights** was assessed.

Results of the meta-analysis

- Only one measure, curtailment by increasing the cut-in speed, could be included in the meta-analysis. The main obstacles to including more measures were: the small number of studies available for each measure, thus limiting statistical power, as well as the heterogeneous nature of the data.
- Results of the meta-analysis showed that when the cut-in speed was higher, the number of bats killed decreased significantly, with an average reduction of **66.8 %** compared to turbines with lower cut-in speeds.
- However, when we examined other factors such as the difference in cut-in speed or climate conditions, we did not find any significant effect.
- Due to the small number of studies available and the heterogeneity of the data, more primary research is need to confirm and clarify these results.

Summary of the narrative synthesis on the effectiveness of mitigation measures (full species names given in Annex I)

The decision to apply a measure must be taken on a case by case basis, taking into account the specificity of the project and the environment, and after comprehensive assessment of the project. Moreover, more research is needed on local species in France, as most of the scientific data available come from species that do not occur in France, especially bat species.

Measure	Description	Taxonomic Group	Reference / Risk of bias / Page number	Species	Country / Environmental context	Efficacy level *(Selon la conception et les objectifs de l'étude, certaines études fournissent des résultats détaillés, d'autres des résultats plus succincts. Cela explique également pourquoi des résultats contrastés peuvent apparaître au sein d'une même étude ou entre différentes études)*	Conclusion
Mortality prediction	Model developed to assess the risk of bird collision with wind turbines.	Birds	*Smales et al., 2013* Weak (p. 32)	* White-bellied sea eagle * Tasmanian wedge-tailed eagle	*Tasmania* Coastal area	With a 95 % avoidance rate, the difference between estimated (based on a predictive model that estimates the number of birds likely to die from collision) and observed (the actual number of bird carcasses near turbines) mortality rates ranged between **0 and 0.4**. The model thus accurately predicts bird mortality caused by wind turbines.	These promising results are too preliminary for the effectiveness of this measure to be evaluated within the framework of this review; more studies are needed.
Micro-siting et macro-siting	Optimization of the precise location of wind turbines within a given area, taking into account local factors such as landscape attributes, wind direction and environmental impact to maximize energy production and minimize disturbance.	Bats	*Million et al., 2015* Weak (p. 32)	* Pipistrelles * Serotines * Noctules * Long-eared bats * Mouse-eared bats	*France* Intensely farmed landscapes	* Increased activity of the *Plecotus -Myotis* group in the presence of fallows. * Increased activity of the *Pipistrellus* and *Eptesicus -Nyctalus* groups in the presence of hedgerows. * Increased activity of the *Eptesicus -Nyctalus* group in the presence of grass strips.	These promising results are too preliminary for the effectiveness of this measure to be evaluated within the framework of this review; more studies are needed.
		Birds	*Smallwood & Thelander, 2005* Strong (p. 32)	Raptors: * Golden eagle * Red-tailed hawk * American kestrel * Burrowing owl * Barn owl * Great horned owl (*Bubo virginianus*)	*USA* Mountain landscape with pastures	* Mortality rates were **1.5 to 3 times** higher when turbines were located in canyons. * Mortality rates were **2.79 to 12 times** higher when turbines were located near rock piles.	
Curtailment by raising the cut-in speed	This measure consists in raising the minimal wind speed at which turbines start generating power and connect to the electricity network. Below this threshold, blades remain static or turn slowly.	Bats	*Brown & Hamilton, 2006* Moderate (p. 33)	Global analysis	*Canada* Agricultural landscape	Mortality rate reduced by **32 %** when cut-in speed was raised from 4 to 7 m/s.	Turbine curtailment by raising the cut-in speed is an effective method for reducing bat mortality, with a decrease ranging from **32 to 82 %** depending on local
			Arnett et al., 2011 Weak (p. 33)	Global analysis	*USA* Forested landscape and open prairies	Mortality rates reduced by **82 %** in 2008 and **72 %** in 2009 with curtailed turbines (5 or 6.5 m/s cut-in speeds) compared to fully operational turbines (no cut-in speed) (**no significant difference** between 5 and 6.5 m/s cut-in speeds).	

			Stantec Consulting Ltd, 2012 Moderate (p. 33)	Global analysis	*Canada* Unspecified	Mortality rates **two times** lower with curtailed turbines (4.5 or 5.5 m/s cut-in speeds) compared to fully operational turbines (no cut-in speed) (**no significant difference** between 4.5 and 5.5 m/s cut-in speeds).	conditions, landscape and the adjustment made.
			Măntoiu et al., 2020 Moderate (p. 33)	Global analysis	*Romania* Pastures	Mortality rate reduced by **78 %** when cut-in speed raised from 4 to 6.5 m/s.	
			Bennett et al., 2022 Weak (p. 33)	Global analysis	*Australia* Prairies and pastures	* Mortality rate reduced by **54 %** when cut-in speed was raised from 3 to 4.5 m/s. * **Inconclusive** results for bat activity.	
			Good et al., 2022 Weak (p. 34)	Global analysis	*USA* Agricultural and forested landscape, wetlands	Mortality rates reduced by **50 %** when cut-in speed was raised from 3 m/s all year round to 3.5 m/s in spring and 5.0 m/s in autumn.	
			Baerwald et al., 2009 Moderate (p. 34)	* Hoary bat * Silver-haired bat	*Canada* Pastures	* Mortality rate reduced by **57.5 %** when cut-in speed was raised from 4 to 5.5 m/s for all species combined. * **Inconclusive** results for individual species.	
Curtailment by blade feathering	This measure consists in adjusting the orientation of the blades so that they are parallel to the wind. This slows down or stops blade rotation. In operation, blades are always perpendicular to the wind to maximize their efficiency.	Bats	*Baerwald et al., 2009* Moderate (p. 34)	* Hoary bat * Silver-haired bat	*Canada* Pastures	Mortality rate reduced by **60 %** when the blade angle was adjusted for wind speeds below 4 m/s.	Adjusting the blade angle is partially effective for reducing bat mortality, with rate reductions ranging between **0 % and 60 %** depending on local conditions and the adjustments made.
			Young et al., 2011 Weak (p. 34)	Global analysis	*USA* Forested landscape	* Mortality rate reduced by **47 %** when the blade angle was adjusted for wind speeds below 4 m/s during the first half of the night. * **Inconclusive** results when the blade angle was adjusted for wind speeds below 4 m/s during the second half of the night.	
			Schirmacher et al., 2020 Very weak (p. 34)	Migratory bats: * Hoary bat * Eastern red bat * Silver-haired bat	*USA* Agricultural landscape	* Mortality rate reduced by **0 to 38 %** when when the blade angle was adjusted for wind speeds below 5 m/s for all species combined. * **Inconclusive** results for individual species.	
Adjustment of curtailment strategies	Increasing the cut-in speed at different times of the night	Bats	*Hein et al., 2013* Moderate (p. 34)	Global analysis	*USA* Forested landscape	* Mortality rate reduced by **47 %** when cut-in speed was raised from 3 to 5 m/s for the whole night. * **Inconclusive** results when cut-in speed was raised from 3 to 5m/s for the first four hours past sunset.	Different adjustment and curtailment strategies produce variable but globally promising effects for reducing bat mortality, with a reduction rate ranging from **47 to 100 %** depending on the context and method used.
	Increasing cut-in speed depending on temperature		*Martin et al., 2017* Weak (p. 34)	Global analysis	*USA* Forested landscape with rivers	Mortality rate reduced by **62 %** when cut-in speed was raised from 4 to 6 m/s when nightly temperatures were above 9.5°C.	
	* Fully feathered blades until wind speed reached 5.0 m/s based on a 10-minute rolling average as measured at a nearby meteorological tower (treatment A). * Fully feathered blades until wind speed reached 5.0 m/s based on a 20-		*Schirmacher et al., 2018* Very weak (p. 35)	Global analysis	*USA* Forested landscape	* **Inconclusive** results between treatment A and B, and treatment A and C. * Mortality rate reduced by **81 %** between treatment C and B (C having the higher mortality rate).	

	minute rolling average as measured at a nearby meteorological tower (treatment B). * Fully feathered blades until wind speed reached 5.0 m/s based on a 20-minute rolling average as measured from anemometers on individual turbines (treatment C).						
	Turbine curtailment based on critical wind speed thresholds varying from 5.0 to 6.5 m/s, defined as the wind speed above which less than 1 % of total bat activity occurs based on previous observations.		*Rnjak et al., 2023* Weak (p. 35)	Global analysis	*Croatia* Prairie and mediterranean scrubland	Mortality rate reduced by **78 %**.	
	Complete shutdown during migration periods.	Bats and birds	*Smallwood & Bell, 2020* Moderate (p. 35)	Global analysis	*USA* Agricultural and mountain landscapes	* Mortality rate reduced by **100 %** for bats. * **Inconclusive** results for birds.	
Selective shutdown	Selected turbines are shut down when a dangerous situation for medium to large birds is detected. Detection, carried out by an observer on site every day of the year from dawn to dusk, was implemented for 10 % of turbines (the most dangerous) during the migratory period. .	Birds	*De Lucas et al., 2012* Moderate (p. 35)	Griffon vulture	*Spain* Unspecified	Mortality rate reduced by **50 %** over two years.	Selective shutdown is significantly effective in the context of a single project, bird mortality reduced by **50 % over two years to 92.8 % over 14 years**. These promising results highlight the importance of conducting additional research to assess the durability of this approach and its applicability on a large scale.
		Birds	*Ferrer et al., 2022* Moderate (p. 35)	Griffon vulture	*Spain* Unspecified	Mortality rate reduced by **92.8 %** over 14 years.	
Curtailment using smart technology	Smart curtailment, integrating bat activity and wind speed data, triggered for wind speeds < 8 m/s, thus allowing making targeted decisions in real-time.	Bats	*Hayes et al., 2019* Moderate (p. 36)	* Eastern red bat * Hoary bat * Silver-haired bat * Big brown bat * Little brown bat	*USA* Agricultural and forested landscape, wetlands	Relative to control turbines, mortality rates were reduced by: * pooled data : **84.5 %** * eastern red bat: **82.5 %** * hoary bat: **81.4 %** * silver-haired bat: **90.9 %** * big brown bat: **74.2 %** * little brown bat: **91.4 %**	Smart curtailment reduced bat mortality by between **74.2 to 91.4 %** depending on the species and the study. However, because some results are inconclusive, additional research is needed to confirm the effectiveness of these methods and optimize their application.
			Rabie et al., 2022 Weak (p. 36)	Global analysis	*USA* Agricultural and forested landscape	Mortality rate reduced by **75 %** compared to control turbines with a 3.5 m/s cut-in speed	
	Smart curtailment using acoustic sensors to detect the presence of bats in		*Rodriguez et al., 2023*	Global analysis	*USA* Unspecified	**Inconclusive** results	

	real-time and adjust the cut-in speed accordingly (without taking wind speed into account).		Strong (p. 36)				
	Implementing automated curtailment using cameras and algorithms to detect and identify birds in flight.	Birds	*McClure et al., 2021* Moderate (p. 36)	* Golden eagle * Bald eagle	*USA* Unspecified	* **63 %** reduction in mortality rate at the treatment site with intervention. * **82 %** reduction in mortality rate at the treatment site relative to the control site.	
	Criticism of McClure et al., 2021/new analysis of their data.	Birds	*Huso & Dalthorp, 2023* Very weak (p. 37)	* Golden eagle * Bald eagle	*USA* Unspecified	**Inconclusive** results	
Ultrasound acoustic deterrence	Ultrasounds emitted by devices fitted on turbines, affecting the ability of bats to use echolocation, to deter bats away from high-risk collision areas.	Bats	*Spanjer, 2006* Moderate (p. 37)	Big brown bat	*USA* In captivity	Activity reduced by **92.4-100 %** depending on the test.	Ultrasonic acoustic deterrence leads to a reduction in bat activity ranging from **30-100 %**. Results on real bat mortality in natural environments also vary greatly, with reductions ranging from **21 to 78.4 %** depending on the study and the species, certain studies being **inconclusive** or even finding an **increase** in mortality for certain species. This variation highlights the need for additional research in order to optimize the effectiveness of this method, that take into account different contexts, species and technical configurations.
			Szewczak & Arnett, 2006 Moderate (p. 37)	Global analysis	*USA* Ponds	No turbines on the test site: activity reduced by **50 %** with the device.	
			Szewczak & Arnett, 2007 Strong (p. 37)	Global analysis	*USA* Ponds	No turbines on the test site: activity reduced by **90-~100 %** with the device.	
			Horn et al., 2008 Moderate (p. 38)	Global analysis	*USA* Agricultural and forested landscape	* Activity reduced by **46.3 %** during the first test period with the device. * **Inconclusive** results for the second test period.	
			Arnett et al., 2013 Very weak (p. 38)	* Hoary bat * Silver-haired bat	*USA* Mountain and forested landscape	2009 * Overall mortality rate per turbine reduced by **21-51 %** with the device * Mortality rates in hoary and silver-haired bats reduced by **50 %** with the device. 2010 * Variation in overall mortality rate ranging from **+2 % to -64 %** with the device. * **50 %** mortality rate reduction in hoary bats and **75 %** in silver-haired bats with the device.	
			Lindsey, 2017 Weak (p. 38)	Migratory bats: * Hoary bat * Eastern red bat * Silver-haired bat	*USA* Pastures with woodland areas	2015 * Activity rate reduced by **80 %** near ponds when deterrent placed at 10m compared to 30m. * Activity rate reduced by **75 %** near turbines when deterrent placed at 10m compared to 30m. * **Inconclusive results** for for bat activity near turbines. * **Inconclusive results** for bat responses to different types of ultrasonic signals (continuous or pulsed). 2016	

						With the deterrent device, activity was reduced by **91 %** in spring, **84 %** in summer, **72 %** in autumn	
			Romano et al., 2019 Very weak (p. 38)	Migratory bats: * Hoary bat * Eastern red bat * Silver-haired bat	*USA* Agricultural and forested landscape, developed areas and wetlands	<u>2014</u> Deterrents mounted on nacelles and towers, continuous signal: * Overall mortality rate reduced by **29.18 %** * Mortality rate reduced by **25.98 %** in hoary bats, **38.66 %** in silver-haired bats, **inconclusive** for eastern red bats. <u>2015</u> Deterrents mounted on towers only: * Overall mortality rate reduced by **32.50 %.** * Mortality rate reduced by **35.89 %** in hoary bats, **56.93 %** in silver-haired bats, **inconclusive** for eastern red bats. <u>2016</u> Deterrents mounted on nacelles and towers, pulsed signal: * **Inconclusive** results for all species combined. * Mortality rate reduced by **72.90 %** in silver-haired bats, **inconclusive** for the other species.	
			Kinzie et al., 2019 Weak (p. 38)	* Eastern red bat * Evening bat * Brazilian free-tailed bat	*USA* Unspecified	<u>2015</u> Continuous signal: * mortality rate reduced by **56 %** for all species combined (excluding eastern red bats) and **inconclusive** for eastern red bats. <u>2016</u> Pulsed signal before the installation of dehumidifiers: * mortality rate reduced by **38 %** for all species combined (excluding eastern red bats) and **inconclusive** for eastern red bats. <u>2016</u> Pulsed signal after the installation of dehumidifiers: * **inconclusive** for all species combined (excluding eastern red bats) and for eastern red bats.	
			Weaver et al., 2020 Weak (p. 39)	* Hoary bat * Brazilian free-tailed bat * Northern yellow bat	*USA* Agricultural landscape and prairies	* Overall mortality reduced by **50 %.** * Mortality reduced by **78.4 %** in hoary bats, **54.5 %** in Brazilian free-tailed bats and **inconclusive** for northern yellow bats	
			Gilmour et al., 2020 Moderate (p. 39)	* Common pipistrelle * Soprano pipistrelle	*England and Wales* Riparian landscape	* Overall activity reduced by **80 %.** * Activity reduced by **40-80 %** in common pipistrelles and **30-60 %** in soprano pipistrelles, depending on the site.	
			Schirmacher et al., 2020 Very weak (p. 39)	Migratory bats: * Hoary bat * Eastern red bat * Silver-haired bat	*USA* Agricultural landscape	* **Inconclusive** results for all species combined. * Eastern red bat mortality **1.3 to 4.2 times** higher with deterrent. * **Inconclusive** results for all other species.	

			Cooper et al., 2021 Strong (p. 39)	Global analysis	*USA* Mountain and forested landscape	**Inconclusive** results between treatment and control turbines, probably due to technical issues.	
Combined measures: curtailment and acoustic deterrence	Curtailment by raising the cut-in speed or by blade feathering combined with ultrasonic acoustic deterrence.	Bats	*Good et al., 2022* Weak (p. 39)	* Hoary bat * Silver-haired bat * Eastern red bat	*USA* Agricultural and forested landscape, developed areas and wetlands	* Mortality rates reduced by **71.6 %** in silver-haired bats, **71.4 %** in hoary bats, and **58.1 %** in eastern red bats with combined measures comparted to control groups (3 m/s cut-in speed). * Curtailment alone reduced mortality by **14.8 %** in silver-haired bats, **65.4 %** in hoary bats, and **38.8 %** in eastern red bats.	Measures combining curtailment and ultrasonic acoustic deterrence show mixed results. Bat mortality was reduced by **11 to 99 %** depending on the species and conditions. However, results are **inconclusive** for certain species, or when species are combined, highlighting the need for additional research.
			Schirmacher et al., 2020 Very weak (p. 40)	Migratory bats: * Hoary bat * Eastern red bat * Silver-haired bat	*USA* Agricultural landscape	* **Inconclusive** results for all species combined. * Mortality rates reduced by **11 to 99 %** in silver-haired bats with a combination of curtailment and acoustic measures. * **Inconclusive** results for other species.	
Combined acoustic and light deterrents	Drone-mounted audio-visual deterrent (emitting a combination of pulsating ultrasonic and white light signals)	Bats	*Werber et al., 2023* Moderate (p. 40)	Global analysis	*Israel* Unspecified	LIDAR detection (assess the device's impact below its flight altitude): * Activity reduced by **40 %** after activation of the device. RADAR detection (assess the device's impact above its flight altitude): * Activity increased by **50 %** after activation of the device.	Bat activity decreased by **40 %** below the device's flight altitude but increased by **50 %** above its flight altitude. These results suggest that the methods need to be adjusted and additional research carried out to ensure effectiveness and minimize undesirable effects.
Mid-frequency acoustic deterrents	Exposure to four types of acoustic signals at two frequency ranges (4-6 kHz or 6-8 kHz) and two temporal modulation patterns (broadband or frequency-modulated oscillating).	Birds	*Thady et al., 2022* Weak (p. 40)	Zebra finch	*USA* In captivity	* Maintained a greater distance from hazards in the presence of acoustic signals. * Adjusted flight trajectories earlier in the presence of acoustic signals. * No difference between signals.	These promising results are too preliminary for the effectiveness of this measure to be evaluated in this review. More research is needed.
Radar deterrents	Electromagnetic fields emitted by strategically placed radars to perturb bat navigation and deter them from approaching collision risk areas.	Bats	*Nicholls & Racey, 2007* Weak (p. 40)	Global analysis	*U.K.* Forested and riparian landscape	Activity reduced on sites exposed to radars (amplitude of effect not given).	The effectiveness of radar deterrence for reducing bat activity is mixed. Activity reduction ranged from **13.3** to **30.8 %** depending on radar signal configurations, but results are often inconclusive. Additional research is needed to
		Bats and insects	*Nicholls & Racey, 2009* Moderate (p. 40)	Global analysis	*Scotland* Forested and riparian landscape	* Activity reduced by **13.3 %** with short pulse length signals. * Activity reduced by **30.8 %** with medium pulse length signals.	
		Bats	*Gilmour et al., 2020* Moderate (p. 39 et 40)	* Common pipistrelle	*England and Wales* Riparian landscape	* **Inconclusive** results for bat activity with radar alone (all species combined and for individual species).	

				* Soprano pipistrelle		* **No additional effect** when radar was combined with ultrasound, compared to ultrasound alone (all species combined and for individual species).	improve and validate the effectiveness of this method.
UV light deterrents	UV light emission from or emitted at wind turbines to make obstacles more visible to birds and bats, as many are sensitive to these wavelengths.	Birds	*May et al., 2017* Weak (p. 41)	Global analysis	*Norway* Coastal area	* Activity reduced by **27 %** with UV light. * Activity reduced by **12 %** with violet light.	UV light deterrents showed mixed results for reducing bird or bat activity. Activity was reduced by **12** to **44 %**, but side effects such as the **significant increase** in insect abundance, were observed, and various results remain **inconclusive**. More research is needed to fully understand the effectiveness of this method and its side effects.
		Bats and insects	*Gorresen et al., 2015* Moderate (p. 41)	Hawaiian hoary bat	*Hawaii* Agricultural landscape	* Activity reduced by **44 %** with UV light. * Insect abundance increase **6-fold** with UV light.	
		Bats, birds, and insects	*Cryan et al., 2022* Moderate (p. 41)	Global analysis by taxonomic group	*USA* Pastures and built landscape	* **Inconclusive** results on the nocturnal activity of bats, birds and insects. * **Inconclusive** results for bat collision risk.	
Changing the rotor diameter	Increasing or decreasing the size of the blades	Bats and birds	*Martin, 2015* Weak (p. 42)	Global analysis by taxonomic group	*USA* Forested landscapes and rivers	* **Inconclusive** results for bats between 93 and 96 m diameter rotors. * Mortality rate reduced by **54 %** in birds with the smaller rotor (93 m diameter).	These promising results are too preliminary for the effectiveness of this measure to be evaluated in this review. More research is needed.
		Birds	*Anderson et al., 2005* Moderate (p. 42)	Global analysis	*USA* Mountain and desert landscapes	Mortality rate reduced by **60 %** for birds, all species combined, and by **76 %** for raptors, but differences were not significant (inconclusive).	
Painting turbines	Base of tower painted black.	Birds	*Stokke et al., 2020* Moderate (p. 42)	Willow ptarmigan	*Norway* Open landscape	Mortality rate reduced by **48.2 %** at painted turbines.	Painting turbines, in particular painting a blade or the base of the tower black, shows promising results for reducing bird fatalities, with reductions ranging from **48.2 to 100%**. However, trials on insects show that colour has a non-negligible attractive effect. Moreover, trials using UV-reflective paint or different patterns and colours on the blades give inconclusive results,
	One blade painted black.		*May et al., 2020* Moderate (p. 42)	Global analysis + white-tailed eagle	*Norway* Open landscape	* Overall mortality rate reduced by **71.9 %** for turbines with a black blade. * Willow ptarmigan mortality reduced b y **100%.**	
	Blades coated with UV-reflective paint.		*Erickson et al., 2003* Weak (p. 42)	Global analysis + by bird group (raptors, passerines, corvids, etc)	*USA* Prairie, woodland, shrubland and rivers	**Inconclusive** results for mortality rates for all species combined and by group of birds.	
	Blades painted with stripes or uniformly with different colours, assessed against different natural backgrounds and at different rotation speeds.		*Hodos, 2003* Strong (p. 43)	American kestrel	*USA* In captivity	* Blades with thin stripes were **4 times** more visible than blank blades. * Uniformly black blades were more visible against diverse backgrounds than red, green or blue blades, and their efficacy depended less on the background.	

	Turbine mast painted with different colours.	Insects	*Long et al., 2011* Moderate (p. 43)	Global analysis	*U.K.* Forested landscape and prairie	* Yellow, white and light grey were the most attractive to insects. * Red lilac was the least attractive.	suggesting that additional research is needed to assess the impact of these methods and for determining the best configurations to use, for both birds and insects.
Texturing turbine surfaces	Replacing the smooth surface of current turbines with textured surfaces.	Bats	*Bienz, 2016* Strong (p. 43)	Global analysis	*USA* In captivity	Number of passes reduced by **58%** with finely textured surfaces compared to smooth surfaces, **inconclusive** for coarsely textured surfaces.	These promising results are too preliminary for the effectiveness of this measure to be evaluated within the framework of this review; more studies are needed.
			Huzzen, 2019 Moderate (p. 43)	Global analysis	*USA* Agricultural and forested landscape	**Inconclusive** results for activity.	
Wind farm repowering	Replacement of one-bladed turbines with three-bladed turbines.	Bats	*Ferri et al., 2016* Weak (p. 44)	Analysis of bat assemblages	*Italy* Mountain landscape with pastures	Changes in the composition of bat assemblages: relative decrease of Geoffroy's bat (*Myotis emarginatus*) and increase of the common pipistrelle.	These promising results are too preliminary for the effectiveness of this measure to be evaluated within the framework of this review; more studies are needed.
	Replacement of vertical-axis turbines with a smaller number of three-bladed turbines.	Birds	*Smallwood & Karas, 2009* Strong (p. 44)	Global analysis	*USA* Mountain landscape with pastures	* **Inconclusive** results between old and new turbines. * Mortality rates reduced by **54%** for raptors, and **66%** for all birds combined at new-generation turbines compared to concurrently operating old-generation turbines.	
Removal of attractive ecological factors	Superficial tilling around turbines to clear natural vegetation.	Birds and insects	*Pescador et al., 2019* Strong (p. 44)	Lesser kestrel	*Spain* Agricultural landscape	* Mortality rate for lesser kestrels reduced by **75 %**, **82.8 %**, and **100 %** depending on the site. * Relative abundance of insects reduced by **72.6 %** for orthoptera, **56.3 %** for lepidoptera, and **68.0 %** for coleoptera.	These promising results are too preliminary for the effectiveness of this measure to be evaluated within the framework of this review; more studies are needed.
	Use of chlorophacinone, an anticoagulant rodenticide, to reduce ground squirrel and gopher populations around turbines.	Birds	*Smallwood & Thelander, 2005* Strong (p. 45)	Raptors Corvids Passerines	*USA* Mountain landscape with pastures	Behavioural changes observed in raptors, corvids and passerines in treated plots: * Longer flight times in these plots. * Longer perching times in these plots.	
	Regular clearance of ground vegetation above 10 cm.		*Shewring & Vafidis, 2017* Strong (p. 45)	European nightjar	*Wales* Forested landscape	**Inconclusive** results on activity rate between cleared and uncleared areas.	
Aviation warning lights	Impact of red flashing Federal Aviation Administration (FAA) lights fitted to wind turbines.	Bats and birds	*Martin, 2015* Weak (p. 45)	Global analysis by taxonomic group	*USA* Forested landscape with rivers	**Inconclusive** results on mortality rates between with and without FAA lighting.	These promising results are too preliminary for the effectiveness of this measure to be evaluated within the framework of this review; more studies are needed.
	Impact of fixed or flashing lights, and different coloured lights.	Birds	*d'Entremont, 2015* Moderate (p. 45)	Nocturnal migratory birds	*Canada* Mountain landscape	* Blue and green colours more attractive to nocturnal migratory birds. * Higher flight altitude with red or while light compared to no light. * Lower flight altitude in the absence of light compared to with flashing lights.	

Elaboration of recommendations

The recommendations presented here are the result of a double approach for improving the effectiveness of measures for minimizing the impact of onshore wind power on biodiversity. On the one hand, a rapid review was conducted to summarize the state of scientific and technological knowledge, highlighting current practices, scientific advances and knowledge gaps. On the other hand, a collaborative workshop was organized for members of the scientific community, the wind power sector, and government agencies. This workshop allowed attendees to discuss the results of the review, and allowed us to gather their different perspectives with the aid of a questionnaire. This approach ensured that recommendations were based on both scientific data and the practical experience of those working the sector.

Recommendations for developers and project operators

Section	Recommendation	Specific actions
Integration of mitigation technology and innovations	Use combined strategies	- Combine curtailment and other measures to maximize the reduction of bird and bat mortality.
	Adopt new technology	- Adopt technologies and specific systems such as curtailment, deterrence, AI-powered detection systems.
	Specific paints and textures	- Test the application of specific paints on turbines to improve visibility and reduce bird collision risk. - Test the application of specific textures on towers to reduce the risk to bats.
	Integrated systems of environmental management	- Put systems in place for adjusting turbine operation in real time, in response to environmental conditions.
Planning and ecological design	Planning and ecological design	- Consider all potential impacts at the start of the planning process to choose sites that cause the least ecological disturbance. - Develop innovative designs to reduce the visual and acoustic impact of wind turbines.
	Use predictive models	- Use models that predict collision risk during the planning stage.
Environmental management and monitoring	Management of environmental factors	- Implement measures that are tailored to local conditions, taking into account their potential impact on local ecosystems. - Prefer integrated and sustainable solutions to preserve the integrity of local ecosystems.
	Monitoring and assessment	- Put post-installation environmental monitoring programmes in place to assess and adjust mitigation measures. - Homogenize monitoring protocols to ensure that data are comparable across different contexts.
Collaboration and data sharing	Collaboration and data sharing	- Promote the sharing of research data and retrospective experience reports. - Contribute to the development of a standardized database where all reports and data can be deposited, in order to make it easier to conduct global analyses. - Publish data on impact and effectiveness with abstracts and keywords in English. - Collaborate with researchers and government agencies to improve practices.
Community involvement	Community involvement	- Involve local communities in the planning stage. - Be transparent in your communication, and promote the active participation of communities in both project planning and post-installation environmental monitoring.

Recommendations for the scientific community

Section	Recommendation	Specific actions
Mitigation technology research and development	Optimization of acoustic devices for bat deterrence	- Fine-tune acoustic deterrence methods by conducting more research, in particular to assess their negative impact over the long term.
	Development of multimodal methods and the use of radars	- Test the effectiveness of radars as a means of deterrence. - Combine acoustic signals with other methods to improve effectiveness.
	New ways of using UV lighting	- Improve UV lighting systems by conducting more research. - Assess the possible ecological impacts, such as attracting insects.
	Improve turbine visibility with paints	- Assess the effectiveness of paints (colour, motifs, where to apply on the turbine).
	Texturing turbine towers	- Improve the type of texture used by conducting more research.
Studies on the impacts on biodiversity and ecosystems	Research on insects	- Determine the direct and indirect impact of mitigation measures on insects. - Develop measures that minimize the impact of wind power on insects.
	Impact of wind farm repowering	- Assess the impact of wind farm repowering on wildlife over the long term.
	Environmental rehabilitation of wind power sites	- Develop optimal practices for the rehabilitation of decommissioned sites. - Assess the effectiveness of restoration measures on biodiversity.
Modelling, prediction and decision-making tools	Develop models for predicting risk	- Create and improve collision risk models, and use the results in the decision-making process.
	Project planning tools	- Design tools for planning projects that are less harmful to biodiversity. - Work with regulators to include these models in the planning process.
Standardized methods and data sharing	Develop standard protocols	- Standardize study protocols to allow the comparison of data.
	Promote data sharing and accessibility	- Foster data sharing in the scientific community. - Use standardized databases to make it easier to carry out global analyses.
International and interdisciplinary collaboration	Strengthen interdisciplinary collaborations	- Foster interdisciplinary research projects.
	International partnerships	- Collaborate with scientists from parts of the world where there are less studies. - Share knowledge to fill local knowledge gaps.
	Interact with operators and policy-makers	- Work with operators to implement scientific recommendations. - Assist the science-to-policy process by being members of committees and working groups.
New methods and technology	Develop new research methods	- Create new methods for assessing impact (drones, AI, advanced sensors).
	Integrate new technology	- Test new technologies designed to mitigate the impact of wind turbines.

Awareness and training	Knowledge dissemination	- Organize events to present recent advances and advise on best practices.
	Training of scientists	- Hire scientists to work in the field of renewable energy. - Offer interdisciplinary educational programmes to train people to become experts with a broad knowledge base.

Recommendations for government agencies

Section	Recommendation	Specific actions
Strengthen the regulation and governance framework	Clear and coordinated regulations	- Clarify regulations concerning onshore wind power. - Improve coordination between different levels of government and regulatory agencies.
Financial support for research and development	Science funding	- Use subsidies and tax incentives to promote mitigation technology research and development. - Fund research in France and in underrepresented regions (South-East Asia, Sub-Saharan Africa, South America).
Standardized methods and data sharing	Standardizing and sharing data	- Support the development of standardized protocols for data gathering and reporting. - Facilitate the creation of data sharing platforms..
Public participation and community involvement	Community involvement	- Establish a legal framework for the involvement of local communities in the project development process.
Support collaborations	Support collaborations	- Foster partnerships between the wind power sector, scientists, and local communities.
Environmental monitoring and continuous assessment	Monitoring and assessment	- Impose the implementation of post-installation environmental monitoring programmes to assess the effectiveness of the mitigation measures in place.

Combining wind power development and biodiversity conservation: towards concrete and collaborative solutions

This report makes a significant contribution to the elaboration and implementation of solutions for minimizing the impacts of onshore wind power on flying species. The recommendations listed above balance the necessary development of wind power with the imperatives of biodiversity conservation, by proposing actions that are both concrete and feasible. The implementation of these recommendations requires that those involved work closely together. It also means that efforts have to be madeto conduct more research, develop new technologies and involve local communities. By adopting an integrated approach and by following the latest guidelines for best practice, it is possible to minimize the environmental impact of wind power and still respond to current energy challenges. We strongly encourage those involved to heed these recommendations and integrate them in their practices and policies.

INTRODUCTION

The current climate crisis calls for a significant reduction in greenhouse gas emissions to mitigate the impact of climate change. According the IPCC (the Intergovernmental Panel on Climate Change), global temperatures could increase by 1.5°C by 2030, 2°C by 2050 and could reach 3°C by 2100 (IPCC, 2023). The effects of climate change are serious, affecting biodiversity, ecosystems and human well-being (IPBES, 2019). The main sources of greenhouse gas emissions are linked to human activity, notably the production of electricity from fossil fuels, which represents 42 % of global CO_2 emissions (Internal Energy Agency, 2022). The energy transition, by reducing the use of fossil fuels and developing renewable energy sources, is therefore crucial to achieve carbon neutrality by 2050, a target adopted by many countries within the framework of the Paris Agreement (UNFCCC, 2015). To reduce the use of fossil fuels beyond electricity production, it is also necessary to switch to electric wherever possible. This makes it all the more necessary to develop renewable energy production above current levels, in order to meet the growing demands for carbon-free electricity.

In parallel, businesses, in accordance with target 15 of the Kunming-Montreal Global Biodiversity Framework, need to reduce their negative impact on biodiversity, including the impact stemming from measures for mitigating climate change (target 8). Energy production, like all other human activity, needs to become more sustainable, and limit its impact on biodiversity (Decision 15/4, U.N. doc. CBD/COP/DEC/15/4 (2022), Stephen, 2023).

Wind power plays a key role in a sustainable energy transition. Worldwide, wind power has increased rapidly over the past decades, becoming a major feature of the energy plan of many countries (REN21, 2021). In France, the total electricity production capacity of wind farms has been multiplied by three in the last decade, reaching 22.2 GW in 2023 (French Directorate General of Energy and Climate (DGCE), 2023). In France's multiannual energy plan (PPE), the capacity of onshore wind farms will be increased to between 33.2 and 34.7 GW by 2028, illustrating the important part wind power plays in France's national energy strategy (French Ministry of Ecological Transition and Solidarity, 2022). Onshore wind power is not only an alternative to fossil fuels, it is also a means to reduce the dependency on other countries for energy and diversify energy sources. However, the rapid and intense development of so-called "renewable" energy sources needs to involve a comprehensive assessment of their impact on biodiversity, so that this development complies with target 8 of the Global Diversity Framework, which states that it is crucial to "increase [the] resilience [of biodiversity] by mitigation, while minimizing negative and fostering positive impacts of climate action on biodiversity".

Despite its advantages, wind power poses environmental challenges, notably by impacting wildlife. Wind farms can have detrimental effects on natural habitats and species (Perrow, 2017). Among the most worrying impacts are collisions of birds and bats with rotor blades and turbine masts, resulting in fatalities (Smallwood, 2013). Studies have shown that collisions can be frequent in certain areas, and that this frequency can vary greatly depending on the bird or bat population density, local environmental conditions, species' flight behaviour, as well as turbine and wind farm characteristics (Marques *et al.*, 2014; Thaxter *et al.*, 2017). In addition to collisions, bats are also susceptible to barotrauma caused by the rapid drop in air pressure near moving turbine blades, resulting in serious and often lethal internal injuries (Baerwald *et al.*, 2008). The installation and operation of wind farms can also affect natural habitats. The construction of wind power infrastructure often requires land clearing, which leads to the destruction or degradation of natural habitats. These activities can lead to habitat fragmentation, reducing the areas available for different species for breeding, feeding and resting (Rodríguez *et al.*, 2013). The noise generated by wind turbines, but also their imposing presence in the landscape may trigger an avoidance response over more or less long distances in many species (Marques *et al.*, 2021). Moreover, wind turbines can generate local microclimate disturbances, such as decreasing soil moisture, affecting local plant and animal communities (Kaffine, 2019; Wu & Archer, 2021).

The impact of wind turbines varies considerably depending on the species. Large birds, such as raptors, and bats are particularly vulnerable to collisions due to their flight behaviour, long lifespan and low reproductive rates (Madders & Whitfield, 2006; Thaxter *et al.*, 2017). Some species, such as the griffon vulture in Spain, suffer particularly high collision rates due to their flight behaviour in certain regions (de Lucas *et al.*, 2008). The location of wind farms also plays a crucial role in the extent of their impact. Sites located on bird migration routes (Masden *et al.*, 2009) or near important natural habitats for bats (Christine *et al.*, 2023) can lead to high collision rates (Desholm & Kahlert, 2005). Moreover, local characteristics, such as wind conditions and topography, can influence species behaviour and their interaction with wind turbines (Cryan & Barclay, 2009). Insects, although much less well studied, are also affected by these installations, with possible repercussions on the food chains and ecosystemic processes they belong to (Weschler, 2023). These interactions highlight the need to understand and minimize the negative impacts of onshore wind power on aerial biodiversity. A review of these impacts has been published by the FRB in 2024.

Wind farms, being Classified Installations for the Protection of the Environment (*Installations classées pour la protection de l'environnement* (ICPE)), are subject to specific environmental obligations. The planning and regulation framework for minimizing the environmental impact of wind power projects in France aims to guarantee the harmonious coexistence of renewable energy development and biodiversity conservation. One of the main tools of this framework is the Strategic Environmental Assessment (SEA), which is required for projects that have a significant impact on the environment (Ademe, 2024; French Ministry of Ecological Transition and Territorial Cohesion, 2023). This assessment ensures that environmental concerns are identified at the start of the planning process, listing potential impacts and suggesting mitigation measures. Environmental Impact Assessments (EIA) are also mandatory for each project, in order to assess more specifically its impact on species and natural habitats (Sénat, 2009). Furthermore, wind power projects need to comply with different legislations, such as energy legislation, planning legislation and environmental legislation. These laws impose strict procedures for authorizing projects, including public consultations and in-depth environmental investigations. Environmental legislation also requires specific measures for the conservation of species and sensitive habitats (French Ministry of Ecological Transition and Territorial Cohesion, 2024).

The "avoid-reduce-compensate" approach is fundamental for managing the environmental impacts of development projects, including wind power projects (Bennett, 2016). At the start of the process, spatial planning plays a crucial role to ensure that wind farms are not built in sensitive areas for biodiversity, such as nesting grounds or migration corridors (Thaxter *et al.*, 2017). This first step in the mitigation hierarchy involves avoiding negative impacts by carefully selecting the sites where wind farms will be built. By avoiding sensitive areas, developers can significantly reduce the risk of collision and habitat disturbance (Perrow, 2017). However, in France, spatial planning in relation to the development of onshore wind power has never really been implemented. Only recently have these considerations started to be included in future projects. When impacts cannot be avoided entirely, mitigation strategies are put in place. The curtailment of turbine activity, including rotor speed adjustment or temporary shutdown during periods of high animal activity, are effective (Adams *et al.*, 2021; Smallwood & Bell, 2020). Among other available mitigation measures, there is also: optimizing the position of the turbines to minimize collision risk, adjusting when turbines operate to avoid periods of high activity of sensitive species, and using detection and deterrent technology for birds and bats. For instance, ultrasonic devices can be used to deter bats away from dangerous areas (Weaver *et al.*, 2020), and radar-assisted detection systems can temporarily shut down turbines when birds are detected nearby (Tomé *et al.*, 2017). When negative impacts persist despite the implementation of mitigation measures, compensation measures are taken. This can include the restoration of degraded habitats elsewhere, the creation of new habitats, or funding conservation programmes for the affected species. These measures tend to compensate for biodiversity loss by improving the state of habitats and populations elsewhere (Perrow, 2017).

A number of guidebooks and recommendations have been published covering different aspects of wind power project planning, development and delivery. These documents clarify the legal framework and offer detailed technical advice. They help developers apply the avoid-reduce-compensate sequence and integrate environmental considerations into the planning and management process (Dreal Hauts-de-France, 2017, IUCN French Committee, 2023). Nonetheless, there is a need for a rigourous assessment of the effectiveness of the different mitigation measures available.

MAIN OBJECTIVE OF THE REVIEW

The French Foundation for Biodiversity Research (FRB) decided to carry out a review of the scientific and technical literature on the effectiveness of the measures for reducing the impact of onshore wind farms on aerial species. This project is part of a larger programme funded by the Mirova Research Centre, which aims to encourage sustainable and responsible practices within the green energy sector. Its objective is to determine the effectiveness of each mitigation measure, as documented by scientific research, in order offer guidance to those involved in the wind power sector (government agencies, regulators, project developers and operators) for improving their practices. The project aims to provide operational recommendations based on solid scientific evidence for optimizing the development and operation of wind farms while minimizing their impact on the environment.

This programme relies on the close collaboration between different specialists and has three complementary areas of activity. First, it involves the production of scientific knowledge syntheses, including updates of previously published syntheses, on the impact of renewable energy – onshore wind power, offshore wind power, and solar power – on biodiversity, as well as three review papers on the effectiveness of the measures in place for minimizing these impacts. Second, it offers research funding opportunities: four innovative projects that will provide new knowledge on this topic have recently been funded. Finally, expert-led workshops are organized to provide an opportunity for scientists, government agencies, regulators, project developers and operators to meet. These workshops aim to foster dialogue, inspire new ideas and optimize biodiversity conservation practices.

This programme stands out by its use of an integrated and holistic approach for tackling the environmental challenges posed by the development of renewable energy. The impacts of the main technologies (onshore and offshore wind power, solar power) are reviewed based on rigourous scientific evidence in order to propose effective mitigation measures. Moreover, by funding innovative research, the programme demonstrates its commitment to the production of new knowledge.

The FRB, in association with the Mirova Research Centre, is responsible for providing a synthesis (a "rapid review") of the interactions beween wind power development and biodiversity. The programme's scientific committee has steered this review towards a review of the academic and technical literature on the effectiveness of mitigation measures and the good practices put in place to minimize the impact of onshore wind power on aerial species, *i.e.* birds, bats and insects. Rapid reviews, an abridged version of systematic reviews, aim to provide relevant information in a condensed format (best practices, success, failures and knowledge gaps). This overview is essential for guiding policy and future practices, as well as for optimizing the selection of projects where financial investments will be steered toward practices that support biodiversity conservation. Therefore, the main question of this Review is the following: **"What is the effectiveness of the existing measures for mitigating the impact of onshore wind farms on aerial vertebrates and invertebrates?"** (see Figure 1). Elements of this question follow the PICO framework (Table 1).

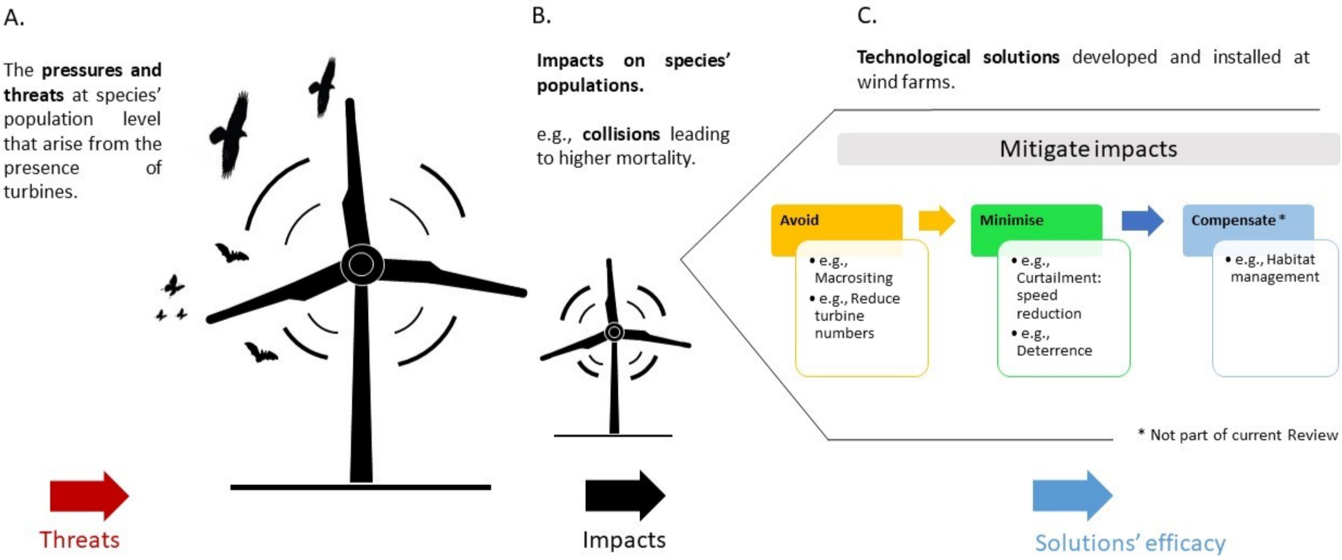

Figure 1. Diagram illustrating the conceptual theory of the review question (from Landgridge et al., 2023). A., the pressures at the species' population level, leading to; B., impacts such as collisions. C., implemented actions to mitigate the impacts of wind energy.

Table 1. Components of the Rapid Review

PICO component	**Definition**	
Population	All flying vertebrates, *i.e.* birds and bats, and flying invertebrates, *i.e.* insects.	
Intervention	All mitigation measures taken at the scale of a single wind turbine, a set of turbines, and/or a wind farm, applying the "avoid-reduce-compensate-offset" approach.	
	Avoid	Includes only "retrospective" post-construction solutions, e.g. comparing wind farm sites near semi-natural or natural habitats and non-habitats.
	Reduce	Includes technological solutions for mitigation, *e.g.* curtailment, acoustic deterrents, etc.
	Compensation	Includes solutions involving the conservation of habitats elsewhere to compensate for the loss of habitats due to turbine construction.
	Offset	Measures taken by companies to offset the negative impact of their development project.
Comparison	Spatial (*e.g.* sites where mitigation measures are in place vs. sites without any mitigation measure) or temporal (*e.g.* before and after the implementation of the mitigation measure) comparisons, known as BACI studies. These can be "before-after", "control-impact", "before-after-control-impact" studies.	
Outcome	All impacts on species' population size and density: *e.g.* collision/mortality, avoidance behaviours, activity/abundance, etc.	

Note to readers:
For more details of the methods used in this review, see the appendices (Appendix II). The bibliographic search strategy, the criteria for selecting documents, as well as the critical analysis of the selected studies and the assessment of their validity are described in the Methods section. The methods used for the narrative and quantitative syntheses and the meta-analysis are also given. This information provides a complete description of the methods used to ensure the scientific rigour and robustness of the conclusions presented here.

DESCRIPTIVE ANALYSIS OF THE SELECTED DOCUMENTS

Search and selection

Bibliographic reference selection process

Records were retrieved from different online publication databases and search engines: 1,250 records from Web of Science, 855 from BASE and 350 from Google Scholar. Searches of specialized websites allowed us to retrieve 17 additional academic and grey literature references.

Of the initial 2,455 records, 1,602 unique references were retained after removing duplicates (Figure 2). 569 citations, for which 473 abstracts were available, were retained after assessing the titles. Of these, 232 references were retained after assessing the abstracts. With the addition of the 96 references that could not be screened from the abstract, a total of 328 references were assessed from the full texts. Full texts were not accessible for only 9 references (2.7 %). After assessing the full texts, 81 relevant articles were selected, consisting of 60 original research articles, 18 reviews and three meta-analyses. Full texts were excluded mainly because interventions (54 %), comparators (25.1 %), populations (9.6 %) or measures (6.3 %) were considered irrelevant.

Sources and types of references

Nearly three-quarters of the selected articles were retrieved through the main online publication databases, primarily Web of Science (31 articles, 51.6 %) (Figure 3). Among these, all were scientific articles, indicating that this database is particularly rich in peer-reviewed academic papers. Web of Science seems to be the main database for studies on the effectiveness of measures for mitigating the impact of onshore wind power on biodiversity. Thirteen additional references (21.7 %) were retrieved using BASE, most of which were technical reports (8), plus four Masters theses and a Ph.D. thesis. It is important to note that most of the records retrieved through BASE were removed because they were duplicates of those from Web of Science. This suggests that BASE is an important source of unpublished and grey literature, offering a complementary perspective to scientific articles. Three references (5 %) were retrieved using Google Scholar, all of which were technical reports. Like BASE, many records from Google Scholar were duplicates of those from Web of Science or BASE. These results indicate that, although Google Scholar is capable of finding a considerable number of references, the added value it provides is relatively low compared to Web of Science and BASE. However, it is still a useful source for getting access to technical reports that may not be indexed in other academic databases. Twelve references (20 %) were retrieved by searching other websites. Among these, most were technical reports (8), followed by scientific articles (3) and a poster. The latter highlights the diversity of documents retrieved using additional search strategies.

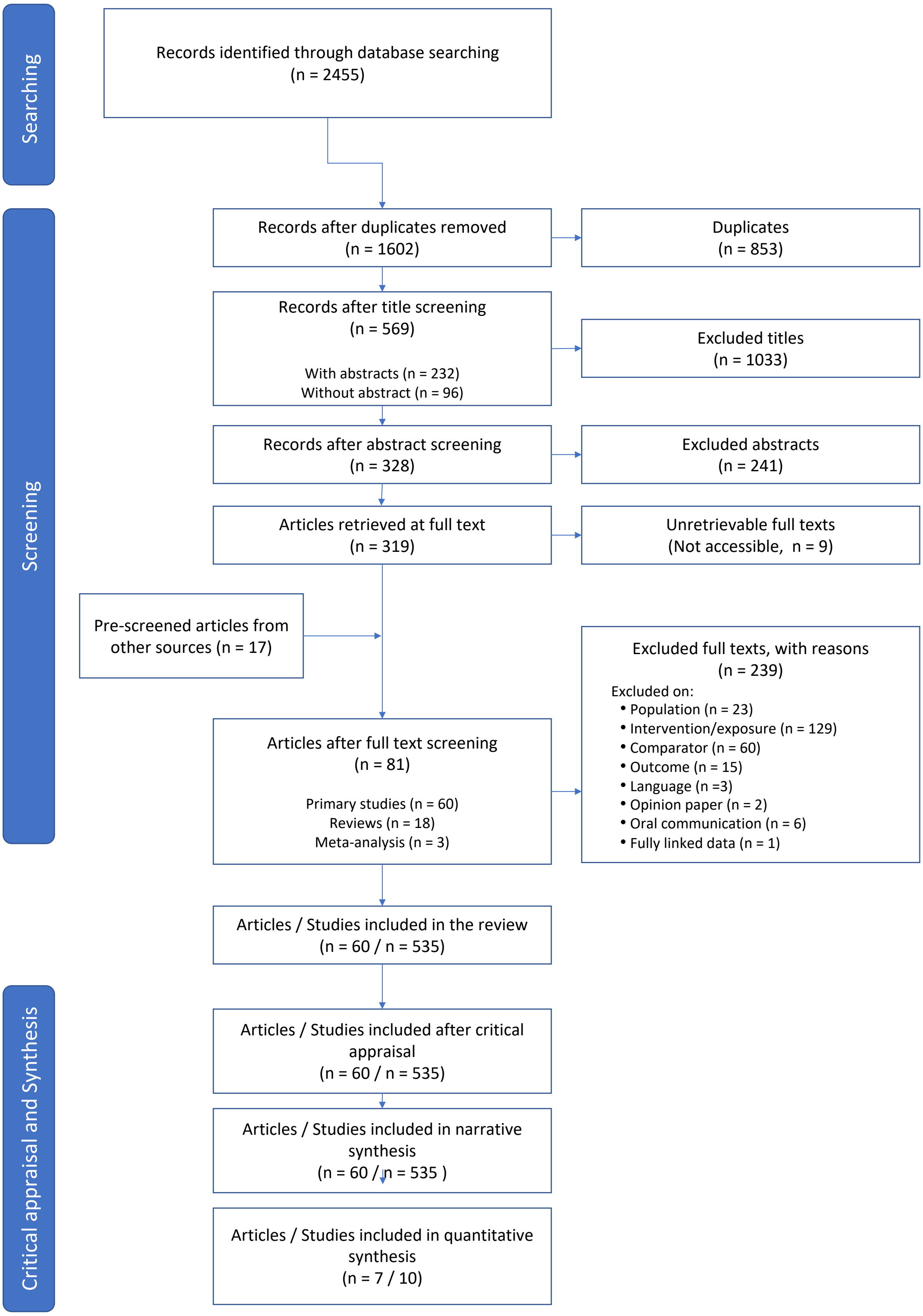

Figure 2. ROSES flow diagram of the selection process of articles, studies and observations included in the systematic mapping study.

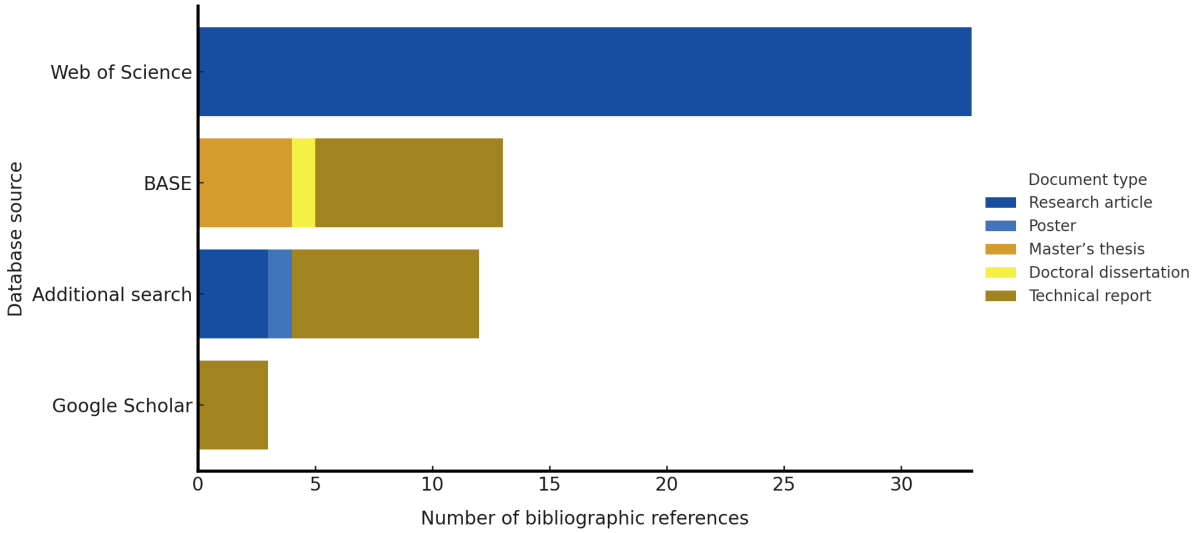

Figure 3. Number of selected bibliographic references by source and document type. Complementary searches were conducted on seven specialized websites.

Key characteristics

Study validity

Statistics show that bibliographic references with a "moderate" global risk of bias rating represent the majority of studies, making up 44.2 % of all references (Figure 4). Documents with a "weak" to "very weak" global risk of bias rating make up 39.4 %. The number of studies with a "strong" global risk of bias rating is not negligible, accounting for 16.3 %. Note that no study was rated as having a "very strong" global risk of bias rating. Studies with a "weak" to "very weak" global rating come primarily from peer-reviewed scientific articles. By contrast, studies with a "strong" global rating are mostly from documents that are not peer-reviewed, such as technical reports, Masters theses and posters (eight documents in total vs. three with a "weak" to "moderate" global rating). However, scientific articles with a "moderate" risk of bias rating still make up around 30 % of all references.

It is important to highlight the recurring difficulty we encountered when assessing certain criteria to determine the risk of bias due to a lack of information given in the documents (*e.g.* what becomes of carcasses once they have been recorded, or whether experimenters had prior knowledge of the type of treatment assigned to subjects, etc.) resulting in an increase in the global risk of bias rating. In addition, the protocols of a number of studies were not rigourous enough to meet certain criteria pertaining to methodology, *e.g.* when assessing mortality, the search area for carcasses was too small, the time interval between two searches was too long, etc. Other points also need to be improved, such as presenting the results separately, making the raw data accessible and systematically disclosing funding sources and conflicts of interest.

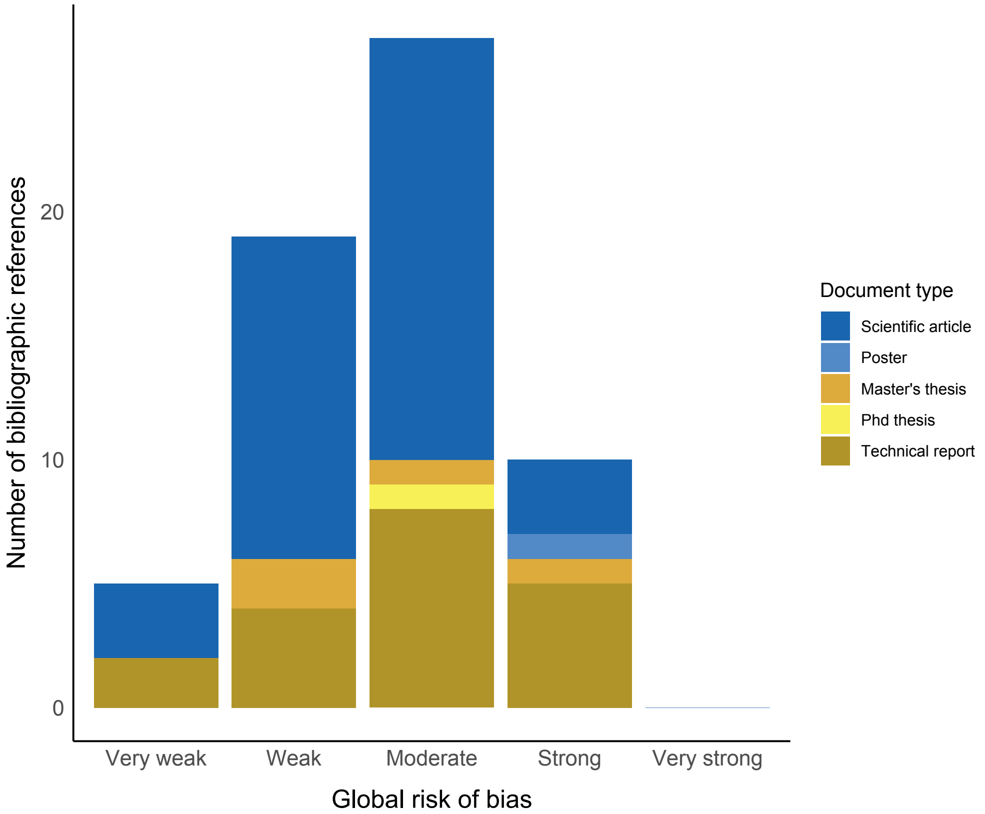

Figure 4. Number of selected bibliographic references in each global risk of bias category by document type.

Temporal evolution

The earliest selected publications date from 2003, which shows that the interest for studying the effectiveness of measures for mitigating the impact of onshore wind power on biodiversity is relatively recent and moderate (Figure 5). Indeed, from 2003 to 2008 the number of publications each year ranged between one and two. From 2009 to 2018, there was a slight increase in the number of publications, with peaks at four per year. From 2019, a more marked and regular increase in the number of publications can be seen, peaking significantly in 2022 with 9 publications. This trend indicates that research efforts to assess and improve the effectiveness of measures for mitigating the impact of onshore wind power on biodiversity have intensified. Wind power has grown rapidly over the past few years, and its impact on biodiversity has only been acknowledged recently. Measures for mitigating its impact have been put in place even more recently, which explains why studies on this subject are recent and still scarce.

Note that our bibliographic search was carried out in late September 2023, so that the numbers are incomplete for that year.

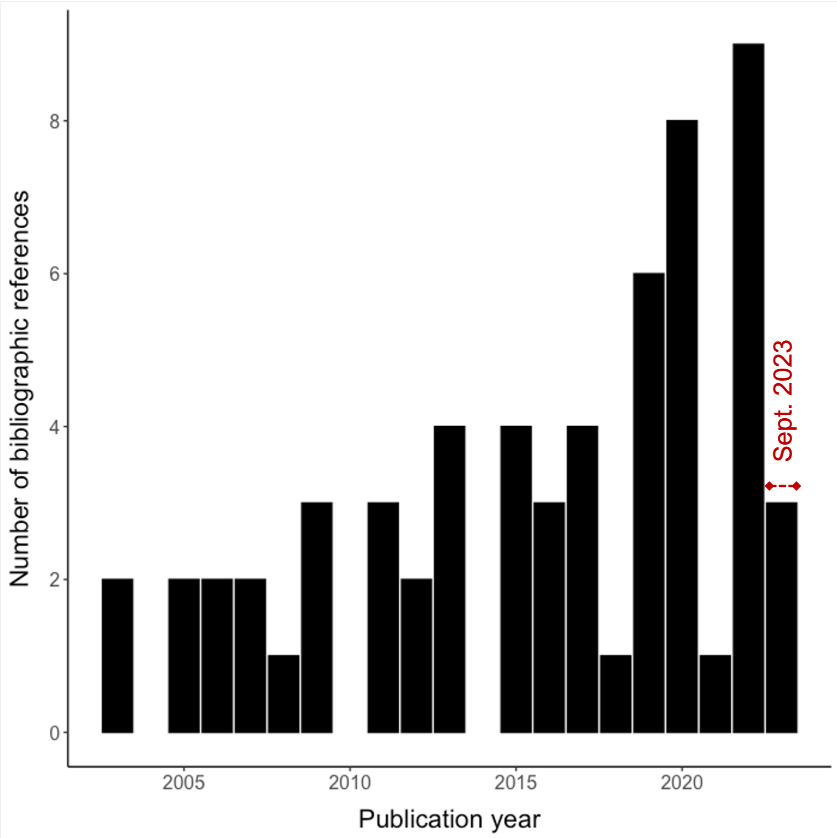

Figure 5. Number of selected bibliographic references per year. The search was carried out in late September 2023.

Geographic distribution

Studies were mostly carried out in North American (~ 70 %) and to a lesser extent in Europe (over 25 %), while other regions, notably those that are important in terms of biodiversity, are under-represented (Figure 6). In the USA (38), different states featured in one to six publications, including California, Texas and Massachusetts. Canada also featured (3), with a broad geographic distribution. In Europe, different countries, belonging almost exclusively to Western Europe, were represented (France, the U.K., Spain, Italy, Norway, Croatia). However, most of these countries featured in only one publication, except the U.K. (6), Spain (3) and Norway (3). In other parts of the world, notably Africa, Asia, Oceania and South America, there are no or very limited data available(one document). The climate in the studied regions varies considerably, ranging from mediterranean to temperate oceanic in Europe and California, to humid subtropical and semi-arid in Texas, humid continental in Eastern Europe, Canada and Massachusetts, and temperate in Australia. By looking at the representation of different climates, beyond the simple geographic distribution of the countries studied, we can see that there is an important heterogeneity in the number of bibliographic references per climate type.

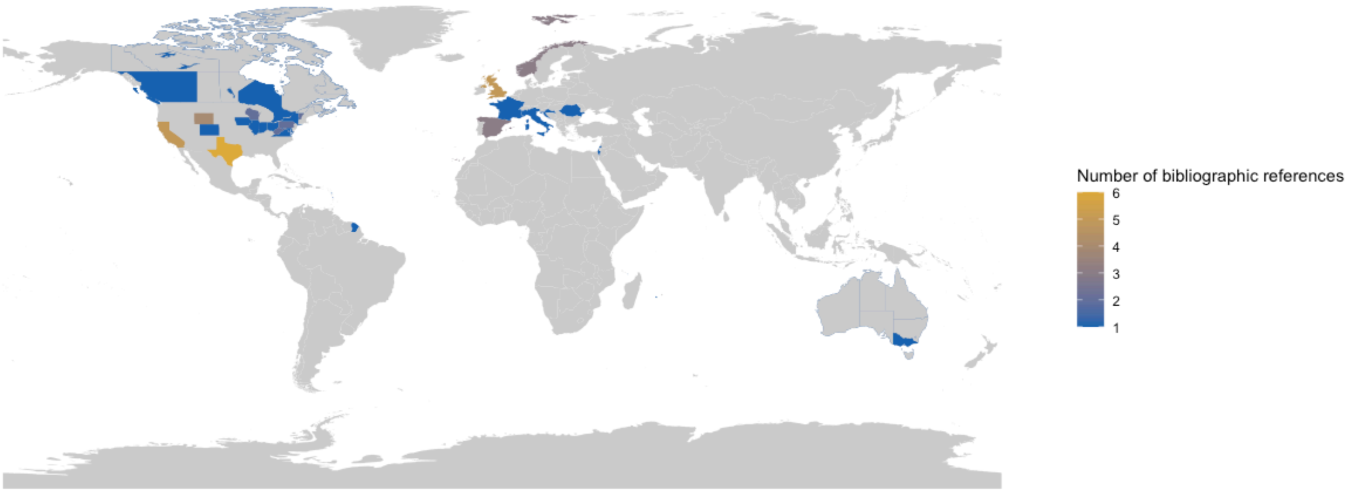

Figure 6. Geographic distribution of the selected bibliographic references.

Taxonomic groups studied

Research on different taxonomic groups was unevenly distributed (Figure 7). Bats featured in 43 bibliographic references (60.6 %) describing 256 case studies (63.2 % of all case studies). Although birds featured in only 21 bibliographic references (25.4 %), they described 261 case studies (64.5 %). This disparity can be explained by the greater number of bird species studied in certain articles, which is often much higher than for bats (usually four species). This difference in the number of species investigated can be explained by the greater number of extant bird species compared to bats. Note that raptors are often studied (11 references for 80 case studies). Insects are highly underrepresented with only four bibliographic references (5.6 %) describing 18 case studies (4.4 %), representing an average of 4.5 case studies per reference.

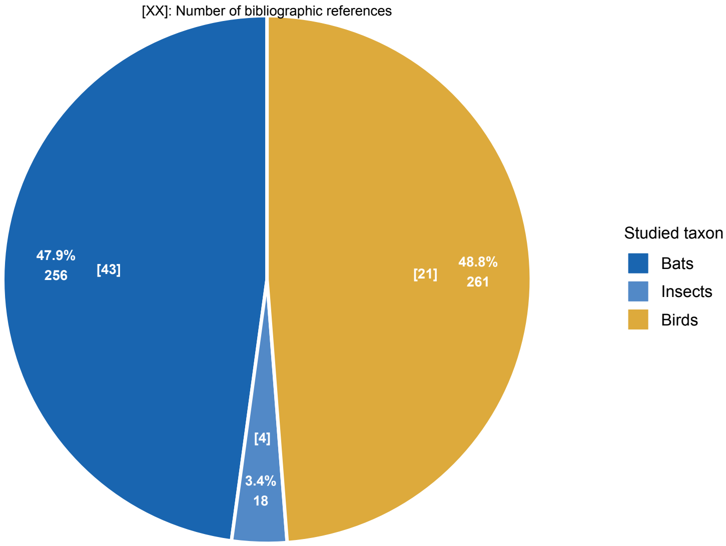

Figure 7. Number of case studies and bibliographic references (in brackets) for each taxonomic group.

Types of mitigation measures studied

Once again, the data show an uneven distribution in the number of case studies and bibliographic references (Figure 8). First of all, it is important to note that certain mitigation measures, although they are represented in a large number of case studies, may actually only feature in a small number of biobliographic references. This disparity can be explained by the fact that multiple case studies may be included in a single reference, which can contain data pertaining to different species, as well as multiple interventions in control-intervention comparisons. For instance, a single study may investigate the effectiveness of different colours or textures for visual deterrence, test different ultrasonic deterrents, or compare different cut-in speeds [1]in various contexts. Therefore, a single bibliographic reference may contain multiple cases studies, thus considerably enriching the knowledge base without increasing the total number of publications.

For birds, the most studied measures in terms of number of bibliographic references were targeted curtailment (6 references, 12 case studies) and painting of turbines (4 references, 93 case studies). The latter included documents analysing the application of paint, either by applying different colours, or by applying paint to various spots on the turbine. Measures such as using UV light as a potential deterrent, changing the rotor diameter, or removing factors that attract animals (through lighting, rodent control, vegetation clearing, ploughing) were each found in two or three references. Other measures, such as the use of acoustic deterrents, wind farm repowering[2], macro-siting (the

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[1] The **cut-in speed** is the minimum wind speed at which the blades start turning and generate electricity. Below this speed, the wind turbine does not generate electricity. This speed is determined by technical characteristics, such as blade design and generator specifications. Cut-in speed is a crucial parameter for optimizing wind energy production and reducing its environmental impact, as it influences the periods when the wind turbine is active and potentially disturbing local fauna, particularly birds and bats.

[2] **Repowering** is the process of replacing older turbines with more modern and efficient models. This can involve replacing the entire turbine, or parts such as blades and generators, or even adding new turbines to increase the site's installed capacity. Turbines from repowering operations are generally bigger, and fewer are required

selection of the location of the wind farm), micro-siting (the selection of the placement of the turbines within a wind farm), and the use of models to predict mortality rates before the installation of a wind farm, were less documented, each measure being found in a single reference, but each containing 4 to 44 case studies.

For bats, ultrasonic deterrents and raising the cut-in speed were the most frequently studied measures, both being documented in 14 references covering a total of 76 and 29 case studies, respectively. Targeted curtailment and feathering[3] accounted for 5 and 4 references for 13 and 7 case studies, respectively, whereas using radar as potential deterrents and texturing wind turbine towers accounted for 3 references covering 24 and 25 case studies respectively. Using UV light as a potentialdeterrent, combining turbine curtailment with ultrasonic deterrents, and repowering, were less frequent, each with 2 references for 10 to 14 case studies. Other measures, such as combining radar and ultrasonic deterrents, changing the rotor diameter, turning off lights that could attract animals, and micro-siting are seldom documented, each measure being found in a single reference comprising 1 to 40 case studies.

Measures mitigating the impact on insects are poorly studied. Analyses are almost always carried out in parallel to those on bats and birds. Each measure is represented in only a single bibliographic reference. Painting of turbines was the most studied measure, with 10 case studies. Using radar as a potential deterrent and removing factors that attract animals (here by ploughing) were both covered in 3 case studies. Finally, deterrence using UV light was documented in 2 case studies.

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compared to older models. Modern wind turbines benefit from technological advances such as advanced control systems, better resistance to extreme weather conditions, and noise reduction mechanisms. Repowering aims to improve the efficiency, reliability and safety of wind facilities, while reducing their environmental impact and maintenance costs. It also maximizes the use of existing infrastructure, such as connections to the electricity network, while taking advantage of technological advancements to increase electricity production from renewable sources.

[3] **Feathering** is the act of angling the blades parallel to the wind to minimize resistance and strain on the structure. When blades are feathered, they point their trailing edge to the wind, reducing the exposed surface and consequently the rotation of the blades. This technique is often used to reduce energy production when winds are too strong or during maintenance work. It also lowers the risks posed to wildlife, particularly birds and bats, by reducing the movement of the blades in certain specific conditions.

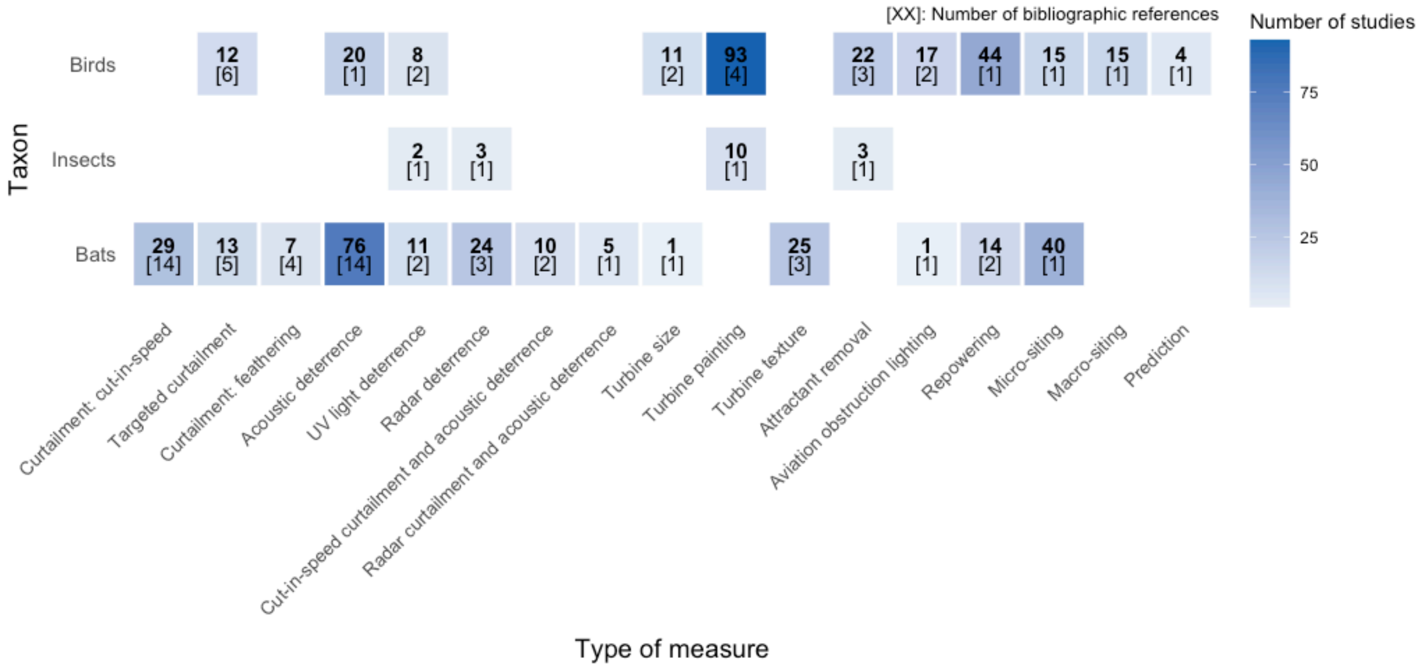


Figure 8. Heatmap of the number of case studies per taxonomic group and type of mitigation measure studied. The number of corresponding bibliographic references is given in brackets. The total number of bibliographic references is greater than the actual number of selected references, because the same reference can include studies of multiple taxa and/or mitigation measures.

Intervention location: in situ vs ex situ

Most studies were carried out *in situ* on wind farms, compared to *ex situ*, *i.e.* in natural environments (not wind farms) or in captivity (Figure 9). *In situ* studies represent 72.1 % of the bibliographic references (44 references) and 68 % of all case studies (364). *Ex situ* studies, although less common, still represent a non-negligible 27.9 % of the bibliographic references (17 references) and 32 % of all case studies (171).

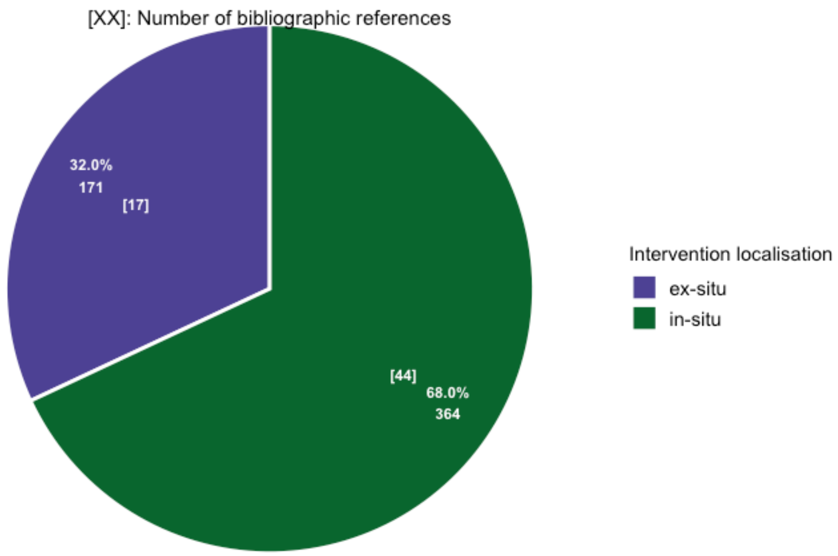


Figure 9. Number of case studies and selected bibliographic references (in brackets) per taxonomic group and intervention location, i.e. in situ *vs* ex situ.

Focus of the in situ studies, by taxonomic group and mitigation measure

Ex situ studies were limited to the analysis of different measures of behavioural activity in the studied species to determine the effect of the intervention in place. *In situ* studies of birds and bats mainly focused on two types of measures: activity and mortality (Figure 10). Activity was measured in different ways. For bats, this included the number of passes (from audio or video recordings), the number of "feeding buzzes", the number of drinking behaviour displays, the amount of time spent in the focal range, etc. For birds, this included flight altitude, the minimum distance from the turbine, changes in flight speed, and the number of sightings within a given period. Mortality was quantified by the number of carcasses found at the foot of the turbines, often presented as a seasonal or annual rate. Results related to mortality were more common, representing 68.4 % of case studies from 34 documents, compared to 30.8 % of case studies (from 10 references) documenting activity. Curtailment, in all its forms, was almost exclusively examined through mortality, with one exception. For bats, a third of the studies on acoustic deterrents focused on activity, with 3 bibliographic references covering 10 case studies, vs 6 references covering 40 case studies investigating mortality. Only one study investigated the structure of species assemblages (in bats), within the framework of a study on wind farm repowering.

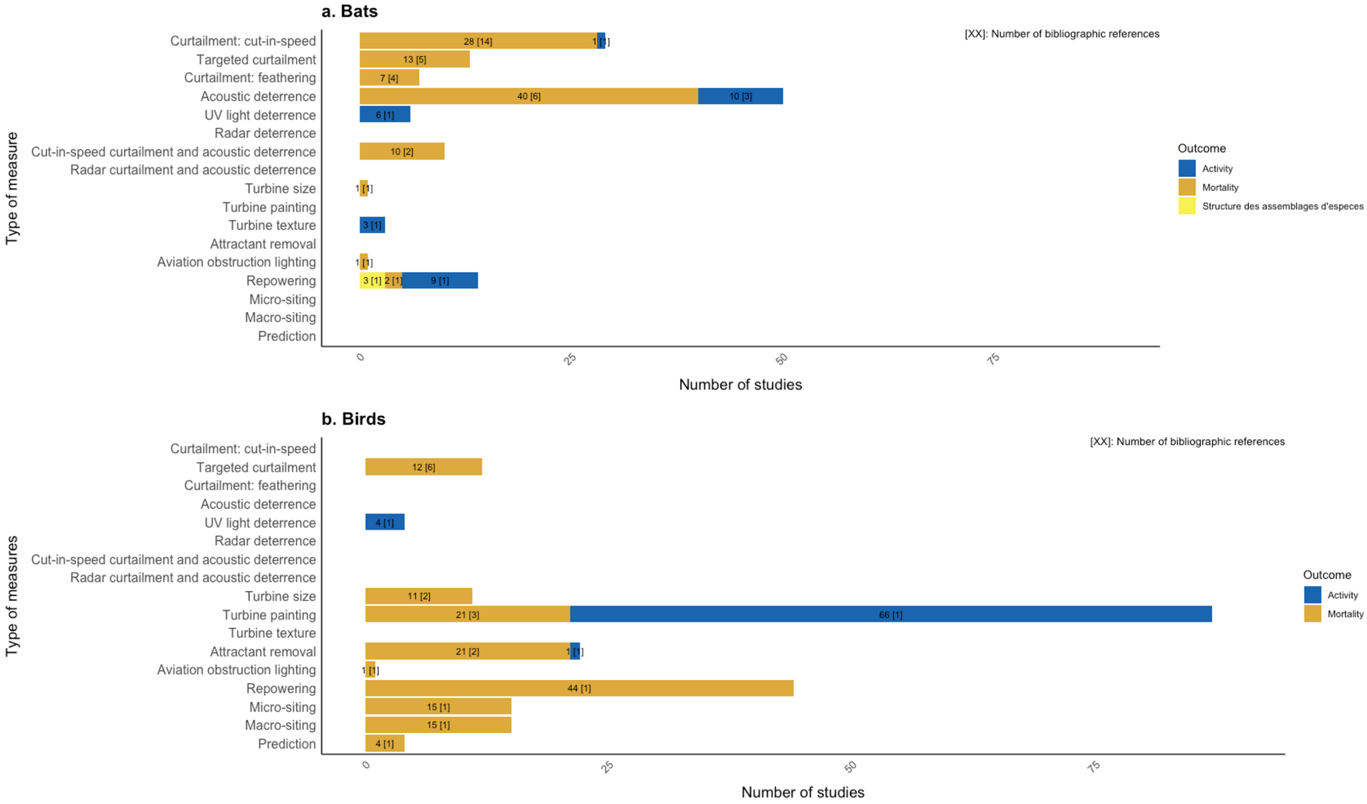


Figure 10. Number of case studies and selected bibliographic references (in brackets) for in situ *studies in (a) bats and (b) birds, per mitigation measure and result category (activity or mortality). The total number of bibliographic references given here is greater than the actual number of selected references, because the same reference can include studies of multiple taxa and/or mitigation measures.*

Suitability of the data for a meta-analysis

Case studies with statistical data that can be used in a meta-analysis, despite being in the majority, only represent 60 % of the selected literature (Figure 11). These case studies include results with explicit mean and standard deviation values, as well as alternative statistics such as 95 % confidence intervals, medians, quartiles and standard errors.

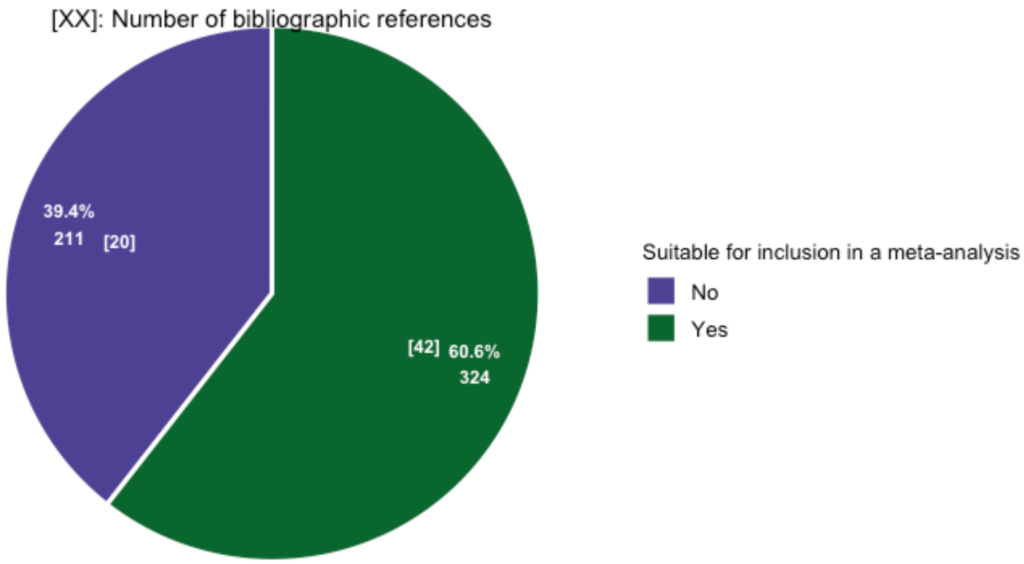


Figure 11. Number of case studies and selected bibliographic references (in brackets) that can be included in a meta-analysis.

For a study to be included in a meta-analysis, it needs to not only measure specific parameters but also be sufficiently similar to other studies in terms of methodology and type of data collected. This includes, but is not restricted to, the type of results studied (here, mortality or activity), the location of the intervention (*ex situ* or *in situ*), and the type of mitigation measure considered (such as curtailment, acoustic deterrence, changing the turbine size, etc.).

The examination of the studies on the effect of measures for mitigating the impact of onshore wind power on birds and bats, with only the variables listed above, reveals an immediate problem: the number of case studies and bibliographic references that can be used for a meta-analysis of a specific mitigation measure is low (Figure 12). The use of ultrasonic deterrents for bats is a case in point: although 76 case studies were described in 14 bibliographic references, only 18 case studies measuring mortality and 5 case studies measuring activity can be used for meta-analysis. These numbers indicate a significant disparity between the number of studies available and those that can be used for rigourous statistical analysis. Here, only the effect on bats of curtailment by raising the cut-in speed could be analyzed, focusing on induced mortality. This analysis was based on 18 case studies from 11 bibliographic references.

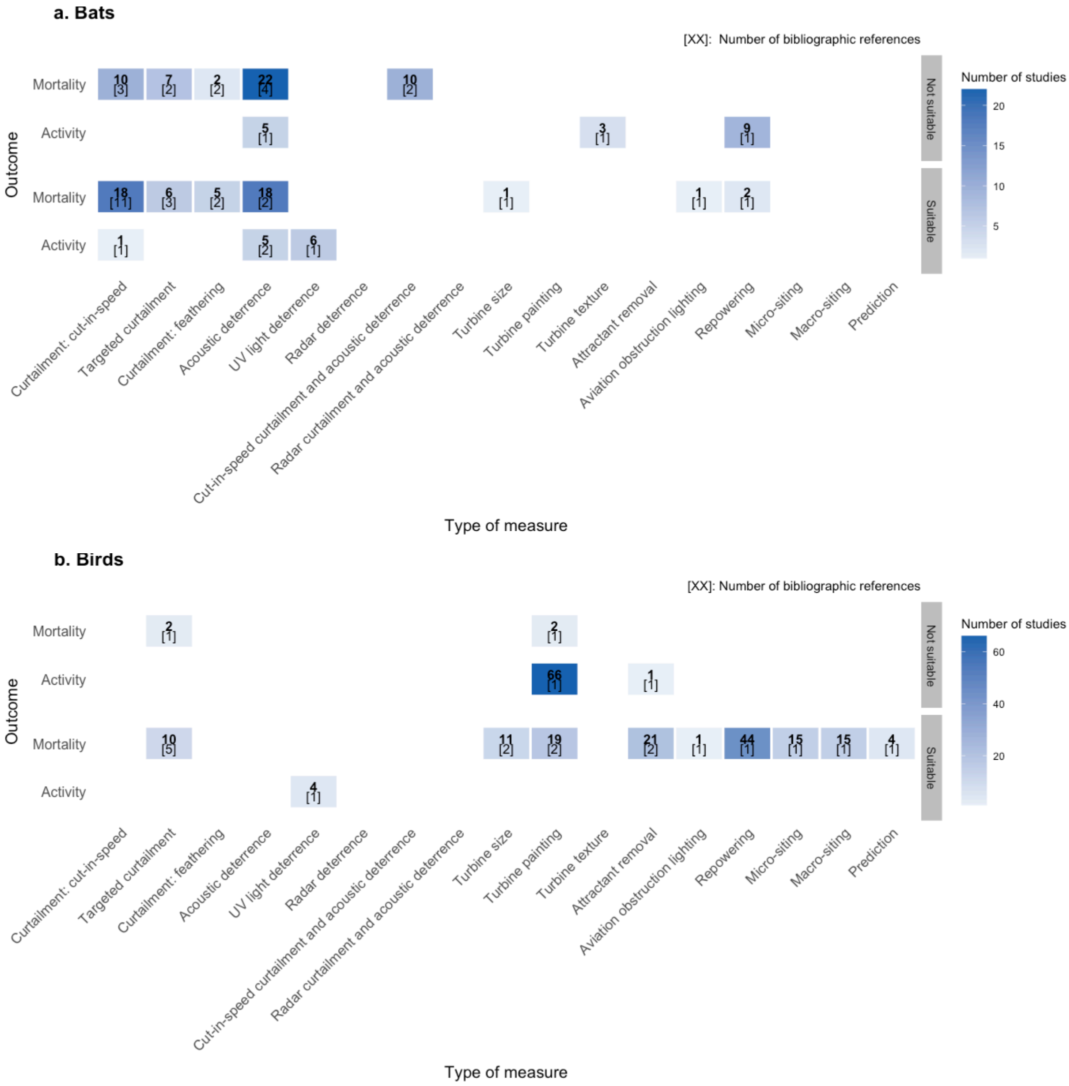


Figure 12. Number of case studies and selected bibliographic references (in brackets) that can be included in a meta-analysis. Numbers are given per mitigation measure and result category, and only for in situ *studies in (a) bats and (b) birds.*

NARRATIVE SYNTHESIS

Pre-installation planning

Predicting mortality prior to the installation of a wind farm

In our survey of the literature, we only found one article that focused on avoiding the impact of wind farms through informed choice. This approach is particularly relevant because it highlights the tools and models that can be used to predict the environmental impacts of wind farms before they are built (this is supposed to be mandatory but seldom done in practice). Predictions can allow the assessment of potential sites to identify those that pose the less risk to birds, thus helping in choosing suitable locations. It optimizes the design and placement of turbines to minimize collisions, by determining their optimal number and configuration. Used in environmental impact assessments (EIA), it helps authorities determine which mitigation measures are needed to obtain planning permits.

- Smales *et al.*, 2013 (*weak* global risk of bias) developed a model to quantify the potential risk to birds of collisions with wind turbines. The article provides a case history of the model's application to two eagle species: the white-bellied sea eagle (*Ichtyophaga leucogaster*) and the Tasmanian wedge-tailed eagle (*Aquila audax fleayi*), and its performance relative to empirical experience of collisions by those species. The study, carried out from 1999 to 2009, involved 62 turbines at two wind farms (Bluff Point and Studland Bay) on the north-west coast of Tasmania. This study integrates detailed bird size and flight data, and blade size and rotation speed. The model succesfully predicts the number of collisions of local or migratory bird populations with wind turbines. For example, for white-bellied sea eagles at Bluff Point wind farm, the model predicted an average annual collision rate of 1.5 for a 95 % avoidance rate, which corresponds exactly to the observed average annual mortality rate. Overall, model estimates closely match the empirical average annual mortality rate for both species at both sites, indicating the model's effectiveness.

Results from this study show that predictive tools can effectively anticipate and mitigate the impact of wind farms on bird populations. The use of such tools for environmental impact assessments is crucial for making informed choices in order to minimize the risk posed by wind farms. However, additional empirical studies are needed to consolidate these results and refine the models, in particular by testing them on a wider range of species and environmental settings.

Localization: macro-siting and micro-siting

Although macro-siting (the selection of the location of the wind farm) and micro-siting (the selection of the placement of the turbines within a wind farm) strategies are crucial for mitigating the negative impacts of wind power on biodiversity, only two studies on this topic were retrieved from our survey of the literature. Moreover, in both publications, the analysis of these aspects was not the main focus of the study.

- Millon *et al.*, 2015 (*weak* global risk of bias) examined bat activity in intensively farmed landscapes with wind turbines in the Champagne-Ardenne region of France from May to September 2013. The study assessed the impact of turbines and landscape features, such as fallows and hedgerows, on three groups of bats: *Pipistrellus* sp., *Eptesicus-Nyctalus* sp., and *Plecotus-Myotis* sp. Samples consisted of ultrasound recordings at fixed sites, measuring bat activity across sites at different times of the year. Bat activity was generally lower on crop land with wind turbines than without turbines, for all groups and all seasons. However, the three groups of bats responded differently to landscape features: during the breeding season, the *Plecotus-Myotis* group responded positively to fallows, whereas the *Pipistrellus* and *Eptesicus-Nyctalus* groups responded positively to hedgerows. The *Eptesicus-Nyctalus* group also responded positively to grass strips. Season-dependent responses to landscape measures were also observed: significant differences were found for hedgerows and bushes, with bats showing opposite responses depending on the season.

- Smallwood and Thelander 2005 (*strong* global risk of bias) analyzed the effect of diverse landscape attributes, such as canyons and rock piles, from March 1998 to September 2001. The authors observed bird behaviour around 1,536 wind turbines in a park in California (USA), recording bird movement and their interaction with turbines. Wind turbines located near canyons or rock piles showed higher mortality rates for raptors, respectively 1.5 – 3 times and 2.79 – 12 times higher. These areas seem to attract more birds, probably because their topography can be used by raptors for hunting or resting.

These two studies highlight the crucial importance of micro- and macro-siting for wind farm planning, demonstrating that the geographic location of turbines can significantly influence the mortality rate of birds and bats, and that strategic choices in terms of location could contribute to the mitigation of their environmental impact. However, it is important to note that the low number of studies on macro- and micro-siting included here is most certainly due to us focusing on papers explicitly mentionning wind energy, when more generalist studies could have also provided relevant information.

Wind turbine curtailment

Raising the cut-in speed and blade feathering

Adjusting the cut-in speed[4] and blade feathering[5] are strategies for minimizing bat fatalities at wind farms. Multiple studies have investigated the effectiveness of adjusting the cut-in speed. Under strong winds, bats do not fly, whereas wind turbines do not generate much power when winds are low. Consequently, preventing wind turbines from turning when winds are low, which is when bats are the most active, can reduce the collision risk while limiting the loss in energy production. Moreover, the higher the cut-in speed, the more the collision risk tends to decrease. Research has shown that slightly changing the cut-in speed can significantly reduce bat mortality without having a significant impact on energy production. The analysis of different curtailment measures and their seasonal impact enables us to better understand how these strategies can be optimized to better protect animals while ensuring that wind farms remain economically viable.

- Brown and Hamilton, 2006 (*moderate* global risk of bias) carried out curtailment experiments by changing the cut-in speed of 20 turbines at a wind farm in southwestern Alberta (Canada) in September 2005. They observed a significant decrease of 32 % in bat mortality when turbines stopped operating below wind speeds of 7 m/s compared to those that stopped below 4 m/s.

- The study of Arnett *et al.*, 2011 (*weak* global risk of bias) took place over two years (2008 and 2009) from July to October and involved 12 turbines at a wind farm in Pennsylvania (USA). Turbines were either: 1) fully operational, 2) curtailed below 5.0 m/s and 3) curtailed below 6.5 m/s. Results showed a significant decrease in bat mortality when turbines were curtailed, but no significant difference between the two cut-in speeds. For both cut-in speeds combined, mortality rates were reduced by 82 % in 2008 and 72 % in 2009.

- Stantec Consulting Ltd., 2012 (*moderate* global risk of bias) monitored bat mortality near 42 turbines divided into three groups: 1) a control group (no curtailment), 2) a curtailed group with a cut-in speed of 4.5 m/s, and 3) a curtailed group with a cut-in speed of 5.5 m/s. This study was conducted in Ontario, Canada from July to December 2011. Mortality in the control group was twice as high as in the curtailed groups. Although mortality rates in the curtailed

[4] The wind speed at which the generator is connected to the network and generates electricity. In certain turbines, blades will turn at the maximum rotation speed or rotate below the cut-in speed when no electricity is being generated.

[5] The wind speed at which the generator is connected to the network and generates electricity. In certain turbines, blades will turn at the maximum rotation speed or rotate below the cut-in speed when no electricity is being generated.

groups were relatively low, the mortality when the cut-in speed was set at 4.5 m/s was slightly higher than when the cut-in speed was set at 5.5 m/s. However, due to the low number of fatalities observed, a statistical analysis of the results could not be carried out.

- Măntoiu *et al.*, 2020 (*moderate* global risk of bias) conducted tests from 2013 to 2016 on 6 wind turbines in the Dobrogea region of Romania. Curtailment measures involved raising the cut-in speed from 4 to 6.5 m/s during high-risk periods (identified as mid-July to late September). The implementation of curtailment measures significantly reduced bat mortality by 78 %.

- The study of Bennett *et al.*, 2022 (*weak* global risk of bias) assessed the effectiveness of raising the cut-in speed of 11 wind turbines located in southwestern Victoria, Australia, from 3.0 to 4.5 m/s. This study was conducted from January to April 2018 (pre-curtailment) and 2019 (during curtailment). Results showed that curtailment significantly reduced bat mortality by 54 %. Bat activity, measured from recordings of bat calls, did not decrease during the study period, suggesting that a reduction in mortality was due to raising the cut-in speed and not a decrease in activity.

- The study of Good *et al.*, 2022 (*weak* global risk of bias) involved monitoring 114 wind turbines in Indiana (USA), from April to October 2021. Cut-in speeds were set at 5.0 m/s during the autumn and 3.5 m/s during the spring. This management action led to a 50 % decrease in bat mortality compared to estimates of mortality under normal operation (3.0 m/s cut-in speed).

- Baerwald *et al.*, 2009 (*moderate* global risk of bias) assessed the effectiveness of two curtailment measures on a wind farm in Alberta, Canada, from July to September 2006 and 2007. Fifteen wind turbines had their cut-in speed raised from 4.0 to 5.5 m/s. Six other turbines were curtailed by altering the angle of their blades to reduce rotor speed. In 2007, results showed that increasing the cut-in speed to 5.5 m/s and and angling the blades in low winds significantly reduced bat mortality by 57.5 % and 60 %, respectively. Although the decrease in mortality of migratory species such as the hoary bat (*Lasiurus cinereus*) and the silver-haired bat (*Lasionycteris noctivagans*) varied between 50 % and 70 %, this was not individually statistically significant.

- Young *et al.*, 2011 (*weak* global risk of bias) tested measures that prevent blades from turning at low wind speeds in 24 turbines in West Virginia, USA, from July to October 2010. Blades were angled (feathered) so that they would only turn at a minimum speed (less than 1 rpm) when wind speeds were less than the cut-in speed of 4 m/s. Turbines were divided into three groups : 1) blades feathered in the first half of the night, 2) blades feathered in the second half of the night, and 3) a conventionally operating control group. Results showed that restricting blade rotation during the first part of the night significantly reduced bat mortality (by 47 %), while restricting blade rotation during the second part of the night led to a non-significant decrease of 23 %.

- In 2012, Young *et al.*, 2013 (*moderate* global risk of bias) feathered the blades of 14 wind turbines in order to reduce rotor speed to less than 2 rpm when wind speeds were below 5.0 m/s. This strategy was tested in Maryland,(USA) and was implemented during the critical period for bat migration, *i.e.* from July to October. These operational adjustments were significantly effective and reduced bat mortality by 62 %.

Adjusting the cut-in speed and blade feathering are effective measures, reducing bat mortality by more than 50 % in most cases while having a limited impact on energy production. However, more

research is needed to confirm the effectiveness of these measures in different contexts, fine tune seasonal configurations and better understand their long term effects on bat populations.

Adjustment of curtailment strategies

Wind turbine curtailment strategies are constantly evolving, becoming more fine-tuned to handle seasonal and bat behaviour variations. We found four studies that tested different combinations of cut-in speed and environmental parameters, such as temperature or the time of night, and assessed their impact on bat mortality. We also identified a study that uses migration periods to determine when turbines should be stopped. These studies provide valuable information on the way specific adjustments of curtailment strategies can improve the effectiveness of these measures. They also allow us to measure the trade-off between animal protection and the potential losses in energy production, providing a solid foundation for optimizing the management of wind farms.

- Hein *et al.*, 2013 (*moderate* global risk of bias) conducted a study in West Virginia (USA) from March to November 2012. They rotated three treatments among 12 turbines: 1) fully operational at 3.0 m/s cut in speed, 2) increased cut-in speed at 5.0 m/s from sunset to sunrise, and 3) increased cut-in speed at 5.0 m/s for the first four hours past sunset. Analyses showed that the “5.0 m/s all night long” treatment resulted in a significant reduction in mortality, estimated at 47 %, compared to fully operational turbines. The most parcimonious model showed a 72.2 % decrease in bat mortality for the “5.0 m/s all night long” treatment when wind speeds ranged between 3-5 m/s for half of the night. The “5.0 m/s for the first four hours past sunset” treatment did not show any significant reduction in mortality.

- Martin *et al.*, 2017 (*weak* global risk of bias) conducted curtailment tests between spring 2012 and autumn 2013 on 16 wind turbines at a wind facility in Vermont (USA). They raised the cut-in speed from 4.0 to 6.0 m/s when temperatures were above 9.5°C. They found a significant reduction of bat mortality of 62 %. During late spring, and early autumn, when overnight temperatures generally fall below 9.5°C, incorporating temperature into the operational mitigation design decreased energy loss by 18 %. Energy loss was < 3 % for the study season and approximately 1 % for the entire year.

- The study by Schirmacher *et al.*, 2018 (*very weak* global risk of bias) took place from July to September 2015 in West Virginia (USA). Three mitigation strategies were evaluted on 15 turbines: 1) treatment A: increased the wind speed requirement to initiate turbine start-up to 5.0 m/s and fully feathered blades until wind speed reached 5.0 m/s based on a 10-minute rolling average as measured at a nearby meteorological tower; 2) treatment B: same as treatment A but based on a 20-minute rolling average; 3) treatment C: same as treatment A but based on a 20-minute rolling average as measured from anemometers on individual turbines. Compared to treatment A, treatment B showed a reduction in bat mortality, although this difference was not statistically significant. By constrast, treatment C showed a significant increase in mortality compared to treatment B of 81.4 %. Analyses showed that using a 20-minute rolling average to initiate turbine start-up reduced the number of operational transitions (starts and stops), thus contributing to a reduction in mortality.

- A recent study by Rnjak *et al.*, 2023 (*weak* global risk of bias) was carried out on 12 wind turbines at a wind farm in Croatia. Initial post-construction monitoring was conducted in 2016 and 2017, and the effectiveness of site-specific mitigation measures were tested in 2019 and 2020. Turbine curtailment was implemented based on critical wind speed thresholds varying from 5.0 to 6.5 m/s, defined as the tolerance threshold of wind speed above which less than

1.0 % of total recorded bat activity occurs. Results showed a significant reduction of 78 % in the estimated number of bat fatalities with the implementation of curtailment measures.

- Smallwood and Bell, 2020 (*moderate* global risk of bias) performed experiments on the effect of shutting down wind turbines during migration season on bird and bat mortality. These were carried out in California (USA) between 2012 and 2014 and involved 31 wind turbines. Results showed that shutting down turbines during bat migration significantly reduced bat mortality by 100 %. However, bird mortality was not significantly impacted by this measure.

Curtailment strategies, such as adjusting the cut-in speed or shutting down turbines at specific times, significantly reduced bat mortality, sometimes by 100 %. Incorporating parameters such temperature, migration period, and the time of night, optimizes these results while limiting losses in energy production. Additional research is needed to adapt these strategies to local conditions and assess their long term impact on biodiversity and on the viability of wind farms.

Selective turbine shutdown

Selective turbine shutdown is a promising measure to reduce the mortality of flying animals, particularly large birds and bats. Although rarely studied (only two studies, one conducted over a short period and one over a long period, were found), this strategy shows encouraging results. It involves the detection in real time of species at risk of collision and selectively shutting down individual turbines . Studies showed that this method can significantly reduce mortality with minimal impact on energy production.

- De Lucas *et al.*, 2012 (*moderate* global risk of bias) specifically investigated the mortality of griffon vultures (*Gyps fulvus*) at 13 wind farms in the Cadiz province (Spain). Out of a total 296 turbines, 244 were selectively shut down and 52 were not. When a dangerous situation for large birds was detected, an observer on site every day of the year from dawn to dusk contacted the wind farm's control office to immediately stop the turbine in question. This measure, implemented in 2008-2009, reduced mortality by 50 %. Around 10 % of wind turbines, considered the most dangerous, were selectively shut down during the critical period from September to December (the migratory period when many birds cross the Strait of Gibraltar). The impact on energy production was minimal, with an annual decrease of only 0.07 %.

- Following on from De Lucas *et al.* (2012) Ferrer *et al.*, 2022 (*moderate* global risk of bias) extended the study of bird and bat mortality across 20 wind farms in the Cadiz area (Spain) over a 15 year period, from 2006 to 2020. The study involved 269 wind turbines, and used the same selective turbine stopping protocol as the one used in 2008. After implementation of the protocol, the mortality of soaring birds (mainly raptors and storks) decreased by 61.7 %; in particular, griffon vultures mortality decreased by 92.8 %. The impact on energy production was negligible (less than 0.51 %). No difference was observed for passerines and bats.

Selective turbine shutdown, base on the real time detection of species at risk of collision, seems promising for reducing the mortality of flying animals, especially large birds. Studies show a significant decrease in mortality, reaching 92.8 % for griffon vultures, and a negligible impact on energy production (< 0.51 % decrease). However, there are few studies on this approach, and additional data is needed to assess its effectiveness in other species, bats in particular, and its feasibility in different contexts.

Integrating smart technology

Technological advances offer new perspectives for the protection of wildlife on wind farms. Smart systems for reducing fatalities, such as real-time acoustic detection devices and detection algorithms, improve the effectiveness of protection measures. Studies that integrate this technology show a significant reduction in bat and bird fatalities, while optimizing wind turbine performance. Four studies have investigated different systems:

- The study of Hayes *et al.*, 2019 (*moderate* global risk of bias) tested a smart curtailment approach, referred to as Turbine Integrated Mortality Reduction (TIMR). This system analyzes bat activity and wind speed data and makes near real-time curtailment decisions from these data. This study, conducted in Wisconsin (USA) in 2015, involved 20 wind turbines split into a control group (10 turbines) and a treatment group (10 turbines). The TIMR approach significantly reduced fatality estimates for treatment turbines relative to control turbines, for each species observed at the study site: pooled data (–84.5 %), eastern red bat (*Lasiurus borealis*, –82.5 %), hoary bat (*Lasiurus cinereus*, –81.4 %), silver-haired bat (*Lasionycteris noctivagans*, –90.9 %), big brown bat (*Eptesicus fuscus*, –74.2 %), and little brown bat (*Myotis lucifugus*, –91.4 %). The approach reduced power generation and estimated annual revenue at the wind energy facility by ≤ 3.2 % for treatment turbines relative to control turbines and reduced curtailment time by 48 % relative to turbines operated under a standard curtailment rule (based on cut-in speed) used in North America.

- Rabie *et al.*, 2022 (*weak* global risk of bias) conducted a comparative study to evaluate the effectiveness and associated costs of two bat mortality reduction strategies on a wind farm in Wisconsin (USA) between July and September 2015. 30 turbines were divided into three groups: 1) a control group with a cut-in speed of 3.5 m/s and the ability to free spin (*i.e.* blades were not feathered) when power was not being generated, 2) a group operating under traditional wind speed-only (WOC) curtailment, with turbine blades feathered below a cut-in speed of 4.5 m/s, and 3) a group controlled by the TIMR system, which integrates real-time bat acoustic data to detect the presence of bats and adjust turbine operation accordingly. The TIMR system activated curtailment when bats were acoustically detected at wind speeds below 8.0 m/s. Overall, the TIMR system reduced fatalities by 75 % compared to control turbines, while the WOC strategy reduced fatalities by 47 %. Over the study period, bat activity led to curtailment of TIMR turbines during 39.4 % of nighttime hours compared to 31.0 % of nighttime hours for WOC turbines. Moreover, revenue losses were approximately 280 % as great for TIMR turbines as for turbines operated under the WOC strategy.

- Rodriguez *et al.*, 2023 (*strong* global risk of bias) evaluated the effectiveness of the EchoSense® system, a smart curtailment technology using acoustic sensors to detect the presence of bats in real-time and adjust cut-in speed accordingly. Tests were carried out in Iowa (USA) in 2020 and 2021, on 69 wind turbines, 5 of which were equipped with the EchoSense® system. Three types of curtailment were compared: 1) a control, with a 3.0 m/s cut-in speed, 2) wind-speed only curtailment (6.9 m/s in 2020 and 5.0 m/s in 2021), and 3) smart curtailment with the EchoSense® system. Results showed there was no statistically significant difference in mortality rates between treatments in 2020 and 2021. However, the EchoSense® system reduced power losses by an average of 41 % in 2020 compared to curtailment at 6.9 m/s and by 56 % in 2021 compared to curtailment at 5.0 m/s. En terms of energy production, the use of the EchoSense® system generated an additional 5,490 MWh in 2020 and 1,684 MWh in 2021.

- McClure *et al*,. 2021 (*moderate* global risk of bias) tested the effectiveness of the IdentiFlight® system, an automated curtailment system, in Wyoming (USA). The study took place over 4 years before and one year after the implementation of the curtailment system from 2014 to 2019. There were 110 wind turbines on the treatment site and 66 wind turbines on the control site, where golden eagles (*Aquila chrysaetos*) and and bald eagles (*Haliaeetus leucocephalus*) were monitored. The IdentiFlight® system uses cameras and algorithms to detect and identify birds in flight, and order curtailment actions for individual turbines if necessary. Results showed that the number of fatalities at the treatment site declined by 63 % between before and after periods while increasing at the control site by 113 %. In total, there was an 82 % reduction in the fatality rate at the treatment site relative to the control site.

- In their critical review of the article by McClure *et al*,. 2021 mentioned above, Huso and Dalthorp, 2023 (*very weak* global risk of bias) identified four major errors: 1) ignoring annual variation in mortality, 2) unfounded causal inference due to a lack of replication, 3) inflated effect size by assuming that the difference in fatality relative to the mean at a neighbouring site would be exactly repeated at the treatment site, 4) inconsistency of data. Corrected results yield a non-significant 50 % (−159 to + 89 % confidence interval) reduction in the fatality rate after implementing the IdentiFlight® system, which contrasts with the 82 % reduction reported by McClure *et al.* (2021). The authors highlight that annual variation in mortality and the lack of adequate replication render the initial estimate unreliable.

Smart technology, such as real-time acoustic detection systems and automated algorithms, are innovative solutions for reducing wildlife fatalities on wind farms. Studies show that these systems can significantly reduce mortality, by up to 84.5 % for bats and 63 % for eagles, and at the same time optimize power generation. However, these results vary depending on the system used, and critics have highlighted the methodological bias of certain studies. Additional research is needed to standardize these approaches, assess their cost-effectiveness and validate their performance on a large scale.

Deterrence and associated methods

Ultrasonic acoustic deterrence

The 14 studies described below provide a detailed and methodological evaluation of ultrasonic deterrent devices for reducing bat collision risk at wind facilities. From testing the behaviour of species in the laboratory to testing these devices in the field under different configurations and in combination with other measures, these studies offer an overview of the efforts made in order to reduce bat collisions with wind turbines.

- The experimental study by Spanjer, 2006 (*moderate* global risk of bias) was carried out in a laboratory in Maryland (USA). This study focused on the response of the big brown bat (*Eptesicus fuscus*) to ultrasound broadcasted by a prototype acoustic deterrent. The trials took place under controlled conditions in an anechoic[6] flight chamber. Six captured adult bats were tested in either feeding (3 bats) or non-feeding (3 bats) trials. In non-feeding trials, bats flew in a chamber where the device was either broadcasting noise or silent, and landing behaviour was recorded. Bats in feeding trials were presented with a tethered mealworm in the same quadrant as the device; capture of the mealworm was recorded when the device was either

[6] An **anechoic chamber** is a room lined with foam designed to absorb sound or electromagnetic waves so that no echo bounces back.

broadcasting noise or silent. In non-feeding trials, bats landed in the quadrant containing the device significantly less when it was broadcasting noise (1.7 % of trials) than when it was silent (22.4 % of trials). In feeding trials, bats never successfully took a tethered mealworm when the device was broadcasting noise but captured mealworms near the device in about 36 % of trials when it was silent. Moreover, bats in both feeding and non-feeding trials flew through the quadrant containing the device significantly less when it broadcast noise than when it remained silent.

- Szewczak and Arnett, 2006 (*moderate* global risk of bias) conducted preliminary field tests during the summer feeding season from July to September 2006 at seven pond sites in California and Oregon (USA). Sites were chosen in areas where there was the possibility of high bat activity. Data was collected using camcorders to quantify the number of "visual passes" of bats entering and leaving the recorded view. Results show that under the ultrasound regime, bat activity was reduced by half.

- Szewczak and Arnett, 2007 (*strong* global risk of bias) continued their tests in August and September 2007 at six different ponds in Arizona, California and Oregon (USA). Their results show a significant reduction in bat activity, with a median activity rate/hour when ultrasound was broadcast estimated at 2.5 to 10.4 % of the activity rate when no ultrasound was broadcast, corresponding to a 90 to nearly 100 % reduction in activity.

- The experiments carried out by Horn *et al.*, 2008 (*moderate* global risk of bias) were conducted at a wind facility in New York (USA) in August 2007, involving two treatment turbines fitted with deterrents and two control turbines. Observations were made using thermal infrared imaging cameras to capture bat activity around the turbines. During the first test period, the average number of bats observed each night was significantly lower at the deterrent-treated turbines (13,1 bats) than at the control turbines (24.4 bats). However, during the second test, no significant difference in bat activity was observed between the deterrent-treated turbines (9.5 bats) and the control turbines (9.6 bats), suggesting that a variety of factors may influence the effectiveness of these devices.

- Arnett *et al.*, 2013 (*very weak* global risk of bias) conducted a study over two years from 2009 to 2010 at a wind facility in Pennsylvania (USA). The set up involved 10 turbines fitted with deterrent devices and 15 control turbines. Results from 2009 showed that 21-51 % fewer bats were killed per treatment turbine than per control turbine. In 2010, after factoring in an approximate 9 % inherent difference between treatment and control turbines, variation increased and ranged 2-64 % fewer bats were killed per treatment turbine relative to control turbines. In 2009, twice as many hoary bats (*Lasiurus cinereus*) and nearly twice as many silver-haired bats (*Lasionycteris noctivagans*) were killed per control turbine than at treatment turbines. In 2010, nearly twice as many hoary bats and nearly four times as many silver-haired bats were killed per control turbine that at treatment turbines.

- The experiments of Lindsey, 2017 (*weak* global risk of bias) were conducted in Texas (USA) during 2015 and 2016. The study focused on migratory bat species: hoary (*Lasiurus cinereus*), eastern red (*Lasiurus borealis*), and silver-haired (*Lasionycteris noctivagans*) bats. Three turbines were fitted with cameras and acoustic detection devices to record bat activity. Continuous or pulsed ultrasonic signals were emitted from a deterrent device placed 10, 20, and 30 m away from paired wind turbines and cattle ponds. In 2015, bat activity varied significantly depending on the distance of the deterrent device to the ponds, with a notable reduction in activity at 10 m compared to 30 m. At 10 m, the reduction in bat activity was 80 % and 75 % at ponds and turbines, respectively. However, no significant difference was observed near wind turbines. Moreover, there was no significant difference in bat activity depending on the type of signal emitted. In 2016, results showed a significant reduction in bat activity during the deterrent trials compared to the silent control periods, with an average 91 %, 84 % and 72 % reduction during spring, summer, and autumn, respectively.

- The study by Romano *et al.*, 2019 (*very weak* global risk of bias) was carried out at a wind farm in Illinois (USA) from 2014 to 2016, and involved 16 turbines in 2014 and 2015 and 12 turbines in 2016. Species studied included hoary (*Lasiurus cinereus*), eastern red (*Lasiurus borealis*), and silver-haired (*Lasionycteris noctivagans*) bats. Deterrent systems configurations varied each year: in 2014 deterrents were mounted on nacelles and towers, and emission was continuous; in 2015, deterrents were mounted only on towers at different heights (26 m and 50 m); in 2016, the system was configured to emit sound in pulses, with deterrents mounted on both nacelles and towers. Results showed a significant reduction in bat fatalities. In 2014, the overall reduction in bat fatality was 29.18 %, and 9.82-38.66 % for individual species. In 2015, this was 32.50 % overall, and -2.48 to 56.93 % for individual species (56.93 % for silver-haired bats). In 2016, overall bat fatality reduction was estimated at 1.71 %. Only the reduction in silver-haired bat fatalities (72.90 %) was significant. These results indicate that the effectiveness of the deterrent system varies between species and different deterrent configurations.

- Kinzie *et al.*, 2019 (*weak* global risk of bias) conducted an in-depth study with different experiments, including flight room tests, ground tests and field studies of turbine configuration. Flight room tests were conducted in a specially constructed flight room to observe the behavioural response of bats in the presence of different continuous or pulsed ultrasonic sounds. Captured bat species included eastern red (*Lasiurus borealis*), evening (*Nycticeius humeralis*) and Brazilian free-tailed (*Tadarida brasiliensis*) bats. Ground tests were conducted at Shawnee National Forest to observe the behavioural responses of bats in a natural environment, with ultrasonic devices emitting continuous or pulsed sound signals placed at different distances away from ponds. For the study of turbines in the field, 12 turbines at a farm in California (USA) were fitted with ultrasonic deterrent devices, some emitting a continuous signal and others emitting a pulsed signal. Results showed a significant reduction in bat activity when ultrasonic deterrents were used. Flight room tests showed that ultrasonic signals (both continuous and pulsed) influenced the foraging behaviour of bats, significantly reducing their activity. Ground tests at Shawnee National Forest estimated a 93.75 % reduction in bat activity in the 0-10 m area with a continuous signal. Field studies showed that ultrasonic deterrent devices reduced bat fatalities by 38 %, prior to the installation of an air-water separation system[7], for species other than the hoary bat. After installation, bat fatalities were reduced by 54 % although this reduction was not statistically significant. The fatality rate of hoary bats was not significantly reduced.

- Weaver *et al.*, 2020 (*weak* global risk of bias) conducted their study at a wind farm in Texas (USA) from July to October in 2017 and 2018. In total, 16 turbines were fitted with ultrasonic deterrent devices. Results indicate a significant reduction in fatalities (50 % overall), with notable reductions for hoary (*Lasirius cinereus*; 78,4 %) and Brazilian free-tailed (*Tadarida

[7] **Air-water separation systems**, also known as condensation seperation systems or dehumidifiers, are devices designed to dehumidify compressed air. In the context of ultrasonic deterrence, these systems play a crucial role in the proper functioning of ultrasonic devices. When a deterrent device emits ultrasounds, it can produce heat and condense ambient air moisture. This condensation can accumulate in the transductors or other parts of the device, reducing its effectiveness by affecting the propagation of ultrasonic waves. Air-water separation systems are installed to prevent this problem by removing excess air moisture before it accumulates in the sensitive parts of the deterrent device.

brasiliensis; 54,5 %) bats. However, no significant effect was observed for northern yellow bats (*Lasirius intermedius*).

- Gilmour *et al.*, 2020 (*moderate* global risk of bias) compared the effectiveness of acoustic and radar deterrence methods for reducing the impacts of human activity on bats. The study was carried out from July to September 2015 at 14 riparian sites in England and Wales. Four treatments were alternated over the sites: radar only, ultrasound only, radar and ultrasound combined, silent control (no sound/radar). Ultrasonic speakers were effective at reducing bat activity, with an overall reduction of 80 % when ultrasounds were used both alone and in combination with radar. By contrast, the use of radar did not have a significant effect on bat activity. Ultrasound treatment produced a deterrent effect for both the common pipistrelle (*Pipistrellus pipistrellus*; 40–80 % reduction in activity) and the soprano pipistrelle (*Pipistrellus pygmaeus*; 30–60 % reduction), however *Myotis* species did not show a significant response.

- Schirmacher *et al.*, 2020 (*very weak* global risk of bias) conducted a comparative study of 16 turbines in Ohio (USA) in 2017. Focus was placed on eastern red (*Lasiurus borealis*), hoary (*Lasiurus cinereus*), and silver-haired (*Lasionycteris noctivagans*) bats. Four treatments were compared: 1) control (deterrents off and cut-in speed set at 3.5 m/s), 2) deterrent (deterrents on and cut-in speed set at 3.5 m/s), curtailment (deterrents off and cut-in speed set at 5 m/s), and 4) combination of deterrent and curtailment (deterrents on and cut-in speed set at 5 m/s). Results showed that the reduction in fatalities was not significant for individual species. Eastern red bat mortality was 1.3 to 4.2 times higher when deterrents were on. Reduction in mortality of all bat species combined due to curtailment was estimated to be between 0-38 %, however this reduction was nullified when in addition to curtailment, deterrents were on. The combined treatment reduced mortality in silver-haired bats by 11-99 % relative to the control.

- The study by Cooper *et al.*, 2021 (*strong* global risk of bias) was conducted at a wind farm in California (USA) from March to October 2020. It involved 44 turbines, and was designed to test a new ultrasonic deterrent system: the StrikeFree™ system. This system uses an array of ultrasonic transmitters distributed along the blade to cover the entire area swept by the turbine blades. Preliminary results suggest that collisions are reduced, but technical difficulties, notably failures in power supply, limited the gathering of statistically significant data. The actual effectiveness of the StrikeFree™ system remains to confirmed by additional tests.

- The study of Good *et al.*, 2022 (*weak* global risk of bias) was conducted at two wind farm in northwestern Illinois (USA) during August to October 2018. Methods included the installation of acoustic deterrent devices and curtailment to compare bat mortality rates under different treatments: control (3.0 m/s cut-in speed), curtailment only (5.0 m/s cut-in speed), and curtailment combined with acoustic deterrence. The combination of acoustic deterrent devices and curtailment significantly reduced bat mortality. For instance, hoary, silver-haired, and eastern red bat mortality was reduced by 71.4 %, 71.6 %, and 58.1 %, respectively. Curtailment alone reduced silver-haired and hoary bat mortality but 14.8 % and 65.4 %, respectively, with also a limited effect on eastern red bats (38.8 % reduction).

- Werber *et al.*, 2023 (*moderate* global risk of bias) conducted a study to test the effectiveness of a drone-mounted audio-visual deterrent. The experiment took place in the Hula valley in northern Israel (not on a wind farm), in July 2020. They used a combination of RADAR, LIDAR and ultrasonic acoustic recorders to monitor bat activity at different altitudes. The drone-mounted deterrent produced a combination of pulsating ultrasound and white light signals. Results showed a significant reduction in bat activity when the deterrent was activated.

Analysis of RADAR data revealed a 40 % decrease in bat activity below the deterrent's flight altitude and a 50 % increase above the deterrent's flight altitude compared to the post-flight control. LIDAR data revealed a 32 % reduction in bat activity compared to periods immediately before and after the treatment.

The use of ultrasonic deterrent devices is an innovative approach for reducing bat collision risk at wind farms. Studies have shown a significant reduction in bat mortality (up to 91 %), depending on the species and the configuration of the device. Additional research is needed to standardize protocols, assess the long term impact on different species and test these devices in different environments in order to optimize operational efficiency and integration.

Acoustic bird deterrents

- Thady *et al.*, 2022 (*weak* global risk of bias) describe a study conducted in a laboratory in Virginia (USA) on zebra finches (*Taeniopygia guttata*) to evaluate the effectiveness of acoustic signals in reducing bird collisions with human-made structures. In a flight corridor containing a physical obstacle, birds were exposed to four types of acoustic signals at two frequency ranges (4-6 kHz or 6-8 kHz) and two temporal modulation patterns (broadband or frequency-modulated oscillating). Relative to control flights, all sound treatments caused birds to maintain a greater distance from hazards and adjust their flight trajectories before coming close to obstacles. There were no statistical differences among different sound treatments, but consistent trends within the data suggest that the 4-6 kHz frequency-modulated oscillating signal elicited the strongest avoidance behaviours.

Radar deterrents

An innovative approach to reduce collisions involves the use of radars not only for animal detection but also as a deterrent to dissuade animals from coming near wind turbines. The radar's electromagnetic fields (EMF) can affect a bird's ability to use the earth's EMF for navigation, thus leading them to avoid areas where radars are operating. Likewise, bats, whose sensory system can be sensitive to electomagnetic interference, can also detect EMFs and adjust their flight paths to avoid these areas. Three studies, conducted exclusively *ex situ* but in natural conditions, explored this use of radars:

- Nicholls and Racey, 2007 (*weak* global risk of bias) conducted an initial study on the aversif effects of EMFs emitted by radar installations on bat behaviour in Britain. The experiment was carried out at 10 radar stations: four civil airport air traffic control (ATC) radar stations, three military ATC radars and three weather radars. Data was recorded from June to September 2006. Automatic bat-recording stations and transect recordings were used to measure bat activity at three different distances from the radar stations: in close proximity with a high EMF strength, an intermediate point with a moderate EMF, and a control site registering no EMF. Bat activity was significantly higher in the control site than at sites exposed to a high EMF.

- In a second study, conducted from June to September 2007 in the northeast of Scotland, Nicholls and Racey, 2009 (*moderate* global risk of bias) compared bat activity at 20 foraging sites during experimental (radar switched on) and control (no radar signal) trials. They also measured the abundance of aerial insects from July to September 2008 using miniature light-suction traps (with and without radar signals). Bat activity and foraging effort per unit time were significantly reduced during experimental trials when the radar was switched on. However, the radar had no significant effects on the abundance of insects.

- Gilmour *et al.*, 2020 (*moderate* global risk of bias) tested the effectiveness of acoustic and radar deterrence methods at 14 sites riparian sites in England and Wales. The study was conducted between June and September 2015. Bat activity was measured from infrared videos and acoustic detection. The experimental setup involved a radar and ultrasonic speakers, used alone or in combination. Results showed that the radar alone had no effect on bat activity, unlike the ultrasound treatment (see the "ultrasonic acoustic deterrents" section above). Moreover, combining radar and ultrasound did not provide any significant additional benefit.

Using radars to elicit an avoidance behaviour and reduce collisions with wind turbines is an interesting approach. These *ex situ* studies show a significant reduction in bat activity in areas exposed to EMFs, suggesting that this method can potentially be used to dissuade animals from coming near wind turbines. However, results vary depending on the context, and certain trials did not show a significant effect. Additional research, including *in situ* and on a large scale, are needed to confirm the effectiveness of this approach and evaluate its effect on other species and environments.

UV light deterrents

The use of UV light to prevent collisions is a promising option. Birds have UV-sensitive photoreceptors and bats can also see UV light, which may help them detect obstacles. Three studies have examined this strategy:

- The study of May *et al.*, 2017 (*weak* global risk of bias) assessed the effectiveness of light in the violet and ultraviolet range in deterring birds from coming near wind turbines, and was conducted in Smøla (Norway) during spring 2014 (March to May). The study was done *ex situ*, using a 2.5 m mast fitted with two types of UV LED lights, within the violet (400 nm) and utraviolet (365 nm) wavelength spectrum. Bird activity was recorded continuously from dusk to dawn using an avian radar system, thus monitoring changes in flight behaviour in response to these lights. Results showed that bird activity (flight abundance), was reduced by 27 % with UV light and 12 % with violet light compared to the control (nights without light). Moreover, vertical displacement was seen, increasing the average flight altitude by 7 m when violet light was activated. This effect persisted over the season below 40 m above sea level during the entire study period.

- Research carried out by Gorrensen *et al.*, 2015 (*moderate* global risk of bias) assessed the effectiveness of UV light for reducing the activity of Hawaiian hoary bats (*Lasiurus cinereus semotus*) near wind turbines to reduce collision risk. The study was conducted on the island of Hawaii, from September to October 2014. Observations were made on a macadamia plantation bordered by pines, where Hawaiian hoary bats are highly active. Methods consisted in illuminating trees with dim flickering UV light, and monitoring bat activity and insect abundance. Bat activity was quantified acoustically and visually, and insects were trapped to evaluate the effect of UV light on their abundance. Results indicated that dim UV light significantly reduced bat activity despite an increase in insect numbers (x6 on average). Bat echolocation activity was reduced b y 44 %. Moreover, the duration of video detections of bats increased by 40 % during UV light treatment.

- Cryan *et al.*, 2021 (*moderate* global risk of bias) conducted an experimental study on two wind turbines at the National Wind Technology Center at the National Renewable Energy Laboratory in Colorado (USA) from August 2018 to October 2019. Turbines were lit at night with dim flickering UV light. The activity of bats, birds and insects was measured with thermal-imaging cameras. No statistical differences were detected in the activity of bats, insects or birds at the test turbine with UV illumination. Precise observations reveal that UV light did not induce significant behavioural changes in bats or increase collision risk.

Results show that UV light is a promising option for reducing collision risk, in particular by reducing the activity of birds and bats near obstacles. However, its effectiveness varies depending on the species and context, suggesting that additional research is needed to optimize its use.

Modification of turbine design

Turbine size

Two studies in the literature assessed the effect of turbine size on bird mortality, focusing specifically on rotor diameter:

- For her Masters thesis, Martin, 2015 (*weak* global risk of bias) evaluated the impact of increasing the cut-in speed on bat and bird mortality, as well as the effect of rotor diameter (93 m vs 96 m). The study was conducted at a wind facility in Vermont (USA), and involved 4 turbines with a 96 m rotor diameter and 12 turbines with a 93 m rotor diameter. Daily fatality searches at all turbines were conducted from June to September 2012 and 2013. Results showed an average mortality of 5.25 bats per turbine for turbines with a 96 m rotor diameter vs 3.17 for turbines with a 93 m rotor diameter, although this difference was not significant. The average bird mortality was higher at turbines with a 96 m rotor diameter (4.50 birds) compared to turbines with a 93 m rotor diameter (2.08 birds) and this difference was significant.

- Anderson *et al.*, 2005 (*moderate* global risk of bias) assessed the impact of turbine rotor diameter on bird mortality in the San Gorgonio Pass in California (USA). The study involved 423 turbines grouped into three types: large tubular turbines (< 26 m rotor diameter), small tubular turbines (< 26 m rotor diameter), and small lattice turbines. Results showed that large tubular turbines were associated with a higher bird mortality rate (0.087/search) compared to small tubular turbines (0.035), even though this difference was not statistically significant. The raptor risk index was higher for large turbines (0.8) than small turbines (0.196) but this was not statistically significant. Overall, bird mortality rates were slightly higher near large turbines for all categories of birds, except corvids, for which no mortality was observed near large turbines.

Results from these studies show that a larger rotor diameter may be associated with a higher mortality in birds and bats. However, this difference is not always statistically significant, and the precise effect of rotor size on collision risk remains unclear, requiring further research to clarify this relationship.

Paint and texture

Five studies investigated the effectiveness of altering the visual aspect of wind turbines, for instance by applying colour or a special coating, to reduce both the risk of collision and the attractivity of these structures for animals. Only one study looked at insects, the other four focusing on birds.

- The study of Stokke *et al.*, 2020 (*moderate* global risk of bias) at the Smøla wind power plant (68 turbines) in Norway, used a BACI approach to test if painting the lower parts of the turbine towers black would reduce the collision risk of willow ptarmigans (*Lagopus lagopus*). Ten turbines were painted and neighbouring turbines were used as controls. Altogether in the

2006-2017 period, 474 carcasses were found, of which 194 were willow ptarmigans. Results showed that there was a 48,2 % reduction in the number of recorded ptarmigan carcasses per search at painted turbines relative to control turbines. The average distance at which ptarmigans were found from the foot of the tower increased significantly in painted turbines from 15.0 to 34.6 m, demonstrating the effectiveness of this mitigation measure.

- May *et al.*, 2020 (*moderate* global risk of bias) also conducted a study at the Smøla wind power plant, from 2006 to 2016, to assess the effectiveness of painting one rotor blade black in reducing bird fatalities. Using a BACI approach, four turbines had one of their blades painted black and four were used as controls. Results showed a significant reduction of 71.9 % of the annual bird fatality rate with a painted blade, with a notable effect on raptors, including white-tailed eagles, for which no carcasses were recorded after painting. The probability of recording raptor carcasses after painting was extremely low (< 0.001), indicating that this measure is highly effective.

- Research by Erickson *et al.,* 2003 (*weak* global risk of bias) examined the effect of coating turbine blades with UV-reflective paint in Wyoming (USA). The study, conducted from July 1999 to December 2000, involved 105 turbines, where some blades were coated in UV-reflective paint to minimize bird collisions. Blades from 69 turbines were treated with UV-reflective paint, whereas 33 other blades where coated with conventional paint. Overall raptor detection was significantly higher in theUV area (0.778 detections/40-minute survey) than in the non-UV area (0.215). Significantly higher use of the UV area was also found for swallows and thrushes. However, overall passerine use was not significantly different between the two areas, primarily due to a higher horned lark abundance in the non-UV area. Fatality rates for UV and non-UV turbines were not significantly different, although overall passerine fatality rates at the UV turbines were two times higher than at the non-UV turbines, primarily due to a higher number of horned lark casualties per turbine. Raptor fatality rates were very similar between UV and non-UV turbines (0.0029 and 0.0031, respectively).

- Hodos, 2003 (*high* global risk of bias) carried out more experimental and theoretical research at the University of Maryland (USA). Using the laboratory methods of physiological optics, animal psychophysics, and retinal electrophysiology, the study examined the visual responses of American kestrels to a variety of patterns on turbine blades. The different configurations included blades with stripes and uniformly coloured blades, tested against different natural backgrounds and at various rotation rates. Results showed that at low retinal velocities[8], thin stripes improve blade visibility. Visibility was four times greater for blades with thin stripes than blank blades at 130 dva/sec (degree of visual angle per second) retinal velocity. However, at higher velocities, such as 240 dva/sec, the visibility of thin stripes decreased markedly, making them almost indistinguishable from blank blades. Moreover, blades painted black were found to be the most visible against a range of backgrounds, and were more effective than red, green or blue blades, whose efficacy varied depending on the colour of the background. For instance, in an environment with a deep blue sky and yellow-brown leaves, black blades were much more visible than the other colours tested.

- Long *et al.*, 2011 (*moderate* global risk of bias) assessed whether turbine colour has an influence on insect numbers at wind power installations in Oadby (U.K.). The experiment was

[8] **Retinal velocity** refers to the speed at which the image of a moving blade crosses the retina. This velocity describes the speed at which an image moves across the retina, influencing the ability of eye to follow and clearly identify objects in motion.

carried out near a 13 m turbine with three blades located in a public park. Ten colours were tested, including common turbine colours such as pure white and light grey, as well as other hues (squirrel grey, sky blue, traffic red, red lilac, traffic yellow, pale brown, opal green, and jet black). The relative attraction of insects to these colours was observed over a period of three years, from June to October, with insects counted at midday and one hour after sunset. Results indicated a significant difference in the attractivity of these colours, with yellow (on average 6 insects/10 minute session) and the common turbine colours white and light grey (on average 4.5 and 3 insects/10 minute session, respectively) being the most attractive. By contrast, red lilac attracted significantly fewer insects (on average 1.25 insects/observation period), making it the least attractive of all the colours tested. UV and infrared spectral reflectance can also affect insect attraction, with colours with higher peaks of reflectance being more attractive. The total number of observations amounted to 2012 insect visits over 59 sessions, with activity peaks in July and less activity in October.

The use of black paint or motifs on turbines seems to be a very promising method for reducing bird collisions, especially for vulnerable species such as raptors and ptarmigans. Colours, however, must be chosen carefully to minimize insect attraction and avoid indirect ecological effects. These results call for a more in-depth study of what may be the optimal visual characteristics of turbines, as well as a targeted implementation of these solutions, taking the local fauna and natural backgrounds into account to maximize the effectiveness of these measures while limiting their impact on other species.

The effect of textured surfaces, compared to smooth surfaces (*i.e.* current wind turbines), on bat behaviour was the focus of two studies, one conducted in captivity and the other at a wind facility:

- Bienz, 2016 (*strong* global risk of bias) tested whether texturing tower surfaces could reduce bat mortality at wind turbines. Behavioural experiments involving bats captured locally in Texas (USA), including species that frequently collide with wind turbines, were carried out at a flight facility. Texture trials were particularly revealing: bats approached and came into contact with smooth surfaces, like that of turbine towers, significantly more often than with finely textured surfaces (12 passes vs 5 passes, respectively). However, coarsely textured sufaces were not significantly better than smooth surfaces. These observations suggest that bats could mistake smooth surfaces for water bodies. Note, however, that the surfaces tested were horizontal and not vertical.

- Huzzen, 2019 (*moderate* global risk of bias) conducted an in-depth study at Wolf Ridge Wind, LLC in north-central Texas (USA), involving two pairs of wind turbines. The aim was to determine whether bat activity and behaviour changed near wind turbines with textured tower surfaces. The applied textured coating was designed following the results of Bienz (2016). Using a combination of night vision, thermal, and ultrasonic acoustic technologies, bat activity was assessed at two pairs of turbines (one textured and a control) from 20 May to 22 September 2017. No significant difference was found in overall bat activty between smooth and textured turbines. Acoustic data enabled the identification of species and detected species-specific differences in echolocation behaviour, with hoary bats showing a marked increase in activity at one textured turbine, but not at the other. These conflicting results may be due to differences in the application of the textured coating between the two towers, as mentioned in the document.

Results from studies on the effectiveness of textured surfaces for reducing the attraction of bats to wind turbines are mixed, but provide an interesting perspective for minimizing the impact of wind power on flying species. Additional research is needed for improving textures, their characteristics, testing their effectiveness *in situ* and better understanding their impact on different species.

Wind farm repowering

Two studies assessed the impact of replacing older turbines with more modern models.

- The study of Ferri *et al.*, 2016 (*weak* global risk of bias) focused on the effects of wind farm repowering on bat assemblage[9] structure in central Italy from 2005 to 2010. Repowering involved replacing older one-bladed turbines with three-bladed turbines. Bat activity was recorded with ultrasonic automatic bat monitoring units before and after repowering. Results showed a change in the structure of bat assemblages, including changes in the relative frequency of certain species as well as other diversity indices. The relative frequency of species such as Geoffroy's bat (*Myotis emarginatus*) and the common pipistrelle (*Pipistrellus pipistrellus*) decreased and increased, respectively, suggesting that some bats may be sensitive to repowering.

- The study of Smallwood and Karas, 2009 (*strong* global risk of bias) assessed the impact of modernizing a wind farm in the Altamont Pass Wind Resource Area in California (USA), where 126 vertical-axis turbines were replaced with 31 modern three-bladed turbines. Fatality searches were conducted during 1998-2003 and 2005-2007. Analyses showed that global fatalitiy rates did not differ between old and new-generation turbines. However, fatality rates were 54 % lower for raptors and 66 % lower for all birds combined at new-generation turbines compared to concurrently operating old-generation turbines during 2005-2007. As new-generation turbines can generate three times more power per megawatt of rated capacity, complete repowering of the area could reduce fatality rates, while signficantly increasing annual wind energy generation.

Repowering, *i.e.* replacing old turbines with more modern models, has the potential to both reduce the impact of wind energy on biodiversity and increase the capacity of current installations. New-generation turbines are more efficient and can generate more energy, which would argue for the complete repowering of existing wind facilities. However, to maximize the ecological benefits of this measure, pre-invervention environmental assessments and post-intervention surveillance need to be carried out alongside other conservation measures.

Management of ecological factors that attract animals

Examples of mitigation measures that reduce attractivity

Three separate studies have focused on the management of ecological factors that can attract animals:

- The study of Pescador *et al.*, 2019 (*strong* global risk of bias) assessed the effectiveness of a mitigation measure centred on lesser kestrels (*Falco naumanni*) at three wind farms in Spain. They analyzed bird mortality by recording deaths over a ten-year period. A mitigation measure was then implemented, involving superficially tilling the soil around the base of 41 turbines (58 turbines were used as a control) thus making these areas less attractive to lesser kestrels by reducing the amount of vegetation and the abundance of potential prey. This measure was monitored for two years before and after its implementation. It resulted in a significant

[9] In ecology, the term "**assemblage**" refers to a group of species that coexist in a given space at a given time, forming a community with dynamic interactions between its members. In general, an assemblage is characterized by the number of species, their relative abundance, and their ecological role within the ecosystem.

reduction in the number of collisions, with a 75 %, 82.8 % and 100 % reduction depending on the wind farm. In parallel, there was a significant reduction in the relative abundance of insects: 72.6 % for orthoptera, 56.3 % for lepidoptera and 68.0 % for coleoptera. Note that this tilling method also has a significant impact on biodiversity, as seen in the reduction in insect populations, as measured during the trial. It would be prudent to not implement this measure in the first instance or when kestrel mortality remains low.

- Smallwood and Thelander, 2005 (*strong* global risk of bias) showed that rodent control significantly impacted the distribution of fossorial rodent burrows around wind turbines. The anticoagulant rodenticide chlorophacinone was applied to control rodent populations including ground squirrels and gophers in wind turbine areas. Their study, conducted at the Altamont Pass Wind Resource Area in California (USA), and involving 1536 turbines, showed that birds, in particular raptors, corvids and passerines exhibited changed behaviours in plots with intermittent or intense rodent control. Unexpectedly, birds were recorded flying for significantly longer periods at these plots than expected by chance. Moreover, some plots were preferred for flying. Perching was also more frequent, and more flights were recorded within 50 m of the turbines. It is important to note that chlorophacinone poses different ecological risks (Erickson and Urban, 2004). This chemical can secondarily poison predators that consume contaminated rodents, potentially affecting a range of carnivores including raptors. The application of chlorophacinone is not specific, and can therefore also poison non-targeted species, persist in the environment, and have long term effects on biodiversity.

- The study of Shewring and Vafidis, 2017 (*strong* global risk of bias) assessed the effectiveness of regularly clearing all ground vegetation above 10 cm, using industrial brush-cutters, in the vicinity of 17 turbines out of the 76 present on a wind farm in South Wales (U.K.). The territorial activity of male European nightjars (*Caprimulgus europaeus*) was monitored using presence-absence surveys conducted twice in June and July. Male display activity was observed in 41 % of treated areas, and 23 % of untreated areas, with no nest confirmed within these locations. Clearing vegetation around wind turbines poses a number of ecological risks (Dale and Polasky, 2007). First, this measure can lead to habitat loss for many species, including insects, small mammals and other animals that depend on plants for food, protection (hiding), or reproduction (nesting), reducing local biodiversity and disrupting food chains. Moreover, clearing the vegetation cover exposes the ground to an increased risk of erosion, particularly sloped terrains, which can lead to soil quality degradation and negatively impact nearby river beds from increased run-off and sediment deposition. These practices can also modify the ecosystem by changing its plant species composition, with more resistant plants becoming dominant at the expense of more sensitive plants, thus modifying the natural dynamics of the ecosystem. Finally, the noise and human activity associated with the regular clearing of vegetation can disturb local wildlife, causing stress and potentially leading to bird population decline, as was reported in certain studies on the effect of wind farms on local wildlife.

Results from the removal of ecological factors that attract animals at wind farms are mixed in terms of mitigating the impact of wind power on biodiversity. Although the number of collisions did decrease in some cases, such measures often have substantial negative ecological consequences, such as a reduction in biodiversity and the disturbance of ecosystems. These impacts limit the interest of such measures, and they should only be envisaged in situations where the ecological benefits outweigh the costs.

Aviation warning lights

Two studies were found that assessed the impact of aviation warning lights on nocturnal flying species:

- In her thesis mentioned above, Martin, 2015 (*weak* global risk of bias) also assessed the impact of red flashing Federal Aviation Administration (FAA) lights fitted to wind turbines. Average bat mortality at the 8 turbines without FAA lighting was 4.50 fatalities/turbine and 2.88 fatalities/turbine at the 8 turbines with FAA lighting. In birds, the average mortality was 3.38 without and 2 with FAA lighting. These differences were not stastically significant.

- d'Entremont, 2015 (*moderate* global risk of bias) specifically studied the impact of different artificial lights on the behaviour of nocturnal migratory birds in north-east British Columbia (Canada) from 2008 to 2012. Marine radar units were used to track bird movement and altitude when exposed to different lights (different wavelengths and flash rates (fixed or flashing)). Results showed that there was a significant interaction between the type of signal and the light colour. Light colours at shorter wavelengths (blue or green) were more attractive to nocturnal migratory birds. In general, birds flew at lower altitudes in the absence of lights than when exposed to flashing lights. Flight altitudes were higher in the presence of red and white lights compared to no lights.

Although aviation warning lights can potentially reduce nocturnal bird and bat fatalities, they can also have a negative impact on biodiversity, and assessments need to be carried out before they are used. As shown by d'Entremont (2015), the navigation and migratory behaviour of flying animals can be impacted. These effects can lead to exhaustion and lower survival rates.

QUANTITATIVE SYNTHESIS: MAIN RESULTS

Note to readers:
For those wishing to access the full details of the methods and results of the quantitative synthesis, these are given in Appendix VI. Detailed information on the models tested, the data used and specific results are described. Readers are invited to read the appendices for a more technical understanding of these analyses.

To assess the effectiveness of the mitigation measures for reducing the impact of onshore wind power on flying species, we performed a mixed-effects linear regression on a single measure: curtailment by raising the cut-in speed. The meta-analysis focused more specifically on bat mortality, all species combined. The decision to focus on this measure and its effect was made on account of the data available (other measures could not be analyzed due to insufficient data).

Results showed that curtailment significantly reduced bat mortality (Figure 13), with a mean reduction of nearly 67 %. This figure suggests that this measure has real potential as a useful tool to minimize the ecological impact of wind turbines. However, certain limitations have been identified, including the heterogeneity of the contexts in which the studies were carried out (different climates, landscapes, and the use of different methodologies), as well as the small amount of data available for certain categories. These constraints affect the robustness of the statistical conclusions and make it difficult to generalize to other geographic or ecological contexts.

We also explored the influence of different factors, such as climate or variation in the cut-in speed, using additional statistical models. Although no significant effect was found with these analyses, they highlight the complexity of the interactions between environmental conditions and the effectiveness of this measure. These results show that it is essential to have a nuanced approach and take into account local conditions when implementing such measures.

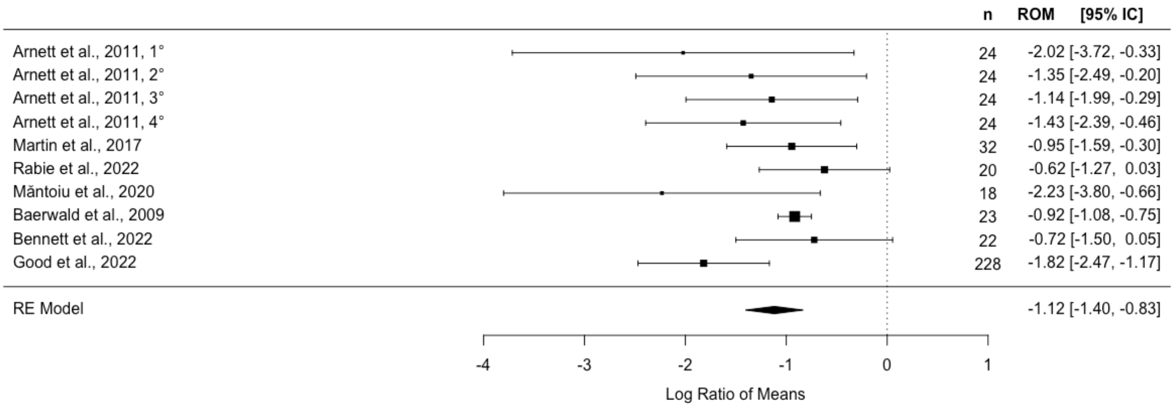


Figure 13. Summary of the linear model on the link between cut-in speed and bat mortality rate. This figure shows the global effect of raising the cut-in speed on mortality, i.e. if turbines are activated at higher wind speeds, the number of bat fatalities decreases. Each black square represents the mean of the observed effect in the study, while horizontal lines on either side of the square are confidence intervals (95 % CI). If a horizontal line (CI) does not cross the vertical 0 line, this means that the effect is considered to be statistically significant ($p < 0.05$). Conversely, if a horizontal lines crosses the vertical 0 line, the result is not statistically significant. A position to the left of the line indicates that raising the cut-in speed is associated with a reduction in mortality, compared to a standard cut-in speed. Finally, the diamond summarizes the results, with the overall mean indicating a protective effect.

In conclusion, turbine curtailment by raising the cut-in speed seems to be an effective measure for reducing the impact of onshore wind power on bat mortality. However, additional research is needed. It should include collecting data that are more balanced and representative of different environmental contexts, as well as using more standardized protocols to improve the comparability of the results from different studies. It would be interesting to carry out new studies and/or systematic reviews for specific conditions. This would reinforce the validity of the the conclusions and refine the recommendations for the optimal implementation of this measure worldwide. These efforts must be continued to improve our understanding and tailor mitigation policies to local conditions and specific species.

DISCUSSION AND PERSPECTIVES: IMPLICATIONS FOR RESEARCH AND DECISION-MAKING

The aim of this synthesis paper was to review the scientific and technical literature on the effectiveness of mitigation measures and the good practices put in place to limit the impact of onshore wind power on biodiversity, especially flying species (birds, bats, and flying insects). This rapid review identified 60 primary research documents, comprising a total of 535 case studies.

First of all, our temporal analysis revealed that there has been a gradual increase in the number of publications on this topic, especially since 2016. This trend is probably linked to a growing awareness of the environmental impact of renewable energy, as well as to improvements in research methodologies. This temporal evolution provides essential context for understanding the emergence and development of mitigation strategies over time.

Moreover, studies were mainly conducted in North America and Europe, reflecting not only the extensive development of wind facilities on these continents, but also the level of funding for environmental research in these parts of the world, as well as a potential language bias. For instance, China, whose wind sector has grown considerably in recent years, could be underrepresented in this analysis, as we probably missed relevant papers in Chinese. This geographic distribution introduces a regional bias in the data, limiting our ability to derive general conclusions. Ecologically and climatically diverse regions such as South-East Asia, Sub-Saharan Africa and South America are largely underrepresented in published studies. These knowledge gaps could lower the effectiveness of these mitigation measures in these regions, since the ecological impact could differ substantially due to differences in the nature of the environment and local ecosystems. It is crucial to encourage and fund research in these regions to ensure that policies and mitigation measures are suitable and effective worldwide. Few studies in our survey have focused specifically on France. For the reasons mentioned above, we cannot provide a categorical assessment for France of the effectiveness of the mitigation measures identified in our survey. It is important to conduct targeted research on the impact of mitigation measures specifically for France, to make up for the lack of data and provide recommendations that are specifically tailored to local conditions.

Our analysis, which focused on flying species, also showed that research was primarily centred on birds and bats. Very few studies focused on insects. This could be explained because the impacts on birds and bats are directly visible, for instance from the number of fatalities caused by collision with wind turbines. Moreover, these species are often protected by specific legislation, such as the avoid-reduce-compensate sequence, in the country in question, unlike insects which are less protected. Birds and bats are also considered to be emblematic species, and, especially for raptors and bats, their longevity means that their populations are very sensitive to increases in mortality, which increases the importance of minimizing these losses. However, by focusing on larger fauna, we fail to grasp the wider systemic impacts of wind farms on ecosystems, and consequently we lower our ability to mitigate these impacts. The underrepresentation of insects is worrying, given their crucial role in many ecological processess, including pollination, the decomposition of organic matter and the regulation of populations of other species through predator-prey interactions. Moreover, neglecting invertebrates could indirectly intensify the mortality risk for bats and birds. Indeed, wind turbines potentially attract insects, creating a focal point for their aerial predators.

In situ and *ex situ* studies are essential for the assessment and implementation of effective mitigation strategies. *Ex situ* studies were conducted in controlled or simulated environments, such as laboratories, semi-natural installations, or in natural environments with selected characteristics but without wind turbines. These studies allow us to understand the mechanisms underlying certain behavioural or ecological responses, while minimizing the interferences and uncontrolled variables often found on wind farms. These studies are essential for testing different mitigation scenarios, assessing the physiological response of species to disturbances, and testing new technology before it is deployed in the field. In parallel, *in situ* studies involve research that is directly conducted in the field, in natural environments where wind turbines are located. These studies allow us to observe the real effects of wind turbines on local wildlife, and provide direct data on for instance bird and bat mortality, changes in animal behaviour, and altered ecological interactions. These studies are essential for testing the effectiveness of mitigation measures under real conditions and adapting these measures to the specificities of each site. Combining the results of *in situ* and *ex situ* studies enriches our knowledge base, provides a more comprehensive understanding and enables a more holistic approach to conservation in the context of wind power. It is advisable to continue combining these two approaches to overcome the specific limitations of each one and benefit from their complementarity.

More specifically, our analysis of the literature showed that much of the *in situ* research focused on mortality rates, probably because of awareness of the environmental urgency and also because it is relatively easy to quantify. However, assessments of the effectiveness of measures for mitigating other types of impact are lacking. It therefore seems advisable to encourage more research on aspects of behaviour and demographics, such as reproduction, migration and offspring survival. This approach would provide a more complete and nuanced assessment of the effectiveness of mitigation measures and improve their implementation for optimizing conservation efforts.

Our survey of mitigation strategies showed that certain strategies, such as acoustic deterrence, the temporal management of turbine operation, and visual signals to make turbines more visible to flying species, were predominant. Despite their prevalence, the effectiveness of these measures was variable and often depended on the local context and the species in question. For instance, acoustic deterrence was found to be very effective for certain species of bats, but less so for others. Moreover, innovative measures, such as coating blades with UV paint or integrating radar technology to detect birds, are promising but they are not sufficiently documented in the scientific literature. This suggests that future research should not only assess the effectiveness of these new technologies but also continue to explore the combination of measures to increase the overall effectiveness of mitigation strategies.

From these observations, we propose the following recommendations for the following mitigation measures:

- **The optimization of acoustic deterrent devices for bats**. Additional research is needed to improve the use of these devices, and verify their effectiveness on a large scale. Integrating this technology directly into the design of wind turbines could maximize the protection of wildlife, while having little impact on turbine operation. Studies also recommend optimizing the sound signals in terms of frequency and amplitude so that they are adapted to the behaviour of specific species, including European species.
- **Combined strategies.** Combining acoustic deterrence and curtailment strategies is recommended to maximize the reduction of bat mortality. Combined strategies should also include proactive management measures, such as integrating these measures at the planning stage, where species-specific characteristics and local environmental conditions are taken into account.
- **Multimodal devices and radars.** Integrating acoustic signalling into multimodal deterrent devices seems like a promising approach. Research is needed to assess whether radars and electromagnetic fields can be effective deterrents. However, it is recommended that radars should not be used on their own due to their limited effectiveness. Studies suggest pursuing research to determine how species perceive and react to electromagnetic fields.
- **Use of UV lighting.** The optimization of UV lighting to reduce bird and bat collisions with wind turbines is strongly recommended. Additional research is needed to improve the design and effectiveness of UV lighting systems, while taking into account their wider ecological impact, such as the fact that they attract insects, which could disrupt local food chains.
- **Painting wind turbines.** Multiple studies recommend apply specific paints to wind turbines to improve their visibility and reduce the risk of bird collisions. Tests under real conditions and additional research are needed to confirm the effectiveness of using motifs, such as thin stripes, and colours that are less attractive to insects, in various environmental contexts.
- **Specific textures.** We encourage the application of specific textures on turbine towers to reduce bat collision risk. Additional research is needed to determine which type of texture should be used and assess their effectiveness for different species of bats in different environments.
- **Managing ecological factors.** The management of ecological factors on wind farms is an interesting approach to mitigate the impact of wind turbines on wildlife. However, we recommend putting in place specific measures that are adapted to the local environment, and take into account their potential impact on neighbouring ecosystems. Thus, as detailed above, modifying the environment near wind turbines can reduce the site's attractivity for raptors, but it is crucial to ensure that these interventions do not cause more far-reaching disturbances, such as habitat loss for other species or an ecological imbalance. The objective is to prefer combined and sustainable solutions that reduce collision risk while preserving the integrity of local ecosystems.

- **Predictive models.** The use of collision risk models to inform policy-making and the design of wind farms is recommended. These models allow the comparative assessment of the collision risk under different wind farm configurations and with different types of turbines.
- **Wind farm repowering and its impact over the long term:** It is essential to continue researching the long term impacts of repowering on local wildlife. A preventive approach is recommended in areas where bats or birds that are important for conservation are present. It is important to assess the impact of repowering to develop effective conservation and management strategies.

Although our analysis of the literature showed that there were practically no studies on either avoidance or compensation/offsetting measures (from the avoid-reduce-compensate sequence), different hypotheses could explain this situation. One reason could be that the keywords used in the biblographic searches were not precise or suitable enough to identify such studies. The specific terms associated with avoidance and compensation/offsetting can vary between authors and research fields, which can lead to incomplete or irrelevant search results. In addition, many studies on avoirdance and compensation/offsetting do not specifically deal with onshore wind power (A. Besnard, pers. comm.). Some studies can be more general or applied to other types of infrastructure, and are thus not directly visible when searches focus exclusively on onshore wind power. Moreover, the article selection criteria for this review may have led to the exclusion of certain papers. For instance, studies using predictive models to identify sensitive areas may have been conducted and published, but since they lack any before-after evaluation, any intervention, or any possibility to measure their effectiveness, they were excluded. The stage of development of research in the field of onshore wind power could also be an explanation. Although on the increase, research on the measures mitigating the impact of onshore wind power on wildlife is still relatively new. Therefore, it may be that fewer studies have been carried out on specific aspects such as avoidance or compensation/offsetting, compared to more commonly studied strategies such as acoustic deterrence or modifying the appearance of wind turbines. Moreover, studies on avoidance and compennsation/offsetting are often complex and expensive, requiring investment over the long term, detailed data on animal behaviour, and in-depth analyses of the impacted ecosystems and of the compensation/offsetting measures that are put in place. These requirements can limit the number of studies carried out in this field, especially in a context where research funds are limited. It is also possible that other studies do exist but are not easily accessible or are published in obscure journals. Unpublished studies, internal reports of companies and undisclosed case studies may contain relevant information, but are not always integrated into research databases. To fill these gaps, it is important to adopt a more inclusive approach to research, promote funding in specific research areas, and encourage the publication and dissemination of scientific results.

Finally, our inability to carry out a complete and detailed meta-analysis of all the data we compiled highlights the need for standardizing data collection and reporting methods. Meta-analyses depend on the ability to compare and synthesize data from multiple comparative studies that follow similar experimental protocols, which demands a certain uniformity in the way that data are reported and analyzed. To maximize the usefulness of individual studies and facilitate their integration into larger meta-analyses, it is essential to develop standard protocols. This means designing and using standardized research protocols in studies on the impact of wind turbines, covering methodological aspects such as sample size, methods used for data collection, and criteria for impact assessment. These protocols should be devised in collaboration with experts to ensure their suitability and applicability. Next, it is important to encourage the use of a standard format for reporting information in publications and technical reports including methodological details, statistical results (including basic statistical parameters such as the mean and the standard deviation) and conclusions. This would greatly facilitate the comparison and integration of different studies. Moreover, it is crucial to promote data sharing within the scientific community, by using accessible data repositories and encouraging researchers to make their data available after publication. Data sharing makes reanalyses and meta-analyses more robust, and their conclusions more reliable.

This synthesis showed that there is a growing awareness of the impact of wind power infrastructure on wildlife, mainly birds and bats, and that the methods used to study this impact are evolving. However, it also highlights a number of significant issues, such as the geographic and taxonomic underrepresentation of certain regions and taxonomic groups (insects). It is essential to promote more balanced and inclusive research, develop standardized protocols for data collecting and reporting, and adopt a more holistic approach that integrates the wider ecological impacts of wind power. These efforts will contribute to a better understanding of the different mitigation measures and will improve their effectiveness, which is essential for harmonizing the development of renewable energies with the need to conserve biodiversity.

EXPERT OPINION

In a collaborative effort to assess and improve the effectiveness of the measures for mitigating the impact of onshore wind power on biodiversity, experts were invited to a meeting to discuss the results of this synthesis. This meeting enabled research institutes, wind farm operators and developers, government bodies and regulators, funding bodies and R&D departments to interact directly and take part in a fruitful and constructive exchange. A questionnaire was handed out afterwards to get feedback on the meeting and the intermediate report. The aim of both the meeting and the questionnaire was to provide a better understanding of the participants' perspectives and experiences of the different mitigation measures, but also of the obstacles they face for their effective implementation. This participatory approach is crucial for validating and enriching our review, and it ensures that the final report is both comprehensive and representative of the reality on the ground.

Current knowledge and practices in place

Speakers highlighted the importance of understanding the complex interaction between wind power infrastructures and local ecosystems. Discussions revealed that there was an in-depth awareness of the direct impacts on wildlife such as bat and bird mortality, as well as of the indirect effects such as the disturbance to natural habitats and animal behaviours. Participants shared information on the different approaches used by their organizations, such as:

- **Ecological planning and design.** Planning and impact studies are crucial for selecting sites that are less likely to be harmful to biodiversity. These analyses assess the potential impact on fauna, flora and ecosystems, and steer the choice to mimize ecological disturbances. Sites are selected to avoid areas of high biological value, and the installation is specifically designed to reduce its ecological footprint, including through the implementation of mitigation measures such as the creation of buffer zones and the restoration of habitats.

- **Post-installation monitoring of the environment**. Monitoring programmes were put in place to assess the impact of wind farms on local widlife and adjust mitigation measures accordingly. These programmes facilitate the identification of problems in real time, and allow managers to react proactively to minimize negative impacts.

- **Adoption of new technology.** The adoption of new technologies and systems for curtailment and deterrence, AI-powered detection systems, as well as painting turbine blades, is widespread and frequently brought up. This trend illustrates the growing adoption of advanced technical solutions for minimizing the impact of wind turbines on the environment.

- **Landscape and ecological management.** The importance of landscape management measures such as the creation of buffer zones, the restoration of natural habitats, or the installation of nesting sites, is well recognized. These initiatives provide alternative habitats and contribute to the reduction of the risk to wildlife, and emphasize the crucial role of biodiversity conservation near wind facilities.

Challenges and constraints

During the meeting (and through the answers given in the questionnaire), multiple challenges and constraints for the implementation of mitigation measures were identified. These challenges are varied, encompassing economic, technical, regulatory and social angles.

- **Economic and financial constraints.** Discussions have highlighted that economic constraints represent a major obstacle for the implementation of mitigation measures. The high initial cost of installing new technology, such as a detection system for bats, or of carrying out structural modifications of the turbines to reduce their visual and acoustic impact, can put investors off. Moreover, participants have expressed their concern over the financial viability of long-term monitoring programmes, even though they are crucial for assessing the effectiveness of the environmental measures implemented.

- **Technical and scientific constraints.** From a technical point of view, participants discussed the limitations of current technology and the need for additional research to improve the effectiveness of mitigation solutions. A particular challenge is the precision of detection systems, which must be able to function in different environmental conditions, and at the same time minimize the number of false alarms that stop the turbines unnecessarily. The questionnaire responses also were also concerned with the homogenization of protocols, which is essential for ensuring the comparability and reproducibility of data collected at different locations.

- **Regulatory and administrative constraints.** Regulatory and administrative constraints were frequently brought up as a significant barrier. The process of getting a project approved can be long and complex, and this complexity can be exacerbated by ill-defined or fluctuating regulation. Participants expressed the need for more clarity in the environmental policy and a better coordination between different levels of government and regulatory agencies to simplify the procedure and cut down processing time.

- **Challenges associated with public concertation and acceptance.** Another important challenge that was brought up was the issue of concertation with local communities and their acceptance of wind power developments. The perceived impact of wind farms, such as the noise or the visual impact, can stir up local opposition, which means that it is crucial to involve the public early in the planning stages. Responses indicated that successful public engagement hinged on transparent communication on both sides and the active participation of communities in the processes of project planning and environmental impact monitoring.

These challenges and constraints highlight the complexity of implementing measures for mitigating the impact of onshore wind power on biodiversity. They stress the need for an integrated approach that combines technological innovation, financial support, clear regulation and a close cooperation with local communities. Overcoming these challenges is crucial for the successful integration of wind power into the energy mix while conserving biodiversity.

Identification of operational and scientific needs

Identification of knowledge gaps and operational needs

During the workshop, it became clear that despite the significant advances in our understanding of the interactions between onshore wind power infrastructure and biodiversity, there remain substantial gaps in our scientific and operational knowledge. These gaps restrict the ability of the sector to put in place effective mitigation strategies that are tailored to the specific challenges faced by different sites. Discussions highlighted a number of topics that demand particular attention:

- **Impacts and measures in insects.** Although the impact on birds and bats has received much attention, the effects on other animal groups, in particular insects, is much less documented. This gap is mainly due to the weak conservation regulation for this group compared to bats, resulting in fewer studies and less data available. Likewise, the presence of bat carcasses facilitates the recognition and study of this impact, whereas the effects on insects, being less protected and visible, do not benefit from as rigourous a documentation or regulation. Additional research is needed to assess the cumulative impact of wind farms on these species.

- **Effectiveness of mitigation measures.** The need for in-depth research on the long-term effectiveness of current mitigation measures was a central theme. Participants stressed the importance of assessing measures for reducing collisions, such as turbine curtailment during periods that are critical for wildlife, as well as habitat management measures, such the restoration of natural habitats to offset the damage caused by the installation of wind turbines. The effectiveness of these measures needs to be assessed rigourously to confirm their actual usefulness in terms of biodiversity conservation. It was acknowledged that although certain measures, such as turbine curtailment, were well documented and frequently implemented, there is a critical need for homogenizing the monitoring protocols to ensure the reproducibility and reliability of the data collected across different sites.

- **Complex ecological interactions.** Participants were preoccupied by the lack of knowledge on complex ecological interactions and the cascading effects caused by wind farms on local ecosystems. It was stressed that the impact of wind turbines was not restricted to its direct effects on wildlife, but encompassed wide-ranging changes to ecosystems, which are often less visible and more difficult to quantify with current methods. These complex interactions include changes in the food chain, habitat modification, and secondary effects on species that are not directly impacted by wind turbines. It is crucial to broaden the research on the impact of onshore wind power to better understand these interactions. This can be done by integrating longitudinal studies that examine the long-term and cascading effects on biodiversity. Cross-disciplinary collaborations will be needed to develop research methods that can capture the complex and often interconnected dynamics of ecosystems affected by wind power installations.

The importance of data accessibility and data sharing

One of the major issues raised during the meeting, and corroborated by the responses in the questionnaire, was the lack of data availability and accessibility. This constraint limits the ability of researchers, developers and operators to fully assess the impact of onshore wind power on biodiversity and the effectiveness of the mitigation measures in place. For instance, as pointed out in our rapid review, no follow-up study conducted in France could be found, which illustrates the crying need for easily accessible documentation. This lack of data availability was identified as an alarming obstacle not only for this review but also for the development of informed policies and the implementation of effective management practices.

- **Lack of data from long-term studies.** Most studies on the impact of wind turbines on wildlife focus on observations over short periods of time, and knowledge of the long term effects on species populations and ecosystems is missing. The limited availability of long and continuous time series is a major obstacle to understanding ecological dynamics over the long term, even though they are essential for designing effective and sustainable mitigation strategies.

- **Data quality and homogeneity.** Participants also raised the problem of data quality and homogeneity. Methods varied considerably from one study to the next, making it difficult to compare and synthesize their results. This lack of homogeneity affected the assessment of biodiversity and environmental impacts, and thus the implementation of evidence-based mititgation measures.

- **Data accessibility and data sharing.** The restricted accessibility of environmental data and retrospective documentation is another critical limitation. Often, data collected by wind project developers are not made publicly available because of confidentiality agreements or commercial restricitions. Moreover, there is a reluctance to share information that could be viewed as negative, and which could influence public opinion or affect the viability of a project. However, a lot of data is still available, even online, but it is often scattered across different websites, each having its own data management system and user interface. This fragmentation makes data gathering extremely time-consuming and inefficient. Centralizing data or creating a single portal giving access to different databases would be a major step forward.

- **Language barriers and the inclusion of international research.** Another barrier to data accessibility is the fact that many documents and technical reports are written exclusively in French, with no keywords or abstract in English. This restricts the visibility and the accessibility of these data for international audiences, including non-French speaking researchers and laboratories in other countries that could benefit from these data. The absence in French documents of keywords in English creates a significant barrier not only for sharing information, but also for using these data in meta-analyses or including them in systematic reviews.

- **Need to consolidate retrospective experience reporting systems.** Finally, there is a critical need for more structured and consolidated retrospective experience reporting systems, which would help those in the sector communicate on lessons learnt and best practices. The absence of such information stops the community from benefitting from the experience from other projects, which could mean that mistakes are being repeated and mitigation measures are not implemented effectively.

To begin addressing these needs, initiatives for standardizing data collection protocols and establishing data sharing platforms for this sector have been proposed. These initiatives will need to be supported by government agencies that guarantee the protection of sensitive data while promoting transparency and collaboration.

Recommendations for research and development

During the meeting, and from the answers given in the questionnaire, it was clearly indicated that there is a need to increase research and develop new technologies. Research and development efforts must be targeted towards the issues that have been identified, while taking advantage of current technological developments:

- **Longitudinal studies on cumulative effects.** Longitudinal studies are crucial for investigating the long-term cumulative effects of wind farms on local biodiversity. These studies should use standardized methods to allow comparisons with data from different ecosystems and geographic regions.

- **Research into technology that minimizes impact.** This implies the development of new technology, such as more precise detection or deterrence systems, including those using AI to anticipate and react in real time to the movement of birds and bats.

- **Assessing the effectiveness of mitigation measures.** Research dedicated to the assessment of the effectiveness of existing mitigation measures is needed. These studies should include the assessment before and after the installation of wind turbines to quantify the effectiveness of different mitigation measures.

- **Innovations in turbine design.** The development and deployment of innovative turbine designs that reduce their visibility and acoustic impact (two key factors in the mortality of birds and bats) should be encouraged. It could also involve optimizing the shape or colour of the blades, and using materials that minimize disturbance.

- **Integrated systems of environmental management.** This involves developing integrated systems of environmental management that use real time ecological, meteorological and operational data to automatically adjust turbine operation in response to environmental conditions.

- **Environmental rehabilitation**. Research is needed on the best practices for the environmental rehabilitation of wind farm sites after decommissioning. This includes the restoration of natural habitats and the management of the environmental restoration programmes over the long term.

- **Promote collaboration.** It is crucial to promote collaboration between universities, research centres, wind energy developers and government bodies. Funding through public-private partnerships could accelerate the development and adoption of the best practices and the best technology.

- **Subsidies and tax incentives.** The use of subsidies and tax incentives for companies that invest in R&D to develop technology that mitigates the environmental impact of wind power should be encouraged.

Conclusions of the collaborative stage

Participants expressed concern over the lack of follow-up studies in France, none having been included in the review due to the lack of availability and accessibility of the data. This lack of data made it difficult to completely assess the effectiveness of mitigation measures, and highlights the importance of such a review for identifying knowledge gaps.

The conclusion of the discussions highlighted the need to improve mitigation strategies by having a better understanding of the complex interactions between wind power infrastructures and local ecosystems. The discussions also identified multiple challenges from different areas , including financial and technical constraints that prevent the effective implementation of these measures, as well as regulatory and social obstacles, highlighting the need for an integrated approach that combines technological innovation, financial support, clear regulation and a close cooperation with local communities.

PROPOSALS FOR THE FUTURE: CONCLUDING SUMMARY OF THE RECOMMENDATIONS OF THE REVIEW AND THE COLLABORATIVE STAGE

The integration of wind power into our energy mix is crucial for responding to the current climate crisis, but it must be done in a way that is not detrimental to conservation of biodiversity. Through this review, some key recommendations have emerged to improve the effectiveness of measures that mitigate the impact of onshore wind farms on the environment.

Planning and development
It is essential to assess the potential environmental impacts of wind energy projects at the start of the planning process to select sites that will have the least environmental impact. The development of new turbine designs that reduce their visual and acoustic impact should be encouraged. Predictive models can be useful to inform policy and planning decisions, whereas measures for managing certain ecological factors on wind farms can reduce the risk they pose to wildlife. The use of integrated environmental management systems would enable the adjustment of turbine operation in real time in reponse to environmental conditions.

Research and development
Using new technology such as smart curtailment or AI-powered detection systems is essential for minimizing the environmental impacts of wind power. So is investing in research and development to improve the effectiveness of current solutions and assess new mitigation solutions. Optimized acoustic deterrent devices, integrating acoustic signalling into multimodal devices, and optimized UV lighting can contribute to reducing bird and bat collisions. Testing the effectiveness of specific paints and exploring the application of specific textures to turbine towers are promising leads. It is also recommended, where suitable in France, to encourage policy makers to allow mitigation measures that are not yet authorized in France, such as ultrasonic deterrence for bats, in order to maximize wildlife protection. In addition, it is important to study the impacts of wind turbines on insects, carry out longitudinal studies to examine the long-term cumulative effects on biodiversity, and identify the best practices for the restoration of sites (*i.e.* environmental rehabilitation) when wind facilities are decommissioned. A better understanding of the complex ecological interactions and the cascading effects associated with wind farms, as well as the assessment of the long-term effects of wind farm repowering, are also needed.

Monitoring and assessment
Environmental monitoring programmes are essential to assess and adjust mitigation strategies. Rigourous evaluations of the effectiveness of existing measures need to be carried out over the long term, by homogenizing the monitoring protocols to ensure that data is comparable. The development of standardized protocols for data gathering and analysis is also crucial.

Collaboration and data sharing
It is vital to promote collaboration between universities, research centres, wind power developers and government bodies. Improving data accessibility and data sharing will enable more precise evaluations of the environmental impacts of wind turbines and the effectiveness of mitigation measures to be carried out. Data sharing needs to be encouraged within the scientific community, as well as the adoption of an inclusive and holistic approach to integrate the wider environmental impacts of wind power. These steps are essential to increase our knowledge base.

Regulation and funding

To simplify procedures and encourage investments, it is important to make regulations clearer and improve coordination between different levels of government. Subsidies and tax incentives can stimulate research and the development of new mitigation technologies. It is also imperative to fund research in underrepresent regions of the world such as South-East Asia, Sub-Saharan Africa and South America, and overcome economic and financial constraints by making investments in long-term monitoring programmes and new technologies economically viable.

By following these recommendations, it is possible to reconcile wind power development and biodiversity conservation, and thus ensure that the transition to renewable energy is sustainable and respectful of the environment.

GENERAL REFERENCES

Adams, E. M., Gulka, J., & Williams, K. A. (2021). A review of the effectiveness of operational curtailment for reducing bat fatalities at terrestrial wind farms in North America. *PLoS One*, 16(11), e0256382.

ADEME. (2024). L'Évaluation Environnementale Stratégique : une nouvelle obligation du PCAET. [https://www.territoires-climat.ademe.fr/ressource/237-84] Consulté le 12/06/2024

Barbier, S., Chevalier, R., Loussot, P., Bergès, L., & Gosselin, F. (2009). Improving biodiversity indicators of sustainable forest management: Tree genus abundance rather than tree genus richness and dominance for understory vegetation in French lowland oak hornbeam forests. *Forest ecology and management*, *258*, S176-S186.

Baerwald, E.F., D'Amours, G.H., Klug, B.J., & Barclay, R.M.R. (2008). Barotrauma is a significant cause of bat fatalities at wind turbines. *Current Biology*, 18(16), R695-R696

Bennet, E.M. (2016). Avoiding harm or doing good? Revising how we think about mitigation hierarchy implementation. *Frontiers in Ecology and the Environment*, 14(5), 258-265.

Christine Reusch, Ana Ailin Paul, Marcus Fritze, Stephanie Kramer-Schadt, Christian C. Voigt. (2023) **Wind energy production in forests conflicts with tree-roosting bats.***Current Biology*, 33(4), 737-743.

Collaboration for Environmental Evidence (C.E.E.). (2023). Guidelines and standards for 'Rapid Reviews'. [https://environmentalevidence.org/information-for-authors/]

Cryan, P. M., & Barclay, R. M. (2009). Causes of bat fatalities at wind turbines: hypotheses and predictions. *Journal of mammalogy*, *90*(6), 1330-1340.

Dale, V. H., & Polasky, S. (2007). "Measures of the effects of agricultural practices on ecosystem services." *Ecological Economics*, 64(2), 286-296.

De Lucas, M., Janss, G. F., Whitfield, D. P., & Ferrer, M. (2008). Collision fatality of raptors in wind farms does not depend on raptor abundance. *Journal of applied ecology*, *45*(6), 1695-1703.

Desholm, M., & Kahlert, J. (2005). Nocturnal migration activity over offshore wind farms: implications for post-construction monitoring programs. *The Condor*, 107(4), 811-816.

Direction générale de l'énergie et du climat (2023). Données et études statistiques. Pour le changement climatique, l'énergie, l'environnement, le logement, et les transports [https://www.statistiques.developpement-durable.gouv.fr/publicationweb/526] Consulté le 12/06/2024

DREAL Hauts-de-France. (2017). Guide régional Hauts-de-France : Prise en compte des enjeux chiroptérologiques et avifaunistiques dans les projets éoliens. [https://www.hauts-de-france.developpement-durable.gouv.fr/?Guide-regional-Hauts-de-France-Prise-en-compte-des-enjeux-chiropterologiques-et-avifaunistiques-dans-les-projets-eoliens]

Erickson, W., & Urban, D. (2004). Potential risks of nine rodenticides to birds and nontarget mammals: a comparative approach (p. 225). Washington, DC: US Environmental Protection Agency, Office of Prevention, Pesticides and Toxic Substances.

Frank, M.H. (2015). Effects of noise from wind turbines on wildlife communication signals. *Proceedings of the Royal Society B: Biological Sciences*, 282(1802), 20142841.

Haddaway, N. R., Bethel, A., Dicks, L. V., Koricheva, J., Macura, B., Petrokofsky, G., ... & Stewart, G. B. (2020). Eight problems with literature reviews and how to fix them. *Nature Ecology & Evolution*, *4*(12), 1582-1589.

IEA (2022). World Energy Outlook 2022, IEA, Paris [https://www.iea.org/reports/world-energy-outlook-2022] Consulté le 12/06/2024

IPCC (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 184 pp., doi: 10.59327/IPCC/AR6-9789291691647

Kaffine, D. T. (2019). Microclimate effects of wind farms on local crop yields. *Journal of Environmental Economics and Management*, *96*, 159-173.

Koricheva, J., Gurevitch, J., & Mengersen, K. (Eds.). (2013). *Handbook of meta-analysis in ecology and evolution*. Princeton University Press.

Langridge, J., Dupuis, L., Hette-Tronquart, N., Jactel, H., & Besnard, A. (2023) How effective are existing solutions to mitigate impacts of onshore wind farms on flying vertebrates and invertebrates? A Rapid Review: a Rapid Review. *PROCEED.*

Marques, A. T., Batalha, H., Rodrigues, S., Costa, H., Pereira, M. J. R., Fonseca, C., Mascarenhas, M., & Bernardino, J. (2014). Understanding bird collisions at wind farms: An updated review on the causes and possible mitigation strategies. *Biological Conservation*, *179*, 40–52.

Marques, A. T., Batalha, H., & Bernardino, J. (2021). Bird Displacement by Wind Turbines: Assessing Current Knowledge and Recommendations for Future Studies. *Birds*, *2*(4), 460–475.

Masden, E. A., Haydon, D. T., Fox, A. D., Furness, R. W., Bullman, R., & Desholm, M. (2009). Barriers to movement: impacts of wind farms on migrating birds. *ICES Journal of marine Science*, *66*(4), 746-753.

Ministère de la Transition Écologique et de la Cohésion des Territoires. (2023). *L'évaluation environnementale.* [**https://www.ecologie.gouv.fr/levaluation-environnementale**]Consulté le 12/06/2024

Ministère de la Transition Écologique. (2024.). Éolien terrestre. [https://www.ecologie.gouv.fr/eolien-terrestre] Consulté le 12/06/2024

UNFCCC (2015). Paris Agreement. United Nations Framework Convention on Climate Change. Ministère de la Transition Écologique et Solidaire. (2022). Programmation pluriannuelle de l'énergie 2019-2028. Gouvernement français .
[https://www.ecologie.gouv.fr/sites/default/files/20200422%20Synthe%CC%80se%20de%20la%20PPE.pdf]

Perrow, M. (Ed.). (2017). Wildlife and Wind Farms-Conflicts and Solutions: Onshore: Potential Effects (Vol. 1). Pelagic Publishing Ltd.

Pick, J. L., Nakagawa, S., & Noble, D. W. (2019). Reproducible, flexible and high-throughput data extraction from primary literature: The metaDigitise r package. *Methods in Ecology and Evolution*, *10*(3), 426-431.

R Core Team (2023). _R: A Language and Environment for Statistical Computing_. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.

REN21 (2021). Renewables 2021 Global Status Report (Paris: REN21 Secretariat). ISBN 978-3-948393-03-8.

Rodríguez, I., Palomino, D., Jiménez, J., Martín, V., Carazo, P., & Ferreras, P. (2013). Impact of an onshore wind farm on breeding raptor populations. *Bird Study*, 60(2), 236-244.

Sénat. (2009.). Les études d'impact environnemental (EIE) et l'évaluation environnementale stratégique (EES). [https://www.senat.fr/lc/lc197/lc197_mono.html] Consulté le 12/06/2024

Smallwood, K.S. (2013). Comparing bird and bat fatality-rate estimates among North American wind-energy projects. *Wildlife Society Bulletin*, 37(1), 19-33

Smallwood, K. S., & Bell, D. A. (2020). Effects of wind turbine curtailment on bird and bat fatalities. *The Journal of Wildlife Management*, 84(4), 685-696.

Stephens, T. (2023). The Kunming–Montreal Global Biodiversity Framework. International Legal Materials 62, 868–887.

Stewart, G. (2010). Meta-analysis in applied ecology. *Biology letters*, *6*(1), 78-81.

Thaxter, C. B., Buchanan, G. M., Carr, J., Butchart, S. H., Newbold, T., Green, R. E., ... & Pearce-Higgins, J. W. (2017). Bird and bat species' global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. *Proceedings of the Royal Society B: Biological Sciences*, *284*(1862), 20170829.

Thaxter, C.B., Gaston, K.J., Evans, K.L., Fuller, R.A., & Ratcliffe, N. (2017). Site selection criteria for reducing environmental impacts associated with large-scale wind energy deployment. *Journal of Applied Ecology*, 54(3), 775-783.

Tomé, R., Canário, F., Leitão, A. H., Pires, N., & Repas, M. (2017). Radar assisted shutdown on demand ensures zero soaring bird mortality at a wind farm located in a migratory flyway. In *Wind Energy and*

Wildlife Interactions: Presentations from the CWW2015 Conference (pp. 119-133). Springer International Publishing.
UICN Comité français (2023). Améliorer la prise en compte de la biodiversité dans la planification et la conception des projets éoliens et photovoltaïques : retours d'expériences et identification de bonnes pratiques en France métropolitaine.
Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of statistical software*, *36*(3), 1-48.
Weaver, S. P., Hein, C. D., & Schirmacher, M. R. (2018). *Ultrasonic acoustic deterrents significantly reduce bat fatalities at wind turbines.Renewable Energy*, 123, 249-254.
Weschler, M. (2023). Wind Energy and Insects: Reviewing the State of Knowledge and Identifying Potential Interactions. University of Wyoming
Wu, S., & Archer, C. L. (2021). Near-ground effects of wind turbines: Observations and physical mechanisms. *Monthly Weather Review*, *149*(3), 879-898.

REFERENCES INCLUDED IN THE SYNTHESIS

★*Reference whose data was used in the meta-analysis*

Anderson, R., Tom, J., Neumann, N., Erickson, W. P., Strickland, M. D., Bourassa, M., & Sernka, K. J. (2005). Avian monitoring and risk assessment at the San Gorgonio Wind Resource Area (No. NREL/SR-500-38054). National Renewable Energy Lab.(NREL), Golden, CO (United States).
★**Arnett, E. B., Huso, M. M., Schirmacher, M. R., & Hayes, J. P.** (2011). Altering turbine speed reduces bat mortality at wind-energy facilities. *Frontiers in Ecology and the Environment*, 9(4), 209-214.
Arnett, E. B., Hein, C. D., Schirmacher, M. R., Huso, M. M., & Szewczak, J. M. (2013). Evaluating the effectiveness of an ultrasonic acoustic deterrent for reducing bat fatalities at wind turbines. *PloS one*, 8(6), e65794.
★**Baerwald, E. F., Edworthy, J., Holder, M., & Barclay, R. M**. (2009). A large-scale mitigation experiment to reduce bat fatalities at wind energy facilities. *The Journal of Wildlife Management*, 73(7), 1077-1081.
★**Bennett, E. M., Florent, S. N., Venosta, M., Gibson, M., Jackson, A., & Stark, E.** (2022). Curtailment as a successful method for reducing bat mortality at a southern Australian wind farm. *Austral Ecology*, 47(6), 1329-1339.
Bennett, V. J., & Hale, A. M. (2018). Texturizing wind turbine towers to reduce bat mortality (No. DOE-TCU-0007033). Texas Christian Univ., Fort Worth, TX (United States).
Bienz, C. (2016). Surface texture discrimination by bats: implications for reducing bat mortality at wind turbines (Master's thesis, Texas Christian University).
Brown, W. K., & Hamilton, B. L. (2006). Monitoring of bird and bat collisions with wind turbines at the Summerview Wind Power Project, Alberta. Terrestrial & Aquatic Environmental Managers ltd.
Cooper, D., Green, T., Miller, M., & Rickards, E. (2020). Bat Impact Minimization Technology: An Improved Bat Deterrent for the Full Swept Rotor Area of Any Wind Turbine (No. DE-EE0007034; CEC-500-2020-008). Frontier Wind LLC, Rocklin, CA (United States).
Cryan, P. M., Gorresen, P. M., Straw, B. R., Thao, S., & DeGeorge, E. (2021). Influencing activity of bats by dimly lighting wind turbine surfaces with ultraviolet light. *Animals*, 12(1), 9.
d'Entremont, M. V. (2015). Movement patterns of noctural avian migrants at a wind energy project in northeast British Columbia (Doctoral dissertation, University of Northern British Columbia).
De Lucas, M., Ferrer, M., Bechard, M. J., & Muñoz, A. R. (2012). Griffon vulture mortality at wind farms in southern Spain: Distribution of fatalities and active mitigation measures. *Biological Conservation*, 147(1), 184-189.
Erickson, W. P., Strickland, M. D., Good, R. E., & Sernka, K. J. (2003). Comparison of Avian Responses to UV-Light-Reflective Paint on Wind Turbines: Subcontract Report, July 1999--December 2000 (No. NREL/SR-500-32840). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Ferrer, M., Alloing, A., Baumbush, R., & Morandini, V. (2022). Significant decline of Griffon Vulture collision mortality in wind farms during 13-year of a selective turbine stopping protocol. *Global Ecology and Conservation*, 38, e02203.

Ferri, V., Battisti, C., & Soccini, C. (2016). Bats in a mediterranean mountainous landscape: does wind farm repowering induce changes at assemblage and species level?.*Environmental management*, 57(6), 1240-1246.

Gilmour, L. R., Holderied, M. W., Pickering, S. P., & Jones, G. (2020). Comparing acoustic and radar deterrence methods as mitigation measures to reduce human-bat impacts and conservation conflicts. *PLoS One*, 15(2), e0228668.

*Good, R. E., Iskali, G., Lombardi, J., McDonald, T., Dubridge, K., Azeka, M., & Tredennick, A.** (2022). Curtailment and acoustic deterrents reduce bat mortality at wind farms. *The Journal of Wildlife Management*, *86*(6), e22244.

Good, R. E., Nasman, K., & Ciecka, A. (2022). Bat Evaluation Monitoring Studies at the Fowler Ridge Wind Farm, Benton County, Indiana. Draft Report: April 1 – October 15, 2021. Prepared for Fowler Ridge Wind Farm, Benton County, Indiana. Prepared by Western EcoSystems Technology, Inc. (WEST), Bloomington, Indiana. January 27, 2022.

Gorresen, P. M., Cryan, P. M., Dalton, D. C., Wolf, S., Johnson, J. A., Todd, C. M., & Bonaccorso, F. J. (2015). Dim ultraviolet light as a means of deterring activity by the Hawaiian hoary bat Lasiurus cinereus semotus. *Endangered Species Research*, 28(3), 249-257.

Hayes, M. A., Hooton, L. A., Gilland, K. L., Grandgent, C., Smith, R. L., Lindsay, S. R., ... & Goodrich-Mahoney, J. (2019). A smart curtailment approach for reducing bat fatalities and curtailment time at wind energy facilities. *Ecological Applications*, 29(4), e01881.

Hein, C. D., Prichard, A., Mabee, T., & Schirmacher, M. R. (2013). Effectiveness of an operational mitigation experiment to reduce bat fatalities at the Pinnacle Wind Farm, Mineral County, West Virginia, 2012. An annual report submitted to Edison Mission Energy and the Bats and Wind Energy Cooperative. Bat Conservation International. Austin, Texas, USA.

Hodos, W. (2003). Minimization of Motion Smear: Reducing Avian Collision with Wind Turbines; Period of Performance: July 12, 1999--August 31, 2002 (No. NREL/SR-500-33249). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Horn, J. W., Arnett, E. B., Jensen, M., & Kunz, T. H. (2008). Testing the effectiveness of an experimental acoustic bat deterrent at the Maple Ridge wind farm. *Report Prepared for: The Bats and Wind Energy Cooperative and Bat Conservation International, Austin, TX*.

Huso, M., & Dalthorp, D. (2023). Reanalysis indicates little evidence of reduction in eagle mortality rate by automated curtailment of wind turbines. *Journal of Applied Ecology*, *60*(10), 2282-2288.

Huzzen, B. (2019). Does a textured coating alter bat activity and behavior in proximity to wind turbine towers? (Master's thesis, Texas Christian University).

Kinzie, K., Hale, A., Bennett, V., Romano, B., Skalski, J., Coppinger, K., & Miller, M. F. (2018). Ultrasonic Bat Deterrent Technology (No. DOE-GE-07035). General Electric Co., Schenectady, NY (United States).

Lindsey, C. T. (2017). Assessing changes in bat activity in response to an acoustic deterrent—implications for decreasing bat fatalities at wind facilities (Master's thesis, Texas Christian University).

Long, C. V., Flint, J. A., & Lepper, P. A. (2011). Insect attraction to wind turbines: does colour play a role?.*European Journal of Wildlife Research*, *57*, 323-331.

*Măntoiu, D. Ş., Kravchenko, K., Lehnert, L. S., Vlaschenko, A., Moldovan, O. T., Mirea, I. C., ... & Voigt, C. C.** (2020). Wildlife and infrastructure: impact of wind turbines on bats in the Black Sea coast region. *European journal of wildlife research*, *66*(3), 1-13.

Martin, C. (2015). Effectiveness of operational mitigation in reducing bat mortality and an assessment of bat and bird fatalities at the Sheffield Wind Facility, Vermont. Master of Sciences, Texas Tech University.

★**Martin, C. M., Arnett, E. B., Stevens, R. D., & Wallace, M. C.** (2017). Reducing bat fatalities at wind facilities while improving the economic efficiency of operational mitigation. *Journal of Mammalogy*, *98*(2), 378-385

May, R., Åström, J., Hamre, Ø., & Dahl, E. L. (2017). Do birds in flight respond to (ultra) violet lighting?.*Avian Research*, *8*, 1-10.

May, R., Nygård, T., Falkdalen, U., Åström, J., Hamre, Ø., & Stokke, B. G. (2020). Paint it black: Efficacy of increased wind turbine rotor blade visibility to reduce avian fatalities. *Ecology and evolution*, *10*(16), 8927-8935.

McClure, C. J., Rolek, B. W., Dunn, L., McCabe, J. D., Martinson, L., & Katzner, T. (2021). Eagle fatalities are reduced by automated curtailment of wind turbines. *Journal of Applied Ecology*, *58*(3), 446-452.

McClure, C. J., Rolek, B. W., Dunn, L., McCabe, J. D., Martinson, L., & Katzner, T. E. (2022). Confirmation that eagle fatalities can be reduced by automated curtailment of wind turbines. *Ecological Solutions and Evidence*, *3*(3), e12173.

Millon, L., Julien, J. F., Julliard, R., & Kerbiriou, C. (2015). Bat activity in intensively farmed landscapes with wind turbines and offset measures. *Ecological Engineering*, *75*, 250-257.

Nicholls, B., & Racey, P. A. (2007). Bats avoid radar installations: could electromagnetic fields deter bats from colliding with wind turbines?.*PloS one*, *2*(3), e297.

Nicholls, B., & Racey, P. A. (2009). The aversive effect of electromagnetic radiation on foraging bats—a possible means of discouraging bats from approaching wind turbines. *PLoS One*, *4*(7), e6246.

Pescador, M., Ramírez, J. I. G., & Peris, S. J. (2019). Effectiveness of a mitigation measure for the lesser kestrel (Falco naumanni) in wind farms in Spain. *Journal of environmental management*, *231*, 919-925.

★**Rabie, P. A., Welch-Acosta, B., Nasman, K., Schumacher, S., Schueller, S., & Gruver, J.** (2022). Efficacy and cost of acoustic-informed and wind speed-only turbine curtailment to reduce bat fatalities at a wind energy facility in Wisconsin. *Plos one*, *17*(4), e0266500.

Rnjak, D., Janeš, M., Križan, J., & Antonić, O. (2023). Reducing bat mortality at wind farms using site-specific mitigation measures: a case study in the Mediterranean region, Croatia. *Mammalia*, *87*(3), 259-270.

Rodriguez, R., Vallejo, G., Saywers, D., Quillen, J., & Denman, K. (2O23) Balancing bat conservation and wind energy production with EchoSense®.

Romano, W. B., Skalski, J. R., Townsend, R. L., Kinzie, K. W., Coppinger, K. D., & Miller, M. F. (2019). Evaluation of an acoustic deterrent to reduce bat mortalities at an Illinois wind farm. *Wildlife Society Bulletin*, 43(4), 608-618.

Schirmacher, M. R. (2020). Evaluating the effectiveness of an ultrasonic acoustic deterrent in reducing bat fatalities at wind energy facilities (No. DOE-BCI-0007036). Bat Conservation International, Austin, TX (United States).

Schirmacher, M. R., Prichard, A., Mabee, T., & Hein, C. D. (2018). Evaluating a novel approach to optimize operational minimization to reduce bat fatalities at the Pinnacle Wind Farm, Mineral County, West Virginia, 2015. An annual report submitted to NRG Energy and the Bats and Wind Energy Cooperative. Bat Conservation International, Austin, TX.

Shewring, M. P., & Vafidis, J. O. (2017). The effectiveness of deterrent measures to minimize disturbance impacts to breeding European nightjar at an upland wind farm site in South Wales, UK. *Conservation Evidence*, *14*, 58-60.

Smales, I., Muir, S., Meredith, C., & Baird, R. (2013). A description of the Biosis model to assess risk of bird collisions with wind turbines. *Wildlife Society Bulletin*, *37*(1), 59-65.

Smallwood, K. S., & Bell, D. A. (2020). Effects of wind turbine curtailment on bird and bat fatalities. *The Journal of Wildlife Management*, *84*(4), 685-696.

Smallwood, K. S., & Karas, B. (2009). Avian and bat fatality rates at old-generation and repowered wind turbines in California. *The Journal of Wildlife Management*, *73*(7), 1062-1071.

Smallwood, K. S., & Thelander, C. G. (2005). Bird Mortaility at the Altamont Pass Wind Resource Area: March 1998--September 2001 (No. NREL/SR-500-36973). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Spanjer, G. R. (2006). Responses of the big brown bat, Eptesicus fuscus, to a proposed acoustic deterrent device in a lab setting. A report submitted to the Bats and Wind Energy Cooperative and the Maryland Department of Natural Resources. Bat Conservation International. Austin, Texas, USA.

Stantec Consulting Ltd. (2012). Wolfe Island Wind Plant Post-Construction Follow-Up Plan - Bird and Bat Resources Monitoring Report No. 6, July - December 2011. Prepared for TransAlta Corporation's wholly owned subsidiary, Canadian Renewable Energy Corporation. File No. 160960494. July 2012.

Stokke, B. G., Nygård, T., Falkdalen, U., Pedersen, H. C., & May, R. (2020). Effect of tower base painting on willow ptarmigan collision rates with wind turbines. *Ecology and evolution*, *10*(12), 5670-5679.

Szewczak, J. M., & Arnett, E. (2006). Preliminary field test results of an acoustic deterrent with the potential to reduce bat mortality from wind turbines. Austin (Tx): Bat Conservation International.

Szewczak, J. M., & Arnett, E. B. (2007). Field test results of a potential acoustic deterrent to reduce bat mortality from wind turbines. Unpublished report. Bat Conservation International, Austin, Texas, USA.

Thady, R. G., Emerson, L. C., & Swaddle, J. P. (2022). Evaluating acoustic signals to reduce avian collision risk. *PeerJ*, *10*, e13313.

Weaver, S. P., Hein, C. D., Simpson, T. R., Evans, J. W., & Castro-Arellano, I. (2020). Ultrasonic acoustic deterrents significantly reduce bat fatalities at wind turbines. *Global Ecology and Conservation*, *24*, e01099.

Werber, Y., Hareli, G., Yinon, O., Sapir, N., & Yovel, Y. (2023). Drone-mounted audio-visual deterrence of bats: implications for reducing aerial wildlife mortality by wind turbines. *Remote Sensing in Ecology and Conservation*, *9*(3), 404-419.

Young Jr, D. P., Nomani, S., Tidhar, W. L., & Bay, K. (2011). Nedpower Mount storm wind energy facility post-construction avian and bat monitoring. Western EcoSystems Technology Inc, Cheyenne, Wyoming, USA.

Young Jr, D. P., Lout, M., Courage, Z., Nomani, S., & Bay, K. (2012). Post-Construction Monitoring Study, Criterion Wind Project, Garrett County, Maryland. April-November 2012. Prepared for Criterion Power Partners, LLC, Oakland, Maryland. Prepared by Western EcoSystems Technology, Inc.(WEST), Cheyenne, Wyoming, and Waterbury, Vermont.

APPENDIX I : LIST OF SPECIES IN THE SUMMARY TABLE OF THE NARRATIVE SYNTHESIS

Taxonomic group	Common name	Scientific name
Bats	Silver-haired bat	*Lasionycteris noctivagans*
	Hawaiian hoary bat	*Lasiurus cinereus semotus*
	Hoary bat	*Lasiurus cinereus*
	Northern yellow bat	*Lasiurus intermedius*
	Eastern red bat	*Lasiurus borealis*
	Brazilian free-tailed bat	*Tadarida brasiliensis*
	Mouse-eared bats	*Myotis* sp.
	Noctules	*Nyctalus* sp.
	Long-eared bats	*Plecotus* sp.
	Little brown bat	*Myotis lucifugus*
	Pipistrelles	*Pipistrellus* sp.
	Serotines	*Eptesicus* sp.
	Big brown bat	*Eptesicus fuscus*
Birds	Golden eagle	*Aquila chrysaetos*
	Tasmanian wedge-tailed eagle	*Aquila audax fleayi*
	Red-tailed hawk	*Buteo jamaicensis*
	Burrowing owl	*Athene cunicularia*
	American kestrel	*Falco sparverius*
	Australian zebra finch	*Taeniopygia guttata*
	Barn owl	*Tyto alba*
	European nightjar	*Caprimulgus europaeus*
	Lesser kestrel	*Falco naumanni*
	Great horned owl	*Bubo virginianus*
	Willow ptarmigan	*Lagopus lagopus*
	White-bellied sea eagle	*Ichtyophaga leucogaster*
	White-tailed eagle	*Haliaeetus albicilla*
	Bald eagle	*Haliaeetus leucocephalus*
	Eurasian griffon vulture	*Gyps fulvus*

APPENDIX II: METHODS

This Rapid Review followed the methods described in the protocol published in PROCEED by Landridge *et al.* (2023). It was carried out in strict compliance with the "Guidelines and Standards for 'Rapid Reviews'" issued by the Collaboration for Environmental Evidence (CEE, 2023).

Bibliographic reference search strategy

Keywords and search equations

To meet our objectives, we combined all terms related to flying animals, mitigation measures and their results. The final search equation was constructed as follows in the Web of Science Core Collection (WOSCC) search engine:

TS=((insect$ OR invertebrate$ OR butterfly OR lepidoptera OR dragonfly OR odonata OR vertebrate$ OR avifauna OR aves OR avian OR bird$ OR bat$ OR chiroptera OR passerine$ OR raptor$ OR vulture$ OR owl$ OR piciforme$ OR columbiforme$ OR passeriforme$ OR falconiforme$) AND (("wind energ*" OR "wind farm$" OR "wind power" OR "wind turbine$" OR "wind technolog*" OR " wind park$" OR "wind power station$" OR "wind power plant$") AND (evaluat* OR solution$ OR mitigatg* OR "risk assessment" OR option$ OR measur* OR priorit* OR reduc* OR avoid* OR compensat* OR minimize OR adapt* OR interven* OR action$ OR manag* OR protect* OR manipulat* OR counteract* OR removal OR engineer* OR plan* OR strateg* OR offset* OR deterren* OR curtail* OR "flight divert*" OR "attract* remov*" OR "nest* management" OR "m?cro-siting" OR deterr*)) AND (impact* OR effect* OR collision$ OR behaviour OR aversion OR repulsion OR disturb* OR mortalit* OR fatalit* OR carcass* OR "population size" OR "population density" OR abundance OR occurrence))

All search equations used for each query of search engines, bibliographic databases and specialized websites are given in Appendix III.

Shortcuts and limitations

Only terms in English were included in the search queries. However, selected publications were either in English or in French, in accordance with the team's language skills. No restrictions on the date or geographic area were applied to database searches. As for specialized websites, the search for documentation in English was prioritized, with only one specialized website being in French.

Literature sources

Only one bibliographic database was queried using the search equation given above: the Web of Science Core Collection database, which was available to the authors of this review via the French National Research Institute for Sustainable Development (IRD). Searches were carried out in the following citation indexes: SCIEXPANDED, SSCI, AHCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, and IC.

Two additional searches were carried out in:

- Google Scholar (https://scholar.google.com/). We used the Publish or Perish (v6) software to retrieve citations. Because of restrictions on the number of characters, the search equation was simplified. Moreover, we prioritized academic publications, limiting each sub-search to the first 100 results, as it has been shown that after 300, document relevance decreases rapidly (Haddaway *et al.*, 2015).

- Bielefeld Academic Search Engine (BASE) (http://www.base-search.net). As with Google Scholar, because of restrictions on the number of characters, the search equation was simplified.

We also searched seven specialized websites for relevant technical documentation:

- The International Renewable Energy Agency (IRENA): https://www.irena.org/
- The Wind Technology Office: https://www.energy.gov/eere/wind/wind-energy-technologies-office
- The U.S. Wind Turbine Database: https://eerscmap.usgs.gov/uswtdb/
- The Bats and Wind Energy Cooperative (BWEC): https://www.batsandwind.org
- The 'Publication Library' of The Scotland Centre of Expertise Connecting Climate Change Research and Policy: https://www.climatexchange.org.uk/research/publications-library/
- Tethys:https://tethys.pnnl.gov/
- La Libraire "Energies renouvelables, réseaux et stockage", Agence de la Transition Ecologique (ADEME) https://librairie.ademe.fr/2889-energies-renouvelables-reseaux-et-stockage

Estimate of search exhaustivity

To ensure the relevance of the search, an interative process was carried out to "calibrate" the search equation to a predetermined list of 15 reference articles (hereafter, the "test list"). This "test list" comprised articles from relevant scientific journals previously identified by the team. We tested different keyword combinations and checked that the reference articles were retrieved. If articles from the "test list" were missing, keywords were added to improve search sensitivity until all articles were retrieved.

Criteria for the eligibility of articles and the selection of studies

Screening was carried out over three stages: 1) from "titles", then 2) from "abstracts", and finally 3) from "full texts".
Note that when assessing titles or abstracts, if the presence of an inclusion criterion was in doubt (or if the information was missing), the article in question would automatically be included in the next stage of the selection process. The technical reports retrieved from specialized websites were only assessed from the full text. To ensure the coherence and reproducibility of these decisions, the reliability of agreement between the three raters was compared using a Fleiss' Kappa test before each selection stage (APPENDIX IV).

Thus, we assessed relevance of the articles that were retrieved using a set of inclusion and exclusion criteria (Table 2).

Table 2. List of eligibility criteria used for the selection of documents from their "titles", "abstracts" and "full texts".

PICO Criteria		Description	Definition(s)
Inclusion criteria	Eligible populations	All flying vertebrates or invertebrates (*i.e.* all species of birds, bats and flying insects) affected by onshore wind farms	Wild species – *i.e.* species freely occurring in natural environments (*in situ*) or used in laboratories (*ex situ*). All non-domesticated species.
	Eligible interventions	Mitigation measures to avoid, minimize and compensate the impacts of onshore wind farms on flying biodiversity	Mitigation measures for minimizing the negative impacts of wind farms on flying biodiversity.
	Eligible comparators	Studies that carry out spatial or temporal comparisons.	BACI type designs: "before-after", "control-intervention", "before-after-control-intervention".

	Eligible effects and measures	All relevant measures and results showing the effect of a mitigation solution.	The size and density of the population in question, *e.g.* population abundance measurements. The mortality/collision rate, *e.g.* the number of carcasses. Changes in flight activity, avoidance behaviour, *e.g.* flight height.
Exclusion criteria	Ineligible populations	All terrestrial non-flying fauna and flora	Amphibians, reptiles, mammals other than Chiroptera (bats), terrestrial insects and plants are not included in this Rapid Review.
	Ineligible interventions	Measures that are not mitigation measures.	Any measure that does not aim to minimize the negative impacts of wind farms on species' populations, either through actions put in place directly on the farms, or by measures taken before, after or in parallel of their activity..
	Ineligible results	Studies that do not study mortality, collisions, behaviour, etc.	Any non-relevant result that does allow the interpretation of a fall in mortality, collision, or avoidance behaviour.

"Critical appraisal": assessing the validity of the studies

We carried out the critical appraisal of both internal (*i.e.* the risk of bias[10] linked to different factors) and external (*i.e.* relevance and generability (Haddaway *et al.*, 2020)) validity. A series of criteria were predefined using the CEE's Critical Appraisal Tool. Each study was ranked for each criterion as having a "weak", "moderate" or "strong" risk of bias. Each criterion was weighted ("weak" = 1, "moderate" = 0.5, "strong" = 0) in order to calculated a global risk of bias coefficient, which allowed studies to be classified according to their global risk of bias rating ("very weak", "weak", "moderate", "strong", "very strong"). Before doing the full critical appraisal, "test phases" were carried out to check that criteria were understood and interpreted in the same way by our different raters (AQ, JL and LD). For each research article, we assessed its robustness, notably in terms of the method for site selection, the number of replicates (taking into account pseudo-replicates), and the sampling and analysis methods (see Appendix V for more detail). When the objective assessment of a given criterion was not possible due to a lack of information, the risk of bias was automatically classed as "strong".

Note that articles with a "strong" global risk of bias were not excluded from the statistical analyses (see the "Synthesis" section).

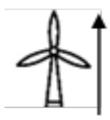
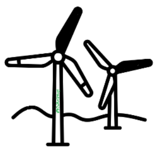
[10] **Risk of bias** is the likelihood that certain characteristics of a study influence the results in a systematic way, leading to conclusions that deviate from the truth. Bias can arise from methods for data gathering and site selection, or from analyses that are not completely impartial or rigourous. Risk of bias can effect the validity and reliability of results in a study.

Syntheses

Methods for the narrative synthesis

All metadata coded from the selected case studies were included in the narrative synthesis. When multiple case studies were extracted from the same article, each was recorded as a unique entry in the Excel spreadsheet with the corresponding metadata. Following the methodology for systematic mapping of environmental sciences (see James *et al.*, 2016), a case study represented a single result associated with a single intervention (*i.e.* a mitigation measure, Table 3) from a single population (*i.e.* a single species or a group of species). Crossing these key variables of the metadata (*e.g.* taxonomic group x solutions x results), the figures and tables of the synthesis were produced to identify research gaps (sub-themes that need additional primary research) and research clusters (sub-themes that are sufficiently covered by existing studies to carry out a quantitative synthesis). Thus the distribution and frequency of the studies on mitigation measures were described, for example using heatmaps. In the light of these results, recommendations were then made.

Table 3. Different types of comparators used in the extraction of metadata. Icons obtained from Flaticon.

Type of comparative study	Illustrated example		Other examples of comparative studies
	Intervention group	**Control group**	
Curtailment : increasing the cut-in-speed	Wind speed +++ m/s : higher threshold 	Wind speed + m/s : lower threshold 	• Targeted curtailment • Curtailment : blade feathering • Combined curtailment and acoustic deterrence
Acoustic deterrence			• Radar deterrence • UV-light deterrence • Combined radar and acoustic deterrence
Turbine size	 +++ m	 + m	• Repowering
Surface painting (including blades)			• Surface texturizing
Micro-siting			• Macro-siting • Removal of attractant features

Methods for the quantitative synthesis

All data were extracted from the text, tables and figures of the selected documents. We used the R package *metaDigitise* (Pick *et al.*, 2018) for the latter. The meta-analysis was carried out with the R software (v4.3.1; R Core Team, 2023) using the *metafor* package (Viechtbauer, 2010). We coded (1) the number of replicates, *i.e.* the sample size (N > 1), (2) the mean effect, and (3) a measure of statistical dispersion transformed into a standard deviation. For taxonomic groups, average values for a community as whole were extracted, for instance "total abundance of bats".

For classification at the species level, species were grouped by taxonomic group (*i.e.* bats, birds or insects).

For each individual study, the geographic coordinates (latitude and longitude) were recorded when available. If there were not given, we used Google Earth to extract the geographic coordinates of the site based on descriptions given by the authors, provided these were precise enough.

Data treatment and statistical analyses

We used the "log response ratio" as a measure of effect size:

$$InR = In\left(\frac{X_E}{X_C}\right) = \ln(X_E) - \text{In}\,(X_C) \quad (1)$$

The effect size provides an estimate of the variation (as a percentage) of the mortality, activity or abundance between sites where the mitigation measure is implemented (experimental group – X_E) and where it is not (control group – X_C). It has the advantage of being directly interpretable in terms of magnitude (Barbier *et al.*, 2009). The variance in effect size is calculated as follows:

$$v = \frac{s_E^2}{n_E \overline{X}_E^2} + \frac{s_C^2}{n_C \overline{X}_C^2} \quad (2)$$

where S_E and S_C are the standard deviations and n_E and n_C the sample size of the experimental and control groups, respectively.

We used a random effects model to take into account the residual heterogeneity of the effect size in the studies, since ecological data is more susceptible to uncontrolled variation in the data than other scientific fields such as medical research (Stewart, 2009; Koricheva *et al.*, 2013). We added a random effect at the level of the publication to take into account the fact that two separate studies from the same article are potentially more similar than two studies from two separate articles. In our models, the response variable is the effect size lnR, which represents the effect size calculated for each study. The explicative variables were: the variance associated with each size effect, which adjusts for the uncertainty of each effect size estimate, and a random effect base of the publication's identifier. Multiple models were tested and compared to determine the effectiveness of a mitigation measure. Different moderators were added to explore some of the potential sources of heterogeneity between the studies. The aim was to understand why some studies showed different effects. For instance, factors such as climate, species, the type of landscape or turbine size could affect the results.

To compare different models and identify the one that worked the best, we used the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC). These tools evaluate each model by assessing how well the model fits the data and preferring models that are not too complex. We calculated AIC and BIC values for each model. Models with the lowest scores were considered the best, because this meant that they were both precise and simple, and thus the most effective for our dataset.

Before carrying out the meta-analysis and to ensure the validity and reliability of its results, we checked certain hypotheses and prerequisites:

- the homogeneity of variances, with Cochran's Q test and the I^2 statistic;
- the absence of publication bias, with a funnel plot and Egger's test of asymmetry;
- the normal distribution of effect sizes, with a Shapiro-Wilk test and by visual inspection of the histograms and the Q-Q plot;
- the assessment of the quality of the studies.

APPENDIX III: SEARCH EQUATIONS USED IN THE LITERATURE SEARCHES

Full search equation, used with the Web of Science Core Collection (WOSCC):

- TS=((insect$ OR invertebrate$ OR butterfly OR lepidoptera OR dragonfly OR odonata OR vertebrate$ OR avifauna OR aves OR avian OR bird$ OR bat$ OR chiroptera OR passerine$ OR raptor$ OR vulture$ OR owl$ OR piciforme$ OR columbiforme$ OR passeriforme$ OR falconiforme$) AND (("wind energ*" OR "wind farm$" OR "wind power" OR "wind turbine$" OR "wind technolog*" OR " wind park$" OR "wind power station$" OR "wind power plant$") AND (evaluat* OR solution$ OR mitigatg* OR "risk assessment" OR option$ OR measur* OR priorit* OR reduc* OR avoid* OR compensat* OR minimize OR adapt* OR interven* OR action$ OR manag* OR protect* OR manipulat* OR counteract* OR removal OR engineer* OR plan* OR strateg* OR offset* OR deterren* OR curtail* OR "flight divert*" OR "attract* remov*" OR "nest* management" OR "m?cro-siting" OR deterr*)) AND (impact* OR effect* OR collision$ OR behaviour OR aversion OR repulsion OR disturb* OR mortalit* OR fatalit* OR carcass* OR "population size" OR "population density" OR abundance OR occurrence))

Simplified search equation derived from the initial full search equation, used with the Bielefeld Academic Search Engine (BASE):

- (insect invertebrate butterfly lepidoptera dragonfly odonata vertebrate avifauna aves avian bird bat chiroptera passerine raptor vulture owl piciforme columbiforme passeriforme falconiforme) AND ("wind energy" "wind farm" "wind power" "wind turbine" "wind technology" "wind park" "wind power station" "wind power plant") AND (evaluation solution mitigate "risk assessment" option measure priority reduce avoid compensate minimize adapt intervention action management protect manipulate counteract removal engineering plan strategy offset deterrent curtail "flight diverted" "nest management" micro-siting macro-siting) AND (impact effect collision behaviour behavior aversion repulsion disturb mortality fatality carcass "population size" "population density" abundance occurrence)

Simplified search equation derived from the initial full search equation, used with Google Scholar:

- (insect OR invertebrate OR butterfly OR dragonfly) AND ("wind energy" OR "wind farm" OR "wind power" OR "wind turbine") AND (evaluation OR mitigation OR measure OR reduce OR avoidance) AND (impact OR effect OR behavio$r OR mortality OR abundance)

- (insect OR invertebrate OR butterfly OR dragonfly) AND ("wind energy" OR "wind farm" OR "wind power" OR "wind turbine") AND (management OR protection OR counteract OR removal OR plan) AND (impact OR effect OR behavio$r OR mortality OR abundance)

- (insect OR invertebrate OR butterfly OR dragonfly) AND ("wind energy" OR "wind farm" OR "wind power" OR "wind turbine") AND (strategy OR offset OR deterrent OR micro-siting OR macro-siting) AND (impact OR effect OR behavio$r OR mortality OR abundance)

- (bird OR bat OR chiroptera OR passerine OR raptor) AND ("wind energy" OR "wind farm" OR "wind power" OR "wind turbine") AND (evaluation OR mitigation OR measure OR reduce) AND (impact OR effect OR collision OR behavio$r OR mortality OR abundance)

- (bird OR bat OR chiroptera OR passerine OR raptor) AND ("wind energy" OR "wind farm" OR "wind power" OR "wind turbine") AND (avoidance OR management OR protection OR counteract) AND (impact OR effect OR collision OR behavio$r OR mortality OR abundance)

- (bird OR bat OR chiroptera OR passerine OR raptor) AND ("wind energy" OR "wind farm" OR "wind power" OR "wind turbine") AND (removal OR plan OR strategy OR offset OR deterrent) AND (impact OR effect OR collision OR behavio$r OR mortality OR abundance)

- (bird OR bat OR chiroptera OR passerine OR raptor) AND ("wind energy" OR "wind farm" OR "wind power" OR "wind turbine") AND ("flight diverted" OR micro-siting OR macro-siting) AND (impact OR effect OR collision OR behavio$r OR mortality OR abundance)

APPENDIX IV: ASSESSING THE CONFORMITY TO ELIGIBILITY CRITERIA WITH FLEISS' KAPPA TEST

Fleiss' Kappa test on title ratings:

- This test was conducted by three independent raters from a list of 161 bibliographic references representing 10 % of the total number of extracted references.
- Results: *Kappa = 0.875*
  z = 19.2
  p-value = 0

The Kappa value indicates that there is a very high level of agreement among the raters (above the 0.75 threshold that is usually considered as an indication of high interrater reliability). Moreover, this agreement is highly statistically significant (p = 0).

Fleiss' Kappa test on abstract ratings:

- This test was conducted by three independent raters from a list of 59 bibliographic references representing 10 % of the total number of previously selected references.
- Results: *Kappa = 0.723*
  z = 9.62
  p-value = 0

The Kappa value of 0.723 indicates that there is a good level of agreement among the raters. Although this value is slightly below the 0.75 threshold, it remains within the range of a good agreement. Once again, this agreement is highly statistically significant (p = 0).

Fleiss' Kappa test on full text ratings:

- The test was conducted by three independent raters from a list of 32 bibliographic references representing 10 % of the total number of previously selected references.
- Results: *Kappa = 0.897*
  z = 8.79
  p-value = 0

This last test has an even higher kappa value (0.897), indicating a very high level of agreement among raters. This agreement is highly statistically significant (p = 0).

Results from the Fleiss' Kappa tests show that agreement between the three raters is very high at every step of the selection process. Whether the selection is done on titles (kappa = 0.875), abstracts (kappa = 0.723) or full texts (kappa = 0.897), the kappa values indicate a significant and reproducible agreement in the decisions of the raters. This concordance ensures the reliability and robustness of the evaluation of the eligibility criteria over the entire bibliographic reference selection process.

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APPENDIX V: CRITERIA FOR THE RISK OF BIAS ASSESSMENT

External validity:

- Has the exposure/intervention taken place *in situ* (at a site with wind turbines)?

Confounding factors:

- Are there potential confounding factors (see sheet 2) that can influence the intervention and/or the result? If yes, have the authors identified, then analyzed/controlled these factors, and did they take them into account in their analysis?

Selection bias:

- Was the selection of subjects or locations after the intervention or exposure random or systematic, and could we assume that before and after groups are interchangeable?
- Were the groups to which the subjects or areas were assigned (type of intervention/control) hidden from those who carried out the experiments?
- Was there a difference in the level of missing data between exposed and control groups during the study or the analysis?

Misclassification of the exposure (observational studies only):

- Are exposure/intervention and comparator groups sufficiently well defined?

Performance bias (experimental studies only):

- Was there alteration of the intervention/exposure or comparator treatment procedure that could have impacted the effectiveness of the intervention or the impact of exposure?
- Was the sample size of the altered treatments unbalanced between the intervention or exposure groups or where altered treatments incorrectly taken into account, which could have influenced estimates of impact or effectiveness?
- When assessing mortality, was a persistence test (correction factor) carried out? If so, does it take into account: carcass size, measurements for each turbine separately? Equally, was a detection test with a control for site-specific differences carried out?
- Has the variation in effectiveness between observers and over time (correction factor) been assessed and used?

Detection bias:

- Could result measurements be influenced by knowledge of the exposure, intervention, subjects or locations, or by wanting a certain result?
- Were data measurement methods the same for all groups?
- Was the search area large enough to detect most carcasses at all wind speeds (> 60 m)?
- Was the time interval between searches sufficiently short (< one week)?
  Were carcasses removed at each visit or was another control applied (e.g. counting only fresh carcasses) to avoid counting the same carcass more than once?

Reporting bias:

- Are results (or effect estimates) presented separately and for the entire set of variables studied?
- Are the raw data accessible?

Statistical conclusion validity:

- Could there be mistakes or were inappropriate methods used in the statistical analyses (including: were the hypotheses of the statistical inference methods used violated)?

Conflicts of interest:

- Have the authors disclosed funding sources and potential conflicts of interest?

APPENDIX VI: DETAILS OF THE QUANTITATIVE SYNTHESIS

Limitations of the quantitative synthesis and preliminary remarks

The initial objective was to carry out a meta-analysis of multiple mitigation measures. However, various constraints related to methodology and data quality have reduced this endeavour to the analysis of a single measure: raising the turbine cut-in speed, which in itself represents a "knowledge cluster" (*i.e.* a sub-theme that is sufficiently well-studied to allow statistical analyses).

The small number of articles and studies available per measure was a major constraint for this type of quantitative analysis. Indeed, a small sample size limits the statistical power of this type of analysis and thus the possibility of detecting significant effects.

The extreme heterogeneity of the data was a substantial problem. The studies used very different methodologies, for instance *in situ* and *ex situ* approaches, and measured different aspects of biodiversity using different protocols. For instance, there were before-after (BA), control-impact (CI), and before-after-control-impact (BACI) studies, which involve very different methodological frameworks. Environmental conditions varied between studies, being carried out in different climates and landscapes. Moreover, some studies focused on all species combined whereas others presented their results for each species individually, but with not enough data to analyze the difference between species. Differences in the size and configuration of the wind farms and wind turbines added another layer of complexity.

There was also a marked imbalance in the amount of data available for each group studied, making it difficult to compare and draw general conclusions from the results.

Another major obstacle was the lack of statistical information. Many studies did not provide sufficient detail regarding the statistical parameters or the results (such as effect size, standard error, and confidence interval) for them to be included in a meta-analysis.

These constraints have important statistical consequences. The heterogeneity of the methods and study conditions would have rendered the results incoherent and unreliable. Differences in methodology and environment could have introduced a significant bias in the effect size, leading to false conclusions. Because of these differences, the assessment of the effects of the different mitigation measures would not have been valid.

Moreover, it must be stressed that meta-analyses need to be carried out in the most rigourous way possible, because they represent the highest level of proof in science. A rigourous meta-analysis integrates data from multiple studies to produce a more precise and reliable estimate of the effects of intervention or exposure. When poor quality methods or data are used, the conclusions may be false or misleading, and the results cannot be trusted. A badly conducted meta-analysis can not only lead to wrong scientific interpretations, but these false conclusions can influence policy and practical decisions.

In summary, because of small sample sizes, extreme data heterogeneity, an imbalance in the information available and a lack of statistical information, conducting an exhaustive and statistically robust meta-analysis of all mitigation measures would have produced unreliable and scientifically incorrect results. Consequently, we decided to focus on a single measure (turbine curtailment by raising the cut-in speed), for which data were relatively more coherent and usable.

Methods for the meta-analysis

This brings us to the description of the meta-analysis conducted on this single measure. The analysis included a total of 10 case studies from 7 different bibliographic references. This is less than the amount of data that was initially available (Figure 12). For the sake of rigour and optimal homogeneity, we excluded case studies that presented results for individual species, and only retained results for all species combined. Moreover, studies where the protocol was too specific, such as assessing the effect on mortality of curtailment during specific hours of the night, were also excluded. Note that the final dataset, although pruned and limited to a single measure, was not balanced between the groups for the different variables we extracted, namely geographic location, climate, landscape, study design (BA and CI), turbine size, control cut-in speed, post-intervention cut-in speed, the difference between the two speeds, as well as other variable methodological factors that were not extracted. For instance, for climate, case studies fell into the following categories: humid subtropical (4 case studies), humid continental (3 case studies), dry continental (2 case studies), and mediterranean (1 case study).

As mentioned above, the heterogeneity between studies can affect the statistical power and the robustness of the estimates. Categories with few case studies will have a limited statistical power, making the estimates less reliable and more sensitive to random variation. The underrepresentation of certain categories could induce a selection bias. Results may not be representative of the general population or real conditions. The ability to generalize results to other contexts or populations may be limited by having unbalanced data.

Given these risks, and because of the very small sample size, we decided to only test 4 models: a basic model with no explanatory variable, assessing only the effectiveness of raising the cut-in speed, and three models each integrating a different explanatory variable (the difference between control and intervention cut-in speeds, the intervention cut-in speed by itself, and climate, as a point of discussion).

Preliminary tests (APPENDIX VII) were carried out to determine the feasibility of conducting a meta-analysis on our dataset. In the light of these results, we came to the conclusion that a meta-analysis was feasible, while keeping in mind the slight deviations from the hypotheses and the imbalance in the data.

Results

The model without a moderator (Model 1), which examines the direct relationship between the measure and its effects without taking into account any other factor, showed a significant mean effect of the measure in limiting the impact on biodiveristy compared to the control (Table 4, Figure 14). The mean effect estimate (log-ROM), which measures the difference between groups as a ratio, was -1.1022, with a standard error[11] (SE) = 0.1633, a z score[12] = -6.7480 and a probability p[13] < 0.0001, which means that this effect is statistically highly significant. In terms of Ratio of Means (ROM), the mean effect of the intervention was 0.332. This corresponds to a significant mean mortality reduction of 66.8 % in the intervention group compared to the control group, *i.e.* with a higher cut-in speed.

The analysis of the variables “difference between control and intervention cut-in speeds” (Model 2, p = 0.24), “intervention cut-in speed” (Model 3, p = 0.36) and “climate” (Model 4, p > 0.50) did not show any significant effect.

The model without a moderator had a lower AIC (17.1024) and BIC (17.4968) compared to the other models (Table 5), suggesting a better-fit of this model (see Methods – Synthesis – Data treatment and statistical analysis). The model without a moderator is therefore preferable, as it simple and fits the data better.

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[11] **SE (standard error)**: the standard error indicates to what extent the mean effect estimate will vary if the study was repeated multiple times. A low SE means that the estimate is more accurate.

[12] **z (z-score)**: the z-score is a statistical value that show how many times the effect estimate deviates from 0 (or no difference), in terms of standard deviation. A z-score farther from 0 means that the effect is stronger.

[13] **p (p-value)**: the p-value is the probability that the observed effect is due to chance. A low p-value (e.g. p < 0.0001) means that is very unlikely that the effect is due to chance, which means that the effect is statistically significant.

The lack of significance for the variables associated with cut-in speeds was surprising. Some studies compared different curtailment cut-in speeds with the control cut-in speed and found that higher cut-in speeds were associated with a lower mortality. However, certain factors limit our conclusions. We were not able to include all the studies available due to a lack of detailed information regarding basic parameters. Moreover, our sample size was small and our dataset was unbalanced. As discussed above, these factors can introduce bias in our results. For the same reasons, it was difficult to conclude with certainty from our analyses that climate had no effect.

The analyses, despite their limitations, showed that the results obtained provided valuable indications regarding the effect of cut-in speeds on bat mortality, with an effectiveness that is shown to be very high. Future research using large samples and more balanced data are needed to confirm these results and improve our understanding of the effects of explicative variables.

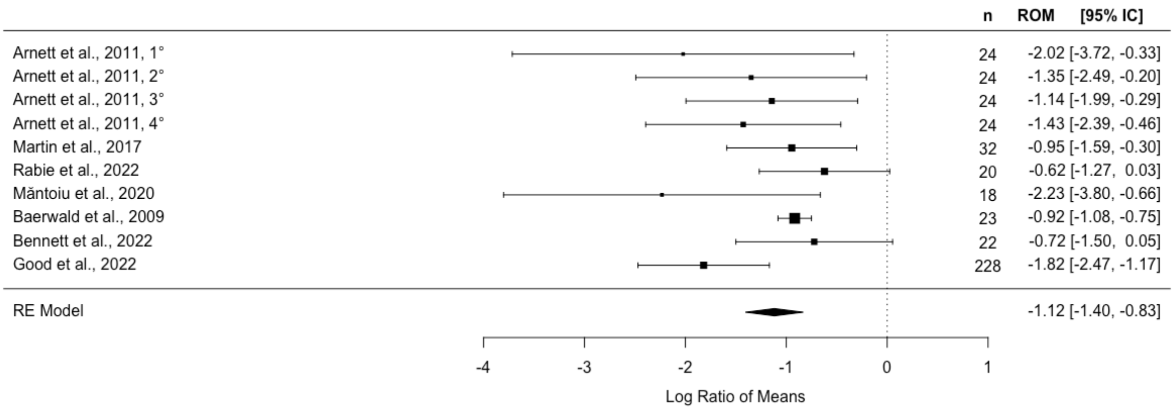


Figure 14. Summary of the meta-analysis of the effect of cut-in speed on mortality rates. Black squares indicate the means, and lines on either side the 95 % confidence interval for effect size. Confidence intervals that do not cross the vertical 0 line represent statistically significant effects ($p < 0.05$). Note that mean values to the left of the 0 line indicate that higher cut-in speeds reduce mortality compared to control speeds.

Table 4. Estimates of statistical coefficients for each model tested in the meta-analysis

Model	Estimate	SE	z-score	p-value	95%.CI low	95% CI high	Mean ROM	95% CI ROM low	95% CI ROM high	% Mean reduction
Model 1	**-1.1022**	**0.1633**	**-6.7480**	**<.0001**	**-1.4223**	**-0.7821**	**0.332**	**0.241**	**0.457**	**66.8%**
Model 2 (Intercept)	-0.5976	0.4417	-1.3531	0.1760	-1.4633	0.2681	0.550	0.231	1.307	45.0%
Diff_Cut.In.Speed	-0.2958	0.2524	-1.1722	0.2411	-0.7905	0.1988	-	-	-	-
Model 3 (Intercept)	-0.0097	1.2078	-0.0080	0.9936	-2.3769	2.3576	0.990	0.093	10.576	1.0%
Int_Cut.In.Speed	-0.2052	0.2242	-0.9152	0.3601	-0.6445	0.2342	-	-	-	-
Model 4 (Intercept)	-1.2516	0.4954	-2.5264	0.0115	-2.2225	-0.2806	0.286	0.108	0.755	71.4%
Climate.Humid continental	0.1241	0.6238	0.1989	0.8424	-1.0986	1.3467	1.132	0.333	3.846	-13.2%
Climate. Humide sub-tropical	-0.1065	0.8004	-0.1331	0.8941	-1.6752	1.4622	0.899	0.187	4.316	10.1%
Climate.Mediterran ean	0.5289	0.8512	0.6213	0.5344	-1.1395	2.1972	1.697	0.320	9.000	-69.7%

Table 5. Comparison of different goodness-of-fit and homogeneity estimates for each model tested in the meta-analysis

Criterion	Model 1 (no moderator)	Model 2 (with Diff_CutInSpeed)	Model 3 (with Int_CutInSpeed)	Model 4 (with Climate)
logLik	-6.5512	-5.6319	-5.8144	-4.8284
Deviation	13.1024	11.2637	11.6287	9.6569
AIC	17.1024	17.2637	17.6287	19.6569
BIC	17.4968	17.5020	17.8671	18.6157
AICc	19.1024	23.2637	23.6287	79.6569
Variance Components (sigma^2)	0.0877	0.0549	0.0943	0.3222
Residual heterogeneity (QE)	Q (df = 9) = 13.8172, p = 0.1290	QE (df = 8) = 10.9684, p = 0.2035	QE (df = 8) = 13.0633, p = 0.1097	QE (df = 6) = 10.5201, p = 0.1044
Test of moderators (QM)	-	QM (df = 1) = 1.3740, p = 0.2411	QM (df = 1) = 0.8376, p = 0.3601	QM (df = 3) = 0.5354, p = 0.9110

<u>APPENDIX VII:</u> PRELIMINARY TESTS TO ASSESS THE FEASIBILITY OF THE meta-analysis

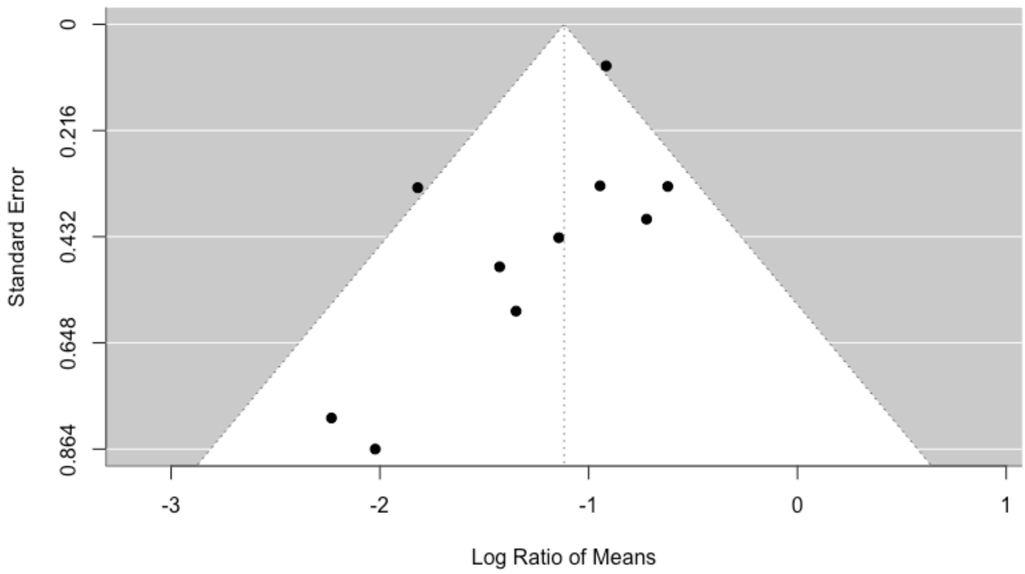
<u>Statistical tests for heterogeneity:</u>

- Test de Cochran Q : Q = 13.81718 p-value = 0.1289789
- Indicateur I^2 : 38.29543 %

Although the p-value of the Q test is not significant, the I^2 value indicates moderate heterogeneity.

<u>Checking for publication bias:</u>

- Funnel plot



- The Egger test:

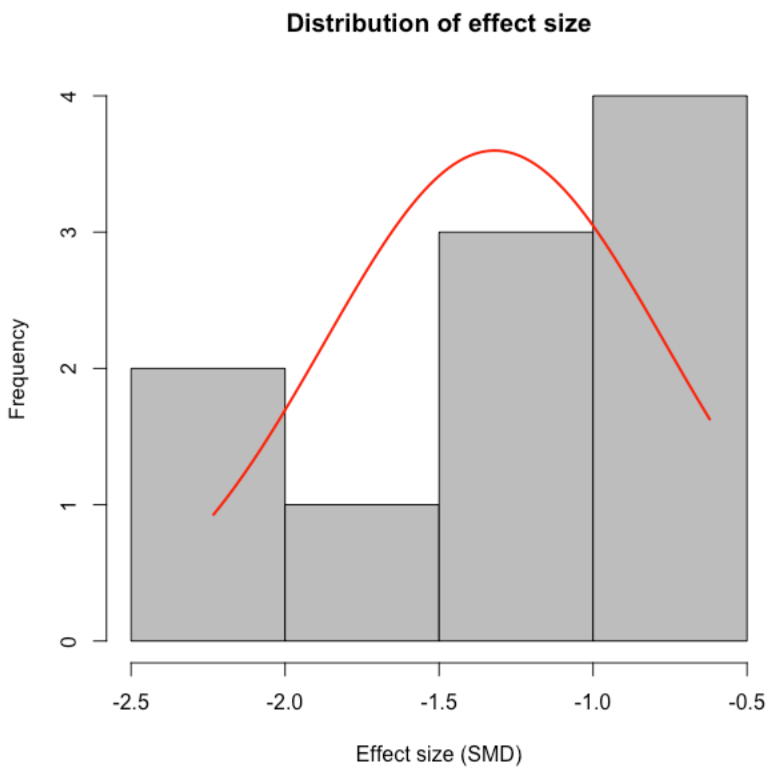
Funnel plot asymmetry test: t = -1.9383, df = 8, p = 0.0886

Intercept value (when the standard error of the intercept (SEI) tends toward 0): b = -0.8181 (CI: -1.0855, -0.5508)

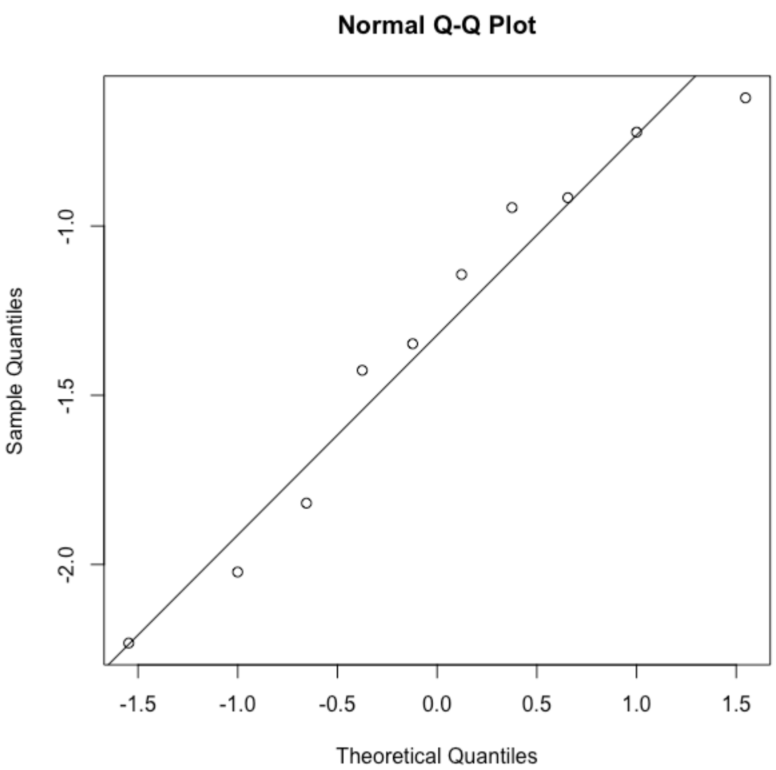
The intercept is negative (-0.8181) and its confidence interval (-1.0855 to -0.5508) does not include 0, which could suggest a slight asymmetry. However, this asymmetry is not statistically significant based on the p-value.
A negative publication bias in the context of a meta-analysis means that studies with negative results or smaller effects are underrepresented in the literature.

Checking the normal distribution of effect sizes:

- Histogram of the distribution of effect sizes



- Q-Q plot



- Shapiro-Wilk test: W = 0.9401021 p-value = 0.5541501

The histogram shows some deviation from a normal distribution, especially at the extremities. The Q-Q plot shows that points deviate from the line, especially at the extremities. This suggests that the data can deviate from a normal distribution, even if these deviations are not sufficiently important to be detected by the Shapiro-Wilk test with a p-value of 0.55.

Two additional statistical tests were carried out for confirmation:

- The Kolmogorov-Smirnov test: D = 0.15014, p-value = 0.9536
- The Anderson-Darling test: A = 0.26435, p-value = 0.6121

The non-significant p-value of these two tests are much higher than the 0.05 threshold, suggesting that these data are sufficiently compatible with a normal distribution.

The statistical tests (Shapiro-Wilk, Kolmogorov-Smirnov, Anderson-Darling) indicate that there is no significant evidence for deviation from a normal distribution. However, visual inspection of the histogram and the Q-Q plot suggests some deviation, especially at the extremities.
In practice, the statistical tests suggest that the data can be considered to be normally distributed in most applications. The deviations observed by visual inspection can be due to the inherent variability of the data or the sample size. For the meta-analysis, we can assume that the data is normally distributed, while keeping the mind the slight deviations that can be seen.

In summary, the preliminary tests carried out to determine the feasibility of a meta-analysis with our dataset showed that the selected studies presented a moderate but non-significant heterogeneity (Q test: $p = 0.13$; $I^2 = 38.3$ %). The Egger test showed a slight asymmetry in the publication bias with a negative intercept (b = -0.82), however this asymmetry was not significant (but note p = 0.09). The Shapiro-Wilk test confirmed that the effect sizes were normally distributed (W = 0.94, p =0.55). Moreover, most of the bibliographic references included here had a “weak” global risk of bias rating (8 out of 10), which reinforces the validity of the meta-analysis. In the light of these results, we came to the conclusion that a meta-analysis was feasible, while keeping in mind the slight deviations from the hypotheses and the imbalance in the data.