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RESEARCH ARTICLE

The Global Energy Transition: Ecological Impact, Mitigation and Restoration

An ecological vulnerability index to assess impacts of offshore wind facilities on migratory songbirds

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Abstract

1. As offshore wind (OSW) energy expands globally, migratory songbirds are at risk of mortality from collisions with turbine blades, though the magnitude of this threat and which species are most vulnerable, remains poorly understood. Ecological vulnerability indices are commonly used to assess species' susceptibility to harmful factors, with results used to direct scarce research and monitoring resources to species showing relatively high vulnerability. These indices are based on the traits that elevate a species risk to adverse impacts (sensitivity), the overlap in occurrence between a species and the potentially harmful agent (exposure) and the influence of this exposure on the species' local or global persistence (resilience).
2. We modified ecological vulnerability indices for seabirds to assess vulnerability of migratory songbirds to OSW related mortality. As a pertinent case study, we considered songbirds that fly across the Northwest Atlantic during their autumn migration. We utilized readily available information on each species' migratory behaviour, life history, and conservation status to calculate an index score that could range from 1 (lowest vulnerability) to 125 (highest vulnerability).
3. We found scores of 3 to 55.2 for the 101 songbird species evaluated, with New World warblers (Parulidae) over-represented among the highest scoring species. We found the scores to be sensitive to uncertainty in index components, highlighting the importance of considering scoring uncertainty when evaluating ecological vulnerability indices. Finally, we found that for seven of the top 10 highest scoring species, modest improvements in population trends had the potential to lower the scores substantially.
4. *Synthesis and applications*. Our methodology is readily applicable to other regions where offshore wind (OSW) development is planned and songbird migration is common, allowing research and monitoring activities to be targeted to species most likely to be negatively affected by OSW facility encounters.

KEYWORDS
conservation, ecological vulnerability index, migration, offshore wind, passerines, renewable energy, songbirds

1 | INTRODUCTION

With the global rise of renewable energy, offshore wind (OSW) facilities are proliferating, with 64.3 gigawatts (GW) already in operation and another 380 GW expected in the coming decade (GWEC, 2023). Although a rigorous environmental review typically accompanies the siting of OSW facilities, not all potential ecological impacts are easily estimated (Allen & Campo, 2020). Notably, the effect of OSW on migratory songbirds (passerines) remains largely unknown (Fox & Petersen, 2019). Many songbirds are found over the open ocean during migration (Newton, 2023; Williams & Williams, 1990) and, in several species, nearly all individuals utilize the same offshore migratory corridor in a given season (e.g. DeLuca et al., 2015; McKinnon et al., 2017; Townsend et al., 2020). Large fatality events from bird strikes with offshore platforms have been documented within migration hotspots (e.g. in the North Sea; Hüppop et al., 2016). As the world's OSW 'footprint' grows, the number of facilities located within highly travelled songbird migratory corridors will increase, rendering billions of migrating songbirds potentially susceptible to turbine-related mortality (e.g. Bureau of Ocean Energy Managment, 2023; Newton, 2023). There is a clear need to assess which species might experience population level impacts from OSW expansion, and to direct resources toward mitigating this impact (Molis et al., 2019). Here we modify an existing OSW avian ecological vulnerability index (Garthe & Hüppop, 2004) for use on migratory songbirds, demonstrating its value by evaluating species that migrate in the autumn over the Northwest Atlantic. This location is a songbird migratory hotspot (Dokter et al., 2018), and is poised to experience rapid expansion in OSW energy development over the next decade (GWEC, 2023).

Collision with man-made structures is a major conservation issue for migratory songbirds, with between 100 million and 1 billion individuals dying annually from building strikes in the United States alone (Loss et al., 2014). Where songbirds migrate over water, offshore wind turbines and other tall structures pose a collision risk, having many similar characteristics to high-rise buildings, such as height and the presence of artificial lighting (Drewitt & Langston, 2008). In the North Sea, for example, a few days of monitoring per year at a single offshore research platform revealed an average of 150 collision fatalities per year, representing 34 songbird species (Hüppop et al., 2016). There are many other such migration hotspots within planned or existing OSW facilities globally (e.g. Afsharian et al., 2020; GWEC, 2023; Yong et al., 2015). It could be reasonably argued that, for species that are widespread and common, the increased mortality risk from OSW facilities has little impact on their long-term persistence (Fox & Petersen, 2019). However, for species that already face multiple stressors that precipitate population declines (Pirotta et al., 2022), the cumulative effects of additional mortality from OSW turbines could represent a threat to their persistence (National Research Council, 2007). There is thus a need for tools that can systematically and transparently rank the vulnerability to OSW facilities for the hundreds of species that migrate over the open ocean each year (Willmott et al., 2013).

Ecological vulnerability indices are commonly used to assess species' exposure to harmful factors (Furness et al., 2013; Hunter et al., 2015; Reid et al., 2023; Waugh et al., 2012). These indices are based on the biology of a species that renders it more or less susceptible to harm (sensitivity), the species presence within locations where harm could occur (exposure), and the influence of this factor on a species local or global persistence (resilience) (Hunter et al., 2015; Reid et al., 2023; Waugh et al., 2012). Such an index was recently used to assess the vulnerability of all coastal Australian birds to OSW (Reid et al., 2023), and there are other more generalized approaches that assess vulnerability to OSW among all volant species (Band et al., 2007; Willmott et al., 2013). These indices are particularly useful relative to OSW impacts because directly observing collisions and mortality of birds in the open ocean is very difficult and expensive (Dirksen, 2017; Fijn et al., 2015). This difficulty may be especially acute for songbirds, which transit offshore locations solely during their migration, mainly using powered (flapping) flight, and not foraging or resting while over open water (Newton, 2023). Previous indices have either excluded songbirds or lumped them with disparate taxa using broad assumptions about avian OSW exposure and sensitivity. These approaches may miss songbird-specific factors that increase vulnerability for this group (e.g. Willmott et al., 2013).

Here, we tailor a previously published ecological vulnerability index to evaluate the vulnerability of songbirds migrating across the Northwest Atlantic to OSW turbine mortality. Each autumn, the Northwest Atlantic is traversed by over 100 species as they move from breeding locations in North America to over-wintering habitat in South America and the Caribbean Islands (Williams & Williams, 1990) (this contrasts with spring when prevailing winds favour an inland route). The Northwest Atlantic currently hosts 2 OSW facilities (42 MW), with coastal U.S. states set to develop capacity for 54 GW of power per year in the next decade (GWEC, 2023). The total designated OSW lease areas occupy 9307 km^2 of coastal ocean from North Carolina to Maine (Methratta et al., 2023), which covers a substantial part of the nearshore habitat in the Northwest Atlantic. Most migratory songbirds depart from coastal areas around civil twilight (Smolinsky et al., 2013), potentially exposing them to OSW facilities soon after migratory departure. We utilized systematic methods to populate our scoring system using easily obtained information on the behaviour, patterns of occurrence, and life history of songbirds. We also explored how scoring uncertainty influences the final vulnerability ranking. Finally, we documented how a change in each species' population trend might influence final index scores as a way of recognizing that the conservation status of species can change over time via management or policy actions outside of OSW mitigation measures.

2 | MATERIALS AND METHODS

To determine which species should be included in our analysis, we started with the 187 North American songbird species classified as Neotropical migrants by the U.S. Fish and Wildlife Service (U.S. Fish & Wildlife Service, 2022). We retained from this list only species with breeding locations from Lake Superior (western coast) to the Atlantic Ocean, and north of Cape Hatteras, North Carolina, including Southeastern Canada. We then examined each species' migratory corridor using information in Birds of the World (Billerman et al., 2022), and removed 13 species for which it is very unlikely that migrating individuals reach the Atlantic coast in the autumn, and one species now considered extinct (Bachman's Warbler, *Vermivora bachmanii*; Schuldheisz, 2023). Our final list included 101 passerine species (see Table S1).

We applied an ecological vulnerability index scoring system to these 101 species. Our index is adapted from two existing protocols used to assess seabird vulnerability to OSW in Europe, where overall vulnerability was determined by scores related to behaviour and conservation status (Furness et al., 2013; Garthe & Hüppop, 2004). We modified several categories for applicability to migratory songbirds, but maintained the same formula and structure. We produced species-specific scores (from 1 to 5) for two categories related to sensitivity, two related to exposure, and two related to population-level resilience to mortality from collisions with OSW turbines (Table 1). The two categories for sensitivity scoring are flight manoeuvrability (wing-loading index) and collision vulnerability (skyscraper mortality index). The two categories for exposure scoring are migration corridor (extent of offshore migration) and flight timing (day vs. night). The two categories for resilience scoring are breeding population trend (North American Breeding Bird Survey trend) and conservation status (International Union for the Conservation of Nature (IUCN) Red List status).

2.1 | Sensitivity

To characterize flight manoeuvrability, we obtained wing loading estimates for each species (average body mass in grams divided by average wing area in mm^2) and converted it into a score from 1 to 5 (Table 1). We judged wing loading, as opposed to measures of wing shape (e.g. aspect ratio), to be the most useful proxy for manoeuvrability in a collision context as it correlates closely with a species' mid-air turning ability; this, in turn, should determine how easily an individual in flight can quickly adjust to the presence of rotating turbine blades (Fernandez-Juricic et al., 2018; Lindhe Norberg, 2002). For 16 species with no published wing loading measurements, we imputed this value using the average from other species within its genus or family (Table 1).

To assess collision vulnerability, we used a published species-specific index of vulnerability to collisions with high-rise buildings (Table 1; Loss et al., 2014). Flight altitude is an important indicator of OSW collision for seabirds; however, this information is uncommonly measured for songbirds migrating across open water. We thus considered species with a higher propensity for colliding with high-rise buildings during migration to be more inclined to collide with structures occupying a similar vertical space over the ocean. We acknowledge that flight altitudes on land may not be the same as over water, and many characteristics of turbines differ from buildings. However, songbirds often fly at lower altitudes over water than land (Bruderer & Liechti, 1998), so we consider this index to be a conservative indicator of collision risk. We imputed collision risk values for 14 species following the same procedure as with wing loading.

2.2 | Exposure

To characterize exposure due to species' characteristic migration corridor location, we obtained offshore autumn sighting records for each species from three separate sources: U.S. Department of Interior shipboard survey data, offshore eBird records, and eBird records from Bermuda. The former two data sources provide direct records of which songbird species are regularly recorded in flight over the open ocean during autumn. We included records from Bermuda as it is the only oceanic island that sits within the Northwest Atlantic, and as such provides a temporary refuge for individuals as they traverse this large stretch of ocean on their autumnal migratory route south (Mejías & Mejías, 2020). We thus consider records of migrating species on Bermuda as a high-quality source of information on which species regularly traverse the open ocean around the island in autumn. We combined these information sources to create a single score for all 101 species that indicates the extent that individuals of each species fly across the open ocean rather than close to coastlines in autumn (see Table 1).

We produced a flight timing score between 1 and 5 for each species based on the language describing what time of day a species initiates migratory flights within the 'Movements and Migration' sections of Birds of the World (Billerman et al., 2022). Songbirds that migrate at night are considered to be at higher risk of colliding with structures than those that migrate during the day (Colling et al., 2022). For 11 species where we could find no information, we imputed their score using the average value derived from the most closely related species.

2.3 | Resiliency

To score each species' resiliency to OSW mortality, we incorporated breeding population trend estimates from the U.S. Geological Survey Breeding Bird Survey (BBS; Sauer et al., 2023), and each species' red list threat status from the IUCN (IUCN, 2022). The BBS trend data are based on a systematic annual survey of all bird species observed in North America from June and July, including counts of the number of individuals observed per unit of effort. Sauer et al. (2023) then estimated annual population trends from these annual counts, which we used here. For four species with no BBS trend, we obtained trend information from the IUCN Red List (IUCN, 2022). We converted all trends into scores from 1 to 5 (Table 1).

To score conservation status, we obtained the IUCN Red List status for all 101 species we considered (IUCN, 2022). The IUCN

TABLE 1 The data sources, data processing, and scoring methodologies used to create each of the three vulnerability index combined scores.

Scores	Data sources	Data processing	Scoring
Sensitivity (flight manoeuvrability)	Poole (1938) Hartman (1961) Andrews et al. (2009) Gray (2019) Chu et al. (2022)	Wing loading from published sources for 85 species. For 16 species, we imputed the value for wing-loading using the average from the most closely related group available within our dataset (genus or family)[d]	We scored each species based on the quintile their wing-loading index fell into (i.e. lowest quintile = 1, highest = 5)
Sensitivity (collision vulnerability)	Loss et al. (2014)	We extracted estimated species vulnerability to collisions with high-rise buildings for 87 species.[e] For 14 species, we imputed the value for collision vulnerability[d,f]	We scored each species based on the quintile their collision index fell into (i.e. lowest quintile = 1, highest = 5)
Exposure (migration corridor)	Sullivan et al., (2009) and eBird (2023) Northwest Atlantic Seabird Catalogue (USDOC, 2021) Partners in Flight (2020)	We tallied the number of observations of each species from the three data sources.[a,b] We normalized each of the three counts by estimated population size. We *z*-transformed the resulting normalized count data and selected the largest *z*-score for each species	We scored each species based on the quintile their largest *z*-score fell into (i.e. lowest quintile = 1, highest = 5), making each species relative to all other species in our sample
Exposure (flight timing)	Birds of the World (Billerman et al., 2022)	We located language related to migration flight timing for 90 species. We imputed data for 11 species with no information on flight timing using the average of the closest available taxonomic group[c]	Nocturnal = 5 Nocturnal or occasional daytime movements = 4 Day and night = 3 Diurnal or occasional nocturnal movements = 2 Diurnal = 1
Resilience (population trend)	USGS Breeding Bird Survey (Sauer et al., 2023) IUCN Red List of threatened species (IUCN, 2022)	We extracted population trend from BBS 1966 to 2021, as well as uncertainty in the trend estimate for 97 species. For four species, we extracted the population trend estimate from the IUCN Red List[g]	Rapidly growing (>1.5) = 1 Growing (0.5 to 1.5) = 2 Stable (0.5 to −0.5) = 3 Declining (−0.5 to −1.5) = 4 Rapidly declining (<−1.5) = 5 For the four species with IUCN Red List data, we categorized Increasing as 2 and Decreasing as 4
Resilience (conservation status)	IUCN Red List of threatened species (IUCN, 2022)	We extracted the IUCN Red List status for each species	Least concern = 1 Near threatened = 2 Vulnerable = 3 Endangered = 4 Critically endangered = 5

Note: Each of the combined scores (sensitivity, exposure, and resilience) incorporated two metrics (categories).

[a]The NWASC contains data from several Christmas Bird Counts with pelagic elements, due to the potential for land based sightings to influence results we excluded these datasets from our study.

[b]We excluded three songbird species that have breeding populations on Bermuda: White-eyed Vireo (*Vireo griseus*), Eastern Bluebird (*Sialia sialis*), and Grey Catbird (*Dumetella carolinensis*).

[c]Golden-winged Warbler's Flight Timing sub-score was imputed from Blue-winged Warbler, its mostly closely related species, not from the genus as a whole.

[d]Exceptions included Bicknell's Thrush (*Catharus bicknelli*), which was imputed from the visually indistinguishable Grey-cheeked Thrush (*C. minimus*). and Willow and Alder Flycatcher (*Empidonax traillii* and *E. alnorum* respectively), which were lumped in all sources under the species, Traill's Flycatcher (*E. traillii*).

[e]Loss et al. standardized the number of fatalities for each species by their North American population size and overlap with study sites in a regression. Then, to get their final value, they took 10 to the absolute value of each residual from their regression, rendering all numbers positive. The sign of the residual indicated if a species was more or less likely than the average to experience collision mortality. We took the final values and transformed them with the sign of the residual on which they were based so as to indicate if a species is more or less likely than average to collide with a high-rise.

[f]For American Pipit (*Anthus rubescens*), the closest related group was not Genus or Family but the Superfamily Passeroidea, as such the value for American Pipit was based off of the average of Passeroidea.

[g]For four species with no published trend (Grey-cheeked Thrush, Bicknell's Thrush, American Pipit (*Anthus rubescens*), and Kirtland's Warbler; *Setophaga kirtlandii*) we used the population trend estimate published by the International Union for the Conservation of Nature's (IUCN) Red List (IUCN, 2022).

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status is based on a species' current population trend, population size, and the extent of its geographic range (IUCN Species Survival Commission (SSC), 2012). The latter two factors are often not correlated with a species' population trend, and thus provide unique information on a species' resilience to OSW mortality. We converted Red List status into scores from 1 to 5 (Table 1).

2.4 | Vulnerability index

Using the category scores as described above, we created an overall vulnerability index for each species (Figure 1), averaging each category score into its respective combined score and creating each species vulnerability index (SVI) using the equation (Garthe & Hüppop, 2004):

$$\text{SVI} = \frac{\text{FM} + \text{CV}}{2} \times \frac{\text{MC} + \text{FT}}{2} \times \frac{\text{PT} + \text{CS}}{2},$$

where FM is flight manoeuvrability, CV is collision vulnerability, MC is migratory corridor, FT is flight timing, PT is population trend, and CS is conservation status; all are represented as scores from 1 to 5. The final vulnerability index ranged from 1 to 125, with 1 being very low vulnerability (score of 1 in all three categories) and 125 being very high vulnerability (score of 5 in all categories). A species with moderate scores in all categories has a higher vulnerability index than a species with high scores in one category and low scores in all others (Garthe & Hüppop, 2004). To provide context regarding the expected range of index values, we created a null distribution by randomly generating category scores and calculating final index values for 100,000 hypothetical 'species' using the above formula (see Figure S4). We then compared the realized scores for our 101 species to this random distribution of index scores.

For the top 10 highest scoring species, we used radar graphs to visually illustrate the contribution of category scores on the species' final index value. Finally, we used binomial generalized linear models (GLM) to evaluate whether any songbird family was more, or less, likely be in the top 10. For this analysis, the null expectation was that each family would have a number of species present in the top 10 which is proportional to the total number of species in that family within our 101 species set.

2.5 | Uncertainty

We explicitly considered the effect of two sources of uncertainty inherent in our index: data quality and positioning of category score cut-offs. The data we used to build each category score contained some level of uncertainty that can be ascribed to lack of information (e.g. imputed values or population trends based on low sample sizes). Similarly, to combine all category scores into a final index, we created five groupings within each category using various cut-off values (Table 1). If we had chosen a different cutoff value, some species would have had a higher or lower final vulnerability index score.

To assess scoring uncertainty, we conducted a sensitivity analysis by modifying uncertain category scores and recalculating the final vulnerability index. We modified all inherently uncertain scores up and down one scoring level, where 'inherently uncertain' was defined as scores where the value for a species was imputed or the source of the original data indicated a high degree of uncertainty (e.g. BBS population trends). We considered BBS trend values coded by USGS as 'Yellow' or 'Red' to be inherently uncertain as these species' trends were created using sparse data (Sauer et al., 2023). For scores based on continuous data, we modified the underlying values up and down by 10% to represent a moderate level of uncertainty in

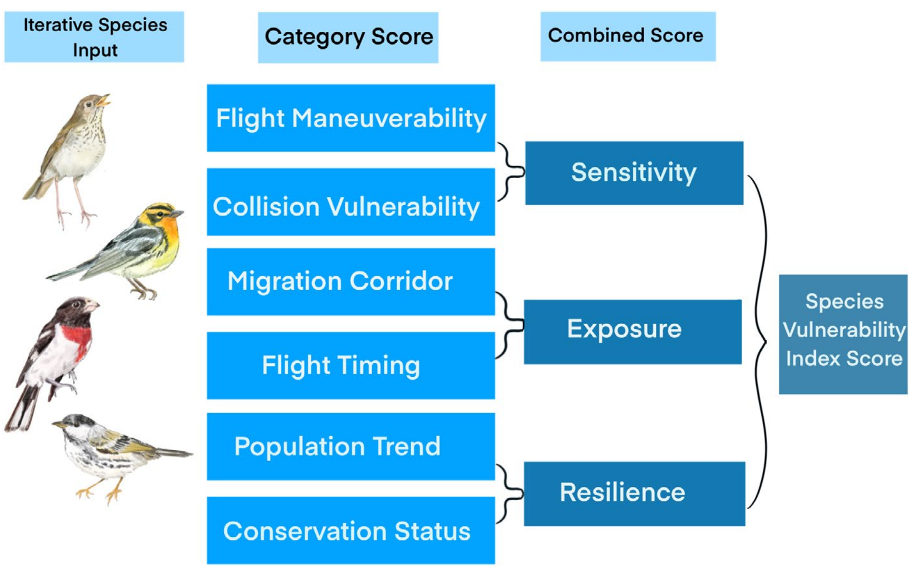


FIGURE 1 Each species identified as migrating across open ocean waters of the Northwest Atlantic in autumn was assigned a score from 1 to 5 in each category representing the combined scores: sensitivity, exposure and resilience (see text for details). These combined scores were then multiplied to create a single vulnerability index score per species. Illustration by Amy Green-Tkacenko.

data quality or interpretation. After adjusting category scores one at a time for each species, we recalculated the final vulnerability index. We used the maximum and minimum of these recalculated index values for each species as an estimate of plausible upper and lower bounds for the final index score.

2.6 | Change in conservation status

Several of our index components are based on fixed characteristics of each species' biology; these will not change over time or in response to conservation and management actions offshore, or within their breeding and over-wintering habitats. In contrast, the resilience score is composed of population trend and conservation status, both of which can respond to conservation and management actions. If either of the resiliency factors for a species improved via management, the species' OSW vulnerability index score would necessarily drop. We thus explored to what extent a species' population growth would need to increase, or decrease, to change its vulnerability index score so that it either dropped out of the top 10 or entered into the top 10. We first increased the population trend of each of the top 10 highest scoring species by one score cut-off until it's overall index value decreased such that it fell out of the top 10. We then considered the 'next top ten species' (those just below the top 10) and determined how much their population trend must decrease before the species would enter the top 10.

3 | RESULTS

3.1 | Vulnerability index

The vulnerability index we assigned to the 101 songbird species ranged from 3 to 55.2, with the median being 24 (Figure 2). The species with the highest vulnerability index was Blackpoll Warbler (*Setophaga striata*; vulnerability score of 55.2). The scores of the top 10 species occurred within the 80th to 94th percentiles of our random 'null' distribution of possible index scores (see Figure S4). New World warblers (Parulidae) were the only family to be over-represented in the top 10 species (70% of species in the top 10% were warblers) relative to their representation in the full species list (37%; binomial GLM, p-value = 0.03). No families were significantly under-represented in the top 10.

The median score in each combined group was 3 for sensitivity, 3.5 for exposure, and 2 for resilience (see Figure S5). Forty-five species were commonly observed over offshore waters (migratory corridor score of 4 or 5), with the remainder likely having autumn migratory corridors that are nearer the coastline. Seventy species had a higher collision risk than the average on which the underlying metric is based. Sixty-two species had breeding population trends below zero, indicating declining populations, whereas 39 had trends indicating stable or increasing breeding populations. The two species with the highest rates of breeding population decline were Bank Swallow (*Riparia riparia*) and Eastern Meadowlark (*Sturnella magna*). None of the 101 species we considered were classified by IUCN as endangered, but one was classed as 'vulnerable' (Bicknell's Thrush, *Catharus bicknelli*) and six as 'near threatened'. Five (50%) of the top 10 highest scoring species met or exceeded the average value for each combined score (sensitivity, exposure, and resilience) (Figure 3). Scores for breeding population trend, collision vulnerability, and migratory corridor were most often above the overall average score in the top 10 species (Figure 3).

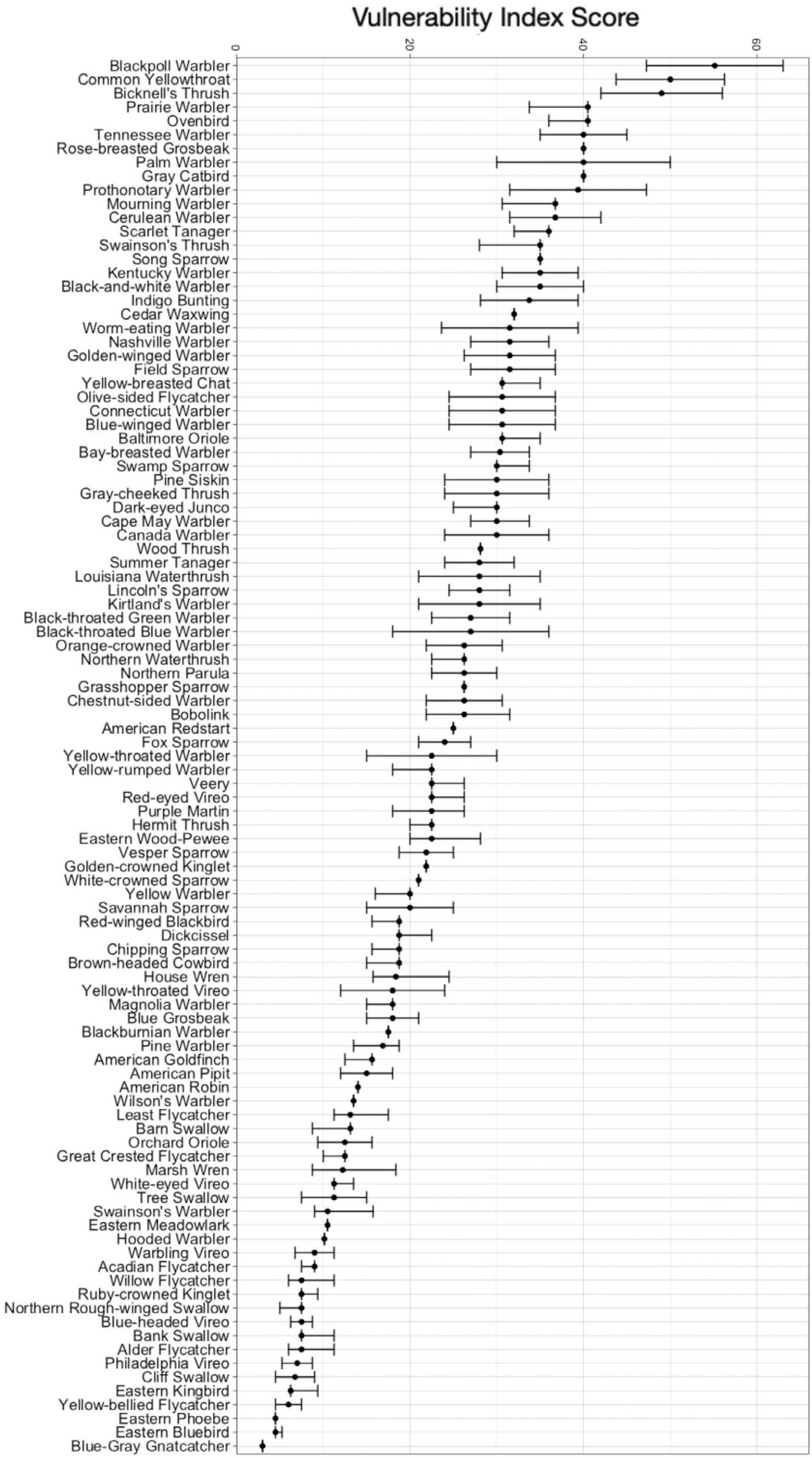
3.2 | Uncertainty

Our sensitivity analysis revealed that modifying uncertain categorical scores or varying continuous metrics by 10% could have significant influence on the final index values. For 85 species, at least one of their category scores was classified as inherently uncertain (Figure 2). Of the species in the top 10, eight (80%) had uncertain category scores. Blackpoll Warbler, Common Yellowthroat, and Bicknell's Thrush each had two uncertain scores. Uncertainty bounds were generally higher for species with higher index values, though there was significant variation even among species with similar rankings. For example, among species in the top 10, Palm Warbler had bounds spanning 20 index points, while Rose-breasted Grosbeak and Grey Catbird showed no change when category scores were modified (Figure 2).

3.3 | Change in conservation status

Of the 10 highest scoring species, all can have their vulnerability index lowered sufficiently to no longer be in the top 10 by improving their population trend (Figure 4). Seven of these species (70%) required only one unit improvement in their population trend score to no longer be in the top 10; two species required an increase of two units (Bicknell's Thrush and Common Yellowthroat, *Geothlypis trichas*); and Blackpoll Warbler required an increase of three units (Figure 4). Notably, not all such changes in population trend resulted in the species improving to the point where it was stable or increasing over time (Figure 4). For example, a modest improvement in the declining breeding population trend of Prairie Warbler (*Setophaga*

FIGURE 2 Final index scores representing relative vulnerability to offshore wind mortality for each of 101 songbird species that traverse the Northwest Atlantic in their autumn migration. The points are the calculated species vulnerability score, while the bars represent score uncertainty bounds (not error bars). Uncertainty bounds were calculated by altering uncertain category scores (up or down) for each species and recalculating the overall species vulnerability score. If a species has no uncertainty bound that means the species had no uncertain category scores with the potential to move the final index.


Vulnerability Index Score
0
20
40
60
Blackpoll Warbler
Common Yellowthroat
Bicknell's Thrush
Prairie Warbler
Ovenbird
Tennessee Warbler
Rose-breasted Grosbeak
Palm Warbler
Gray Catbird
Prothonotary Warbler
Mourning Warbler
Cerulean Warbler
Scarlet Tanager
Swainson's Thrush
Song Sparrow
Kentucky Warbler
Black-and-white Warbler
Indigo Bunting
Cedar Waxwing
Worm-eating Warbler
Nashville Warbler
Golden-winged Warbler
Field Sparrow
Yellow-breasted Chat
Olive-sided Flycatcher
Connecticut Warbler
Blue-winged Warbler
Baltimore Oriole
Bay-breasted Warbler
Swamp Sparrow
Pine Siskin
Gray-cheeked Thrush
Dark-eyed Junco
Cape May Warbler
Canada Warbler
Wood Thrush
Summer Tanager
Louisiana Waterthrush
Lincoln's Sparrow
Kirtland's Warbler
Black-throated Green Warbler
Black-throated Blue Warbler
Orange-crowned Warbler
Northern Waterthrush
Northern Parula
Grasshopper Sparrow
Chestnut-sided Warbler
Bobolink
American Redstart
Fox Sparrow
Yellow-throated Warbler
Yellow-rumped Warbler
Veery
Red-eyed Vireo
Purple Martin
Hermit Thrush
Eastern Wood-Pewee
Vesper Sparrow
Golden-crowned Kinglet
White-crowned Sparrow
Yellow Warbler
Savannah Sparrow
Red-winged Blackbird
Dickcissel
Chipping Sparrow
Brown-headed Cowbird
House Wren
Yellow-throated Vireo
Magnolia Warbler
Blue Grosbeak
Blackburnian Warbler
Pine Warbler
American Goldfinch
American Pipit
American Robin
Wilson's Warbler
Least Flycatcher
Barn Swallow
Orchard Oriole
Great Crested Flycatcher
Marsh Wren
White-eyed Vireo
Tree Swallow
Swainson's Warbler
Eastern Meadowlark
Hooded Warbler
Warbling Vireo
Acadian Flycatcher
Willow Flycatcher
Ruby-crowned Kinglet
Northern Rough-winged Swallow
Blue-headed Vireo
Bank Swallow
Alder Flycatcher
Philadelphia Vireo
Cliff Swallow
Eastern Kingbird
Yellow-bellied Flycatcher
Eastern Phoebe
Eastern Bluebird
Blue-Gray Gnatcatcher

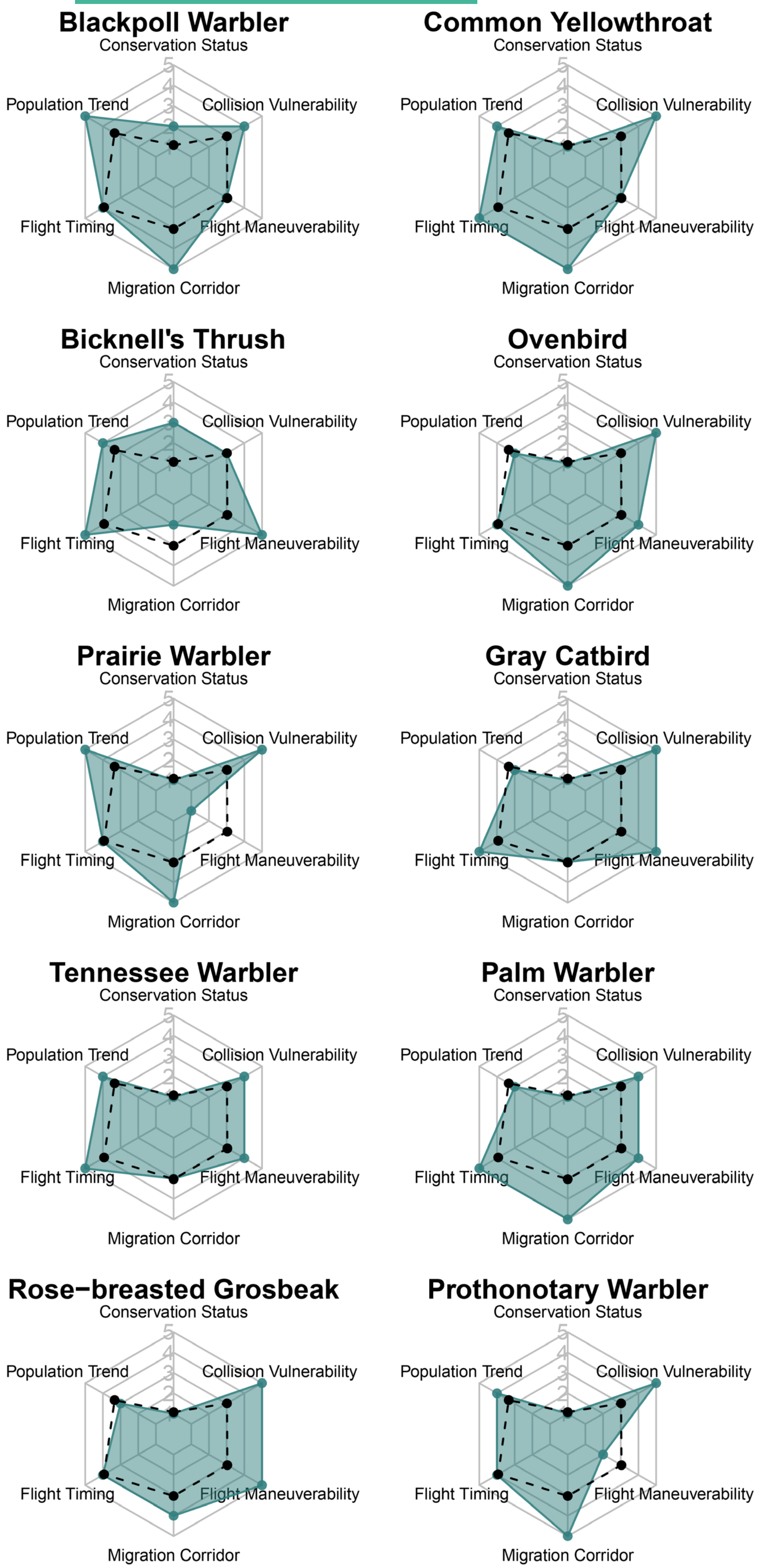


FIGURE 3 Category scores used to calculate the overall vulnerability index score for offshore wind collision mortality for each of the top ten highest scoring species. The blue points and shaded areas represent the scores for each species, while the average score across all 101 species evaluated is depicted as a black-dotted line for reference. Each of the species in the top ten exceeded the average score value across multiple categories, though which categories had higher scores than average varied substantially across species.

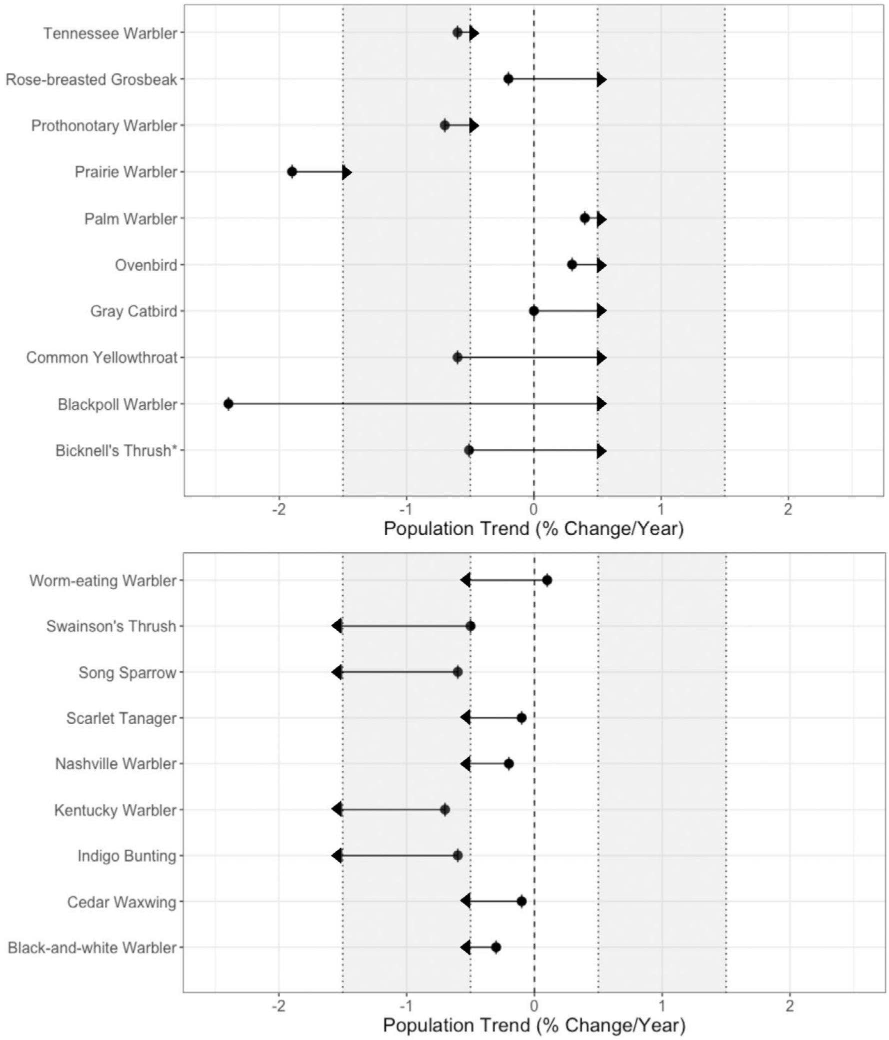


FIGURE 4 The potential influence of conservation and management measures on final vulnerability index scores for the top 10 species, and the next top 10. The top plot shows the increase in population trend required to lower a species' overall vulnerability index enough to drop it from the top 10. The bottom plot shows the reduction in population trend required to raise a species' resiliency score from the 'next top ten' into the top 10. For each species, the closed circle shows the current population trend estimate, and the arrow is the minimum change required to move into or out of the top 10. The dashed line indicates a stable population (annual trend = 0), with species to the right having increasing population trends and those plotted to the left decreasing population trends. The vertical dotted lines and shaded areas indicate the scoring cutoff values for breeding population trend used in the resiliency score. The analysis for the bottom plot was performed on the species with index scores ranked 11th through 20th, which included 13 species due to ties. Four species are excluded from the bottom plot (Mourning Warbler, Cerulean Warbler, Field Sparrow, and Golden-winged Warbler) as it was not possible for them to move into the top 10 ranking with any decrease in their population trend.

discolor) would decrease the species overall index score enough to drop it from the top 10 (Figure 4).

When considering the 13 (four species tie for 20th) species with vulnerability index scores immediately below the top 10, nine have the potential to supplant or tie Prothonotary Warbler (*Protonotaria citrea*) in the top 10 if their population trend worsened. Of these nine species, all required only one unit increase in their population trend score to attain a vulnerability index score in the top 10 of all species. For the remaining four species, changes to their population trend alone would not be sufficient to move their overall scores into the top 10. Thus, our analysis showed that changes to species' population trend can have substantial impacts on vulnerability rankings.

4 | DISCUSSION

The global transition to renewable, low-carbon forms of energy production is driving a construction boom in offshore wind (OSW) energy facilities (GWEC, 2023). These facilities provide a means of electricity production that lies close to major population centers, producing far fewer greenhouse gas emissions than conventional means of electrical generation (Bates & Firestone, 2015; Browning & Lenox, 2020). However, the proliferation of OSW turbines will rapidly transform the ocean's airspace, a habitat used by a variety of volant species (DeLuca et al., 2015; Fox & Petersen, 2019; Solick & Newman, 2021; Willmott et al., 2023). As these facilities continue to be constructed along the coasts, migratory songbirds may encounter multiple wind areas on their migration route, with unknown cumulative effects, potentially increasing the absolute magnitude of the mortality threat each species faces. We identified 101 species of songbird that would be exposed to planned OSW facilities while migrating across the Northwest Atlantic in autumn. Our vulnerability index identified the species which, relative to other songbirds, may be the most at risk from OSW mortality. These species migrate offshore at night, are prone to collisions with high-rise structures, and are already facing population declines. Migratory songbirds flying over open ocean are difficult to study (Desholm et al., 2006; Fijn et al., 2015), often requiring novel and expensive detection systems mounted to turbines (Dirksen, 2017). Our results can provide a transparent and repeatable way to target when and where to deploy these efforts.

Creating ecological vulnerability indices requires choices that carry inherent uncertainty, including dealing with variable quality of underlying data and the way that data are treated to create category scores (Barnett et al., 2008). We found that over 85% of species had at least one inherently uncertain category score that influenced their final index score, and that assuming 10% uncertainty in underlying continuous metrics often resulted in changes to the final index. This level of sensitivity of a vulnerability index to scoring uncertainty may be common, if rarely evaluated (Barnett et al., 2008), and has potential implications for relative risk rankings and prioritization efforts. By making uncertainty in underlying metrics transparent, including its effect on the final index scores, we highlight where added information on migratory behaviour and timing, collision risk, and breeding population trend would be most helpful for elevating confidence in forecasts of OSW mortality impacts. This transparent approach also allows others to repeat or modify our methods to include more information, if available, or to evaluate different configurations of how combined scores are calculated. As improved methods or data become available, species' vulnerability index scores can be updated accordingly (Furness et al., 2013).

Finally, we demonstrate how changes in population trend via conservation and management efforts could alter the relative vulnerability rankings of the species we consider. We found that all of the species with the 10 highest vulnerability scores could see their overall index drop to the extent that they are no longer in the top 10. For the majority of these 10 species, only one unit change in their population trend score allowed this shift. Similarly, nearly 70% of the 13 species immediately below the top 10 could enter this grouping if their conservation trend worsened slightly (Figure 4). These results highlight the fact that, for several of the species we evaluated, even modest success (or failure) in ameliorating non-OSW related stressors could significantly change how we view their relative resilience to additional mortality due to OSW collisions. Such changes to vulnerability indices due to conservation status or breeding population trends are rarely considered in the literature, though our analysis suggests that this is worthwhile.

For species identified as most vulnerable based on our index rankings, additional research into their biology and into empirically documenting collision rates is warranted, especially if this judgement is robust to uncertainty. Our results suggest that three species, Blackpoll Warbler, Bicknell's Thrush, and Common Yellowthroat, should be of particular concern. These three species have the highest vulnerability index scores of the species we evaluated; their vulnerability is insensitive to underlying uncertainty in their category scores; and they would require substantial increases in their resiliency scores to no longer be considered among the species with the highest relative risk. In addition, our finding that Blackpoll Warbler has the highest relative vulnerability to OSW aligns well with other published information about this species (Allison et al., 2008; DeLuca et al., 2015; Smetzer et al., 2017).

Mitigating OSW mortality is extremely difficult for small species, with most approaches requiring monitoring equipment that can detect <300 g individuals in flight and then trigger blade curtailment (Marques et al., 2014). Turbine curtailment, and or other mitigation measures, can be targeted to occur only during times a species' movement is expected to be heavy (i.e. light winds during peak migration) and environmental conditions are conducive to individuals of that species flying at heights where strikes are likely (e.g. during low cloud ceilings). For all such approaches to be successful, however, a detailed understanding of species-specific migratory behaviour and timing are needed, which can be expensive and difficult to obtain (Hüppop et al., 2006; Krijgsveld et al., 2015). Our index strongly suggests that such detailed research would be worth the effort for Blackpoll Warbler, Bicknell's Thrush, and Common Yellowthroat in the Northwest Atlantic; and this list could possibly be expanded out to include other warbler species (e.g. Prairie Warbler, Tennessee Warbler; *Leiothlypis peregrina*). This information, along with other means of monitoring migration in the offshore space, such as weather radar (Cohen et al., 2022), bioacoustics (Desholm et al., 2006), and tracking of individual bird movements (Carlson et al., 2023), can work in concert to inform mitigation moving forward. Together, these tools (each with unique strengths and weaknesses) can identify crucial information that informs mitigation, such as when migratory movements occur and if birds of particular species are migrating within the rotor sweep zone.

The aspects of songbird biology included in our vulnerability index are broadly relevant to species that migrate over open oceans worldwide. The data we utilized is either globally available (eBird), has analogues for other regions (population trends, collision risk), or can be modified to fit local circumstances (e.g. island observations). We selected our categories intentionally to allow for transferability, but should better data becomes available (e.g. direct measurements of overwater flight altitudes), these categories can easily be adjusted. Additionally, while in the Northwest Atlantic we only addressed autumnal migration due to prevailing migratory pathways (Newton, 2023), the migration corridor category can easily be modified to prioritize spring migration, or both spring and autumn migration, depending on the use circumstances. With rapid ongoing development of OSW in Asia and Europe (GWEC, 2023) and plans for OSW in the Gulf of Mexico (GWEC, 2023), the North American Great Lakes (Afsharian et al., 2020), and the northeastern Pacific

Ocean (BOEM, 2023), the potential for mortality impacts on migratory songbird species is growing. The Gulf of Mexico alone is crossed by millions of migrating songbirds each year (Allison et al., 2008). Offshore wind is a relatively new source of added mortality to migratory songbirds in much of the world. Using indices such as ours to prioritize songbird research and monitoring toward those species that may be negatively affected will prove most useful when completed early, while the development of OSW is still in its nascent stage, globally.

AUTHOR CONTRIBUTIONS

Leon A. Green-Tkacenko and Julie L. Lockwood contributed to study conception. Leon A. Green-Tkacenko, Michael C. Allen, and Julie L. Lockwood contributed to design, analysis, drafting, and revising. Leon A. Green-Tkacenko contributed to data acquisition.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

All data were sourced from publicly available datasets. Wing-loading data used to calculate Flight Manoeuvrability scores were sourced from the following articles: Poole (1938), Hartman (1961), Andrews et al. (2009), Gray (2019) and Chu et al. (2022). High-rise collision data used to calculate Collision Vulnerability scores were sourced from Loss et al. (2014). Occurrence data used to calculate Migration Corridor scores were sourced from eBird (https://ebird.org/home) and the Northwest Atlantic Seabird Catalogue, which is accessible via request from NOAA, while population data were sourced from Partners in Flight's Population Estimates Database (https://pif.birdconservancy.org/population-estimates-database/). The processed data used to calculate Migration Corridor scores are available at (https://doi.org/10.5061/dryad.nzs7h450d; Green-Tkacenko et al., 2024). Language regarding flight timing to form Flight Timing scores were sourced from Birds of the World (https://birdsoftheworld.org/bow/home). Trend data used to calculate Population Trend scores were sourced from the United States Geological Survey's Breeding Bird Survey (https://eesc.usgs.gov/MBR/) and the International Union for the Conservation of Nature's (IUCN) Red List (https://www.iucnredlist.org). IUCN conservation statuses used to calculate Conservation Status scores were also sourced from the IUCN Red List.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1: Distributions of vulnerability index scores for each of the 101 species considered in our index.

Figure S2: Distributions of each combined score for all 101 species considered.

Figure S3: Distributions of category scores for each of the 101 species included in our analysis.

Figure S4: Density plot of vulnerability index scores for all species considered in our analysis and for the 100,000 randomly created 'species'.

Figure S5: Scatterplot showing species' combined scores.

Table S1: Category scores, combined scores and species vulnerability index scores for each species considered in our analysis.

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