WREN SHORT SCIENCE SUMMARY

WIND ENERGY-ENVIRONMENTAL RESEARCH & ENGAGEMENT NETWORK

Bird Behavior and Physiology: Implications for Collision and Displacement Risk

Peregrine falcon. *Photo from Getty Images 485350659*

INTRODUCTION

Wind turbines and associated operation and maintenance activities can have negative impacts on avian species both onshore and offshore. The primary effects of concern for birds are (1) collision, whereby individuals make lethal contact with wind turbines, and (2) displacement, a sublethal effect in which the presence of wind turbines or activities associated with them cause wildlife to redistribute and results in increased energy expenditure and a functional loss of habitat. The risk and impact of effects on a species is determined by a combination of stressors, vulnerability, and exposure [1,2]. Although dozens of species may be exposed to operating wind turbines, variation in behavioral and physiological traits among species means that not all species are equally vulnerable to collision and displacement.

AVIAN COLLISION RISK

Individual-level sensitivity to collision effects is shaped by morphological traits (e.g., body size, wing metrics, visual systems) that dictate the limits of flight maneuverability, sensory perception that dictates the awareness of hazards, and behavioral traits (e.g., annual movements, foraging strategies, daily activity budgets) that dictate the characteristics of flights [1].

Morphological Traits

Morphological traits influence the physical mechanics of flight, shaping how birds move through the air and respond to obstacles. Flight maneuverability describes the aerial agility of a species and their ability to avoid collisions with wind turbines in flight. Birds capable of more agile flight may be more likely to avoid collisions with wind turbines by making last-minute flight adjustments [4–6]. The primary elements that impact flight maneuverability are traits related to body size and wing metrics, such as wing loading and aspect ratio [7].

Certain characteristics of body size or shape can reduce flight maneuverability and thereby potentially increase collision risk. Some birds, particularly those with larger bodies and longer wings, take advantage of updrafts to provide lift, allowing them to achieve greater height without expending energy. Updrafts can be generated by rising temperatures (thermal updrafts), landscape features (orographic updrafts), or waves (wave-slope soaring) [8,9]. However, these atmospheric phenomena that can help conserve flight energy for birds often spatially intersects with areas of wind energy development, leading to an increased risk of collisions with wind turbines. In some areas, updrafts are scarcer or weaker in certain months, leading to seasonal patterns of collision [10,11]. Another important flight characteristic, wing loading, is a measurement of the ratio of a bird's body weight to their wing area. High wing loading is associated with lower flight maneuverability and greater reliance on updrafts and soaring flight, and as a result, these species can be at increased risk of collisions [12].

Sensory Perception

Sensory perception, particularly vision, plays a central role in determining how birds detect and respond to hazards in their environment. The visual systems of bird species are shaped by their natural history and ecological niches, and differences in these systems can therefore help explain species-specific variation in collision susceptibility [13,14].

Two key factors that influence a bird's ability to see wind turbines are the configuration of their visual fields (i.e., direction of highest spatial resolution) and optical parameters of their visual system such as contrast sensitivity and visual acuity [15]. Some species may be unable to detect wind turbines because of visual limitations under certain conditions, whereas others may fail to look in the correct direction to see them [16].

In species with laterally placed eyes, forward vision is formed by the overlapping field of view of both eyes. This means that the highest spatial resolution is laterally on each side of the head rather than straight in front, as with humans. Many bird species may have reduced visual capabilities when looking straight ahead [13,16]. Several collision-prone species have relatively small and/or weak frontal binocular fields and prioritize their lateral vision for essential behaviors like predator detection, interactions with conspecifics, and foraging [13]. These characteristics are evident in eagles, which have small frontal binocular fields. Despite having exceptional spatial resolution, they are disproportionately prone to collisions [17]. Similar visual field configurations in cranes (Gruidae) and bustards (Otididae) may contribute to their comparable high collision vulnerability [18].

Golden eagle. *Photo from Getty Images 1181934610*

Certain characteristic behaviors further illustrate the importance of frontal versus lateral vision. Peregrine falcons (Falco peregrinus) approach prey along curved paths that allow them to keep the target in view of their lateral vision [19]. Raptors that primarily look down while foraging in the air, such as eagles, are likely to have large forward-facing blind spots and are unable to view obstacles right in front of them [18].

Contrast sensitivity determines how well an individual can detect differences in brightness between an object and its background and is critical for object detection and avoidance. Variations in photoreceptor spectral sensitivities also mean that species may perceive colors in different ways. Many birds have relatively low contrast sensitivity [20], which may make wind turbines difficult to detect under low-contrast conditions, such as a white tower or blade against a cloudy sky [21]. Detectability may increase under higher-contrast environmental conditions, such as against a bright blue sky.

Behavioral Traits

Behavioral traits such as annual movements, foraging strategies, and daily activity budget determine the characteristics of flight or flight type, which in turn mediate collision vulnerability. These behavioral tendencies influence when, where, and how individuals fly within the airspace around turbines.

Birds are at risk of collision only when their flight paths intersect with the rotor area of a wind turbine, making flight height an important metric of collision exposure. Species that consistently fly below or above the height of wind turbine blades are significantly less vulnerable to collisions [22].

Certain flight types, such as hovering and soaring, are associated with increased collision risk [23]. Hovering is associated with high winds and may blow individuals toward wind turbines in the event of large gusts [24]. While soaring, raptors are particularly dependent on thermals, which increase collision risk. This risk is further exaggerated when thermal conditions are less favorable, meaning that birds fly at lower flight heights than usual, increasing the chances they will encounter wind turbine blades [25].

Common tern. *Photo from Getty Images 2215082021*

Flight behaviors linked with social or reproductive activity can elevate collision risk because of decreased awareness of surroundings. These behaviors vary with age and sex, producing different patterns of vulnerability. For example, adult white-tailed eagles (*Haliaeetus albicilla*) spend more time engaged in social behavior than sub-adults; thus, their collision risk increases when they are focused on social interactions rather than operating wind turbines [26–28]. The behavioral interactions of common terns (*Sterna hirundo)* also demonstrate differences in fatality patterns. Near a wind farm in Belgium, notable differences in fatality rates were reported between sexes throughout the annual cycle. During periods of incubation and chick feeding, almost 80% of fatalities were males, potentially reflecting differences in activity and foraging between sexes during that critical productive time rather than any differences in morphology [29,30]. Another study observed the mortality of skylarks (*Alauda arvensis*) at a wind farm in Portugal, where carcasses collected were almost entirely adult males. During the breeding season, skylarks perform a characteristic song flight with rapid vertical ascension that increases their vulnerability to collision with wind turbines [31].

Seasonal variations in patterns of flight activity can influence collision risk at different times of the annual cycle. While earlier research suggested that migrating birds might be more susceptible to collisions due to unfamiliarity with the landscape [32], more recent work emphasized behavioral state as a better predictor of collision risk. For example, golden eagles (*Aquila chrysaetos*) that were engaged in local movements flew at lower latitudes closer to the rotor-swept zone of wind turbines and turned more frequently than those migrating through; both behaviors increased their risk of turbine collision [33].

AVIAN DISPLACEMENT RISK

Functional habitat, or the amount of useful habitat available to an individual, depends not only on the suitability of local biotic and abiotic conditions but also on whether the habitat is accessible to animals. If organisms perceive the habitat as unsuitable due to high predation risk or if access is blocked, they will move elsewhere [34,35]. Similarly, if animals view new structures like wind turbines as threats or barriers, they may avoid the areas around wind farms (macro-avoidance), rows of wind turbines (meso-avoidance), or individual wind turbines (micro-avoidance) [36,37]. Repeated or severe avoidance can lead to displacement (Figure 1). However, just as with collision, not all individuals are equally vulnerable to displacement effects. Disaplcement can vary significantly across species and ecological contexts, driven by differences in behavior, habitat flexiblity, and sensitivity to disturbance.

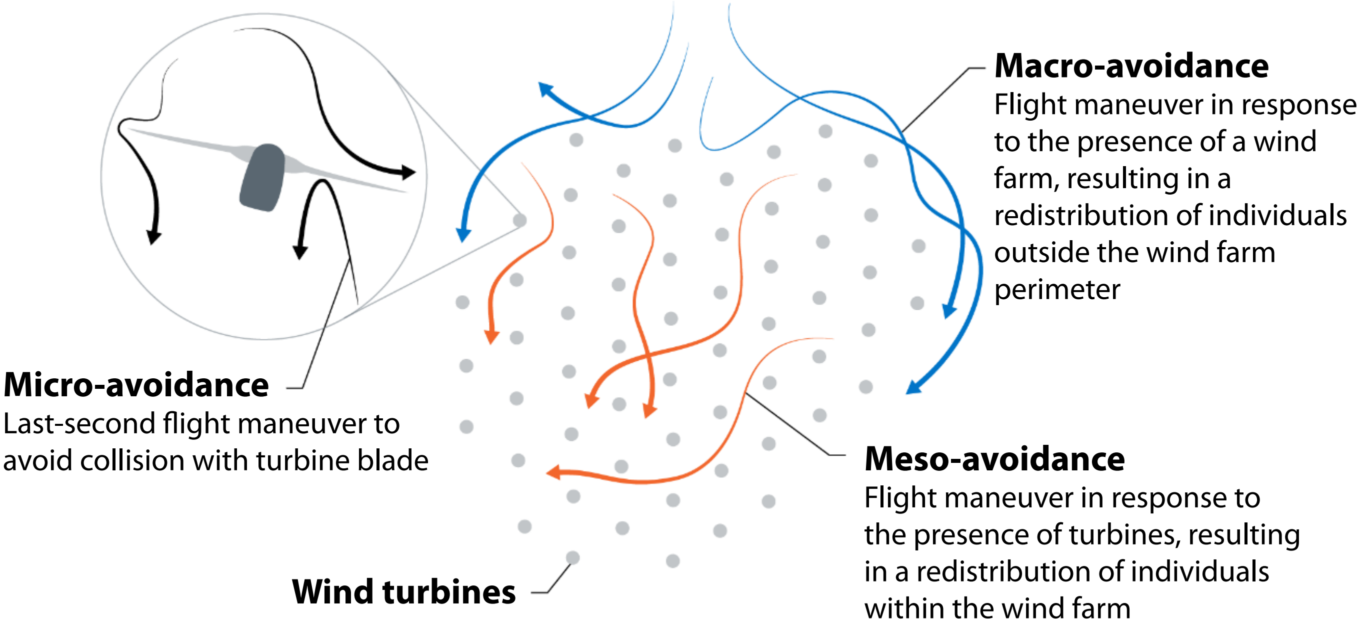

Figure 1. Hypothetical example of three different spatial scales of avoidance. Low macro-avoidance and micro-avoidance are assosicated with higher risk of collision. Disturbance is more likely when individuals display macro-avoidance in response to the entire facility [38].

Black kite. *Photo from Getty Images 540280250*

The primary element driving displacement vulnerability is levels of avoidance of wind energy development. There is an inverse relationship between attraction and avoidance. Birds that show little avoidance of wind turbines are at greater collision risk, and those that show exaggerated avoidance are more susceptible to displacement. Macro-avoidance results in a redistribution of individuals outside the perimeter of the facility, whereas meso-avoidance may redistribute individuals away from areas within a wind farm. Some species are more sensitive to disturbance than others, and some may exhibit habituation, or a lessening of the severity of these impacts over time.

Garvin et al. [39] monitored raptors around a wind farm in southeastern Wisconsin and observed a significant (47%) decline in raptor abundance due to displacement in the 2 years following construction. A follow-up study several years later found differences in species response through time: red-tailed hawk (*Buteo jamaicensis*) abundance returned to preconstruction levels after 8 years, whereas American kestrel (*Falco sparverius*) abundance did not [40]. Some studies measure macro-avoidance of wind farms, which can lead to displacement over time. For instance, Villegas-Patraca et al. [41] recorded flight paths of soaring migrating birds in southern Mexico and found strong avoidance of wind farms during fall and evidence of possible avoidance during spring. Displacement can also be assessed with tracking and space use models. Marques et al. [42] found that black kites (*Milvus migrans*) used areas near wind turbines less than expected given their potential to generate uplift, with reduced use extending to distances of over half a kilometer away from the turbines. Within that distance threshold, bird use decreased as proximity to turbines increased [42].

In 2024, Lamb et al. [43] synthesized 39 empirical post-construction studies on marine bird attraction to or displacement around offshore wind turbines and found that the strength of effects varied between species, among taxa, and with wind farm characteristics. Effects were stronger at sites farther from shore and were more frequently detected at the largest spatial scales during breeding seasons. Effects were significantly negative for species such as gannets, loons, and grebes but were neutral or slightly positive for gulls, waterfowl, and cormorants [43].

Displacement Vulnerability

In addition to direct observational studies, it can be valuable to consider traits of species groups that are more or less likely to lead to displacement to calculate displacement vulnerability indices, metrics that describe the relative likelihood of displacement from wind developments or associated infrastructure and activities.

Avoidance levels and habitat flexibility contribute to displacement vulnerability. Species groups with the greatest displacement vulnerability indices show high macro-avoidance behavior and low habitat flexibility. For example, loons and grebes have high displacement vulnerability because they show pronounced macro-avoidance [44]. Species with high habitat flexibility are less dependent on specific environmental conditions and may be able to thrive in a wider range of habitats; this flexibility can allow species to be more resilient to changes in their environment such as wind facility construction or operations [3].

Mechanisms of Displacement

The exact mechanistic underpinning of displacement is often unknown. For example, are the factors driving the displacement associated with wind farm infrastructure or wind turbine operations? Often, the most critical factor influencing the severity of realized displacement is habitat quality and availability rather than any species-specific traits. If high-quality habitat is plentiful across the landscape, an individual may settle away from wind farms. The spatial distribution of birds is shaped by a complex interplay of factors, including habitat availability, the level of disturbance from energy development and operational activities, avoidance behaviors, and other environmental influences.

Areas for Future Research on Collision and Displacement

- Use technological advancements to address behavioral and ecological knowledge gaps in species susceptible to collision and displacement risk.
- Implement studies with robust designs and appropriate temporal and spatial scale to accurately capture effects. Long-term studies are crucial, as only 14% of studies have sampled 10 or more years after the beginning of operation [45].
- Improve macroscale monitoring technologies, including radar, radiotelemetry, and GPS tags.
- Explore alternative monitoring technologies, such as drones or strike detectors, to estimate collision risk.
- Examine the layout options for wind energy facilities and wind turbine design options to decrease collision risk for raptors.
- Assess habitat suitability differences between wind farm areas and controls to distinguish displacement from confounding factors, such as environmental variables or development features or activities such as transmission lines and shipping lanes.

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Great crested grebe. *Photo from Getty Images 1383539026*

REFERENCES

[1] Goodale, M.W., and I.J. Stenhouse. 2016. “A Conceptual Model To Determine Vulnerability of Wildlife Populations to Offshore Wind Energy Development.” *Human-Wildlife Interaction* 10(1): 53–61. https://doi.org/10.26077/1d31-m472.

[2] Goodale, M.W., and A. Milman. 2016. “Cumulative Adverse Effects of Offshore Wind Energy Development on Wildlife.” *Journal of Environmental Planning and Management* 59(1): 1–21. https://doi.org/10.1080/09640568.2014.973483.

[3] Williams, K.A., et al. 2024. “A Framework for Studying the Effects of Offshore Wind Energy Development on Birds and Bats in the Eastern United States.” *Frontiers in Marine Science* 11: 1274052. https://doi.org/10.3389/fmars.2024.1274052.

[4] Garthe, S., and O. Hüppop. 2004. “Scaling Possible Adverse Effects of Marine Wind Farms on Seabirds: Developing and Applying a Vulnerability Index.” *Journal of Applied Ecology* 41(4): 724–734. https://doi.org/10.1111/j.0021-8901.2004.00918.x.

[5] Furness, R.W., et al. 2013. “Assessing Vulnerability of Marine Bird Populations to Offshore Wind Farms.” *Journal of Environmental Management* 119: 56–66. https://doi.org/10.1016/j.jenvman.2013.01.025.

[6] Everaert, J. 2014. “Collision Risk and Micro-Avoidance Rates of Birds With Wind Turbines in Flanders.” *Bird Study* 61(2): 220–230. https://doi.org/10.1080/00063657.2014.894492.

[7] Jackson, E.K., et al. 2020. “Flight Morphology and Visual Obstruction Predict Collision Risk in Birds.” Preprint. *bioRxiv*. https://doi.org/10.1101/2020.07.20.212985.

[8] Richardson, P.L. 2011. “How Do Albatrosses Fly Around the World Without Flapping Their Wings?” *Progress in Oceanography* 88(1–4): 46–58. https://doi.org/10.1016/j.pocean.2010.08.001.

[9] Duerr, A.E., et al. 2012. “Testing an Emerging Paradigm in Migration Ecology Shows Surprising Differences in Efficiency Between Flight Modes.” *PLoS One* 7(4): e35548. https://doi.org/10.1371/journal.pone.0035548.

[10] Barrios, L., and A. Rodriguez. 2004. “Behavioural and Environmental Correlates of Soaring-Bird Mortality at On-Shore Wind Turbines.” *Journal of Applied Ecology* 41(1): 72–81. https://doi.org/10.1111/j.1365-2664.2004.00876.x.

[11] Péron, G., et al. 2017. “The Energy Landscape Predicts Flight Height and Wind Turbine Collision Hazard in Three Species of Large Soaring Raptor.” *Journal of Applied Ecology* 54(6): 1895–1906. https://doi.org/10.1111/1365-2664.12909.

[12] De Lucas, M., et al. 2008. “Collision Fatality of Raptors in Wind Farms Does Not Depend on Raptor Abundance.” *Journal of Applied Ecology* 45(6): 1695–1703. https://doi.org/10.1111/j.1365-2664.2008.01549.x.

[13] Martin, G.R. 2011. “Understanding Bird Collisions With Man-Made Objects: A Sensory Ecology Approach.” *IBIS* 153(2): 239–254. https://doi.org/10.1111/j.1474-919X.2011.01117.x.

[14] Martin, G.R. 2017. *The Sensory Ecology of Birds*. Oxford University Press.

[15] Caves, E.M., et al. 2024. “Ecological and Morphological Correlates of Visual Acuity in Birds.” *Journal of Experimental Biology* 227(2): jeb246063. https://doi.org/10.1242/jeb.246063.

[16] Martin, G.R., and A.N. Banks. 2023. “Marine Birds: Vision-Based Wind Turbine Collision Mitigation.” *Global Ecology and Conservation* 42: e02386. https://doi.org/10.1016/j.gecco.2023.e02386.

[17] Land, M.F., and D.E. Nilsson. 2012. *Animal Eyes*. Oxford University Press.

[18] Martin, G., and J. Shaw. 2010. “Bird Collisions With Power Lines: Failing To See the Way Ahead?” *Biological Conservation* 143(11): 2695–2702. https://doi.org/10.1016/j.biocon.2010.07.014.

[19] Tucker, V.A., et al. 2000. “Curved Flight Paths and Sideways Vision in Peregrine Falcons (Falco peregrinus).” *Journal of Experimental Biology* 203(24): 3755–3763. https://doi.org/10.1242/jeb.203.24.3755.

[20] Blary, C.L., et al. 2024. “Low Achromatic Contrast Sensitivity in Birds: A Common Attribute Shared by Many Phylogenetic Orders.” *Journal of Experimental Biology* 227(3): jeb246342. https://doi.org/10.1242/jeb.246342.

[21] Potier, S., et al. 2025. “Exploring the Visual System of the Black Grouse (Lyrurus tetrix): Combining Experimental and Molecular Approaches To Inform Strategies for Reducing Collisions.” Preprint. *bioRxiv*. https://doi.org/10.1101/2025.01.12.632585.

[22] Johnston, A., et al. 2014. “Modelling Flight Heights of Marine Birds To More Accurately Assess Collision Risk With Offshore Wind Turbines.” *Journal of Applied Ecology* 51(1): 31–41. https://doi.org/10.1111/1365-2664.12191.

[23] Balmori-de la Puente, A., and A. Balmori. 2023. “Flight Type and Seasonal Movements Are Important Predictors for Avian Collisions in Wind Farms.” *Birds* 4(1): 85–100. https://doi.org/10.3390/birds4010007.

[24] Hoover, S.L., and M.L. Morrison. 2005. “Behavior of Red-Tailed Hawks in a Wind Turbine Development.” *The Journal of Wildlife Management* 69(1): 150–159. https://doi.org/10.2193/0022-541X(2005)069%3C0150:BORHIA%3E2.0.CO;2.

[25] Linder, A.C., et al. 2022. “Quantifying Raptors’ Flight Behavior To Assess Collision Risk and Avoidance Behavior to Wind Turbines.” *Symmetry* 14(11): 2245. https://doi.org/10.3390/sym14112245.

[26] Dahl, E.L., et al. 2013. “White-Tailed Eagles (Haliaeetus albicilla) at the Smøla Wind-Power Plant, Central Norway, Lack Behavioral Flight Responses to Wind Turbines.” *Wildlife Society Bulletin* 37(1): 66–74. https://doi.org/10.1002/wsb.258.

[27] May, R.F., et al. 2010. “Collision Risk in White-Tailed Eagles. Modelling Collision Risk Using Vantage Point Observations in Smøla Wind-Power Plant.” *NINA Report* 639. http://hdl.handle.net/11250/2642580.

[28] Smallwood, K.S., et al. 2009. “Influence of Behavior on Bird Mortality in Wind Energy Developments.” *The Journal of Wildlife Management* 73(7): 1082–1098. https://doi.org/10.2193/2008-555.

[29] Everaert, J., and E.W. Stienen. 2008. “Impact of Wind Turbines on Birds in Zeebrugge (Belgium).” *Biodiversity and Conservation in Europe* 16: 3345–3359. https://doi.org/10.1007/s10531-006-9082-1.

[30] Stienen, E.W., et al. 2008. “Sex-Biased Mortality of Common Terns in Wind Farm Collisions.” *The Condor: Ornithological Applications* 110(1): 154–157. https://doi.org/10.1525/cond.2008.110.1.154.

[31] Morinha, F., et al. 2014. “Differential Mortality of Birds Killed at Wind Farms in Northern Portugal.” *Bird Study* 61(2): 255–259. https://doi.org/10.1080/00063657.2014.883357.

[32] Drewitt, A.L., and R.H. Langston. 2008. “Collision Effects of Wind-Power Generators and Other Obstacles on Birds.” *Annals of the New York Academy of Sciences* 1134: 233–266. https://doi.org/10.1196/annals.1439.015.

[33] Katzner, T.E., et al. 2012. “Topography Drives Migratory Flight Altitude of Golden Eagles: Implications for On-Shore Wind Energy Development.” *Journal of Applied Ecology* 49(5): 1178–1186. https://doi.org/10.1111/j.1365-2664.2012.02185.x.

[34] Gill, J.A., et al. 2001. “Why Behavioural Responses May Not Reflect the Population Consequences of Human Disturbance.” *Biological Conservation* 97(2): 265–268. https://doi.org/10.1016/S0006-3207(00)00002-1.

[35] Gaynor, K.M., et al. 2019. “Landscapes of Fear: Spatial Patterns of Risk Perception and Response.” *Trends in Ecology & Evolution* 34(4): 355–368. https://doi.org/10.1016/j.tree.2019.01.004.

[36] Cook, A.S., et al. 2014. “The Avoidance Rates of Collision Between Birds and Offshore Turbines.” *BTO Research Report 656: Marine Science Scotland, Edinburgh, UK*. https://www.gov.scot/publications/scottish-marine-freshwater-science-volume-5-number-16-avoidance-rates/.

[37] May, R. 2015. “A Unifying Framework for the Underlying Mechanisms of Avian Avoidance of Wind Turbines.” *Biological Conservation* 190: 179–187. https://doi.org/10.1016/j.biocon.2015.06.004.

[38] Dempsey, L., et al. 2025. “New Frontiers in Wind-Wildlife Monitoring Systems.” *Biological Conservation* 311: 111449. https://doi.org/10.1016/j.biocon.2025.111449.

[39] Garvin, J. C., et al. 2011. “Response of Raptors to a Windfarm.” *Journal of Applied Ecology* 48(1): 199–209. https://doi.org/10.1111/j.1365-2664.2010.01912.x.

[40] Dohm, R., et al. 2019. “A Long-Term Assessment of Raptor Displacement at a Wind Farm.” *Frontiers in Ecology and the Environment* 17(8): 433–438. https://doi.org/10.1002/fee.2089.

[41] Villegas-Patraca, R., et al. 2014. “Soaring Migratory Birds Avoid Wind Farm in the Isthmus of Tehuantepec, Southern Mexico.” *PLoS One* 9: e92462. https://doi.org/10.1371/journal.pone.0092462.

[42] Marques, A.T., et al. 2020. “Wind Turbines Cause Functional Habitat Loss for Migratory Soaring Birds.” *Journal of Animal Ecology* 89(1): 93–103. https://doi.org/10.1111/1365-2656.12961.

[43] Lamb, J., et al. 2024. “A Synthetic Analysis of Post-Construction Displacement and Attraction of Marine Birds at Offshore Wind Energy Installations.” *Environmental Impact Assessment Review* 108: 107611. https://doi.org/10.1016/j.eiar.2024.107611.

[44] Kelsey, E.C., et al. 2018. “Collision and Displacement Vulnerability to Offshore Wind Energy Infrastructure Among Marine Birds of the Pacific Outer Continental Shelf.” *Journal of Enviornmental Management* 227: 229–247. https://doi.org/10.1016/j.jenvman.2018.08.051.

[45] Marques, A.T., et al. 2021. “Bird Displacement by Wind Turbines: Assessing Current Knowledge and Recommendations for Future Studies.” *Birds* 2(4): 460–475. https://doi.org/10.3390/birds2040034.