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Perspective

Framework for assessing species vulnerability whilst on migration to a spatially explicit anthropogenic pressure

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ABSTRACT

Animals are having to adapt to increasing anthropogenic activities and the pressures these create. The impacts experienced when encountering novel pressures on migration may be particularly acute compared to those routinely experienced in other parts of the annual cycle. To mitigate avoidable population declines, stakeholders must rigorously assess which species are vulnerable to these pressures and develop effective management solutions accordingly. However, inconsistent approaches to these assessments often hinder regulatory efficiency and decisions.

Here we present a consistent assessment framework for quantifying vulnerability to an identified spatially explicit pressure that might impact populations during migration. Standardised terminologies, methods for consistently scoring sensitivity and exposure, and for quantifying and assessing the role of uncertainty on the vulnerability index, are outlined. The framework is demonstrated using the 29 populations of Anatidae that migrate over UK waters annually and may be exposed to collision risk from offshore wind farms. Sawbills and sea ducks were more vulnerable than swans, geese and other ducks. Even with data uncertainty accounted for, the five most vulnerable species remain consistent, indicating future research and conservation could focus on these species.

This consistent framework makes use of accepted terminologies and can be used to develop vulnerability assessments for any migratory species group to any identified anthropogenic pressure. Outputs can be used to guide research efforts and support the implementation of conservation measures even if uncertainty in data remains. Comparisons between different assessments presented using this framework can be used by regulators to inform strategic planning decisions.

1. Introduction

The global extinction risk for migratory species is increasing, with 20 % of the 'Convention on Migratory Species' listed species being threatened with extinction, and 44 % having decreasing population trends (UNEP-WCMC., 2024). These species may experience a range of pressures from anthropogenic activities across their annual cycles, from diffuse pressures such as climate change, to those that may be more spatially and temporally explicit. An example of a diffuse pressure is the increased likelihood of extreme weather due to climate change causing increased mortality of migrants (Yang et al., 2021). However, migrating animals attempting to undertake directional movement may also be subject to spatially explicit pressures such as collision risk and barriers to movement, induced by anthropogenic structures or hazards within the migratory pathways (Buchan et al., 2022). The types of anthropogenic activities that create these spatially explicit pressures have a defined geographical location that can be quantified. These might include buildings, roads, fences, wind turbines, hunters' traps, fishing nets, unexploded ordnance, electricity transmission cables, oil rigs and tidal turbines. Indeed declines in some migratory species have been attributed to increasing cumulative impacts from spatially explicit pressures caused by anthropogenic activities within migratory corridors (UNEP-

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WCMC., 2024). Migratory periods may be relatively brief in duration when compared to the rest of a species' annual cycle, but considering their vulnerability to anthropogenic pressures during this period is critical (Buchan et al., 2022). Migration is a finely balanced physiological, behavioural and energetic process, and many species have limited options to stop, feed or rest sufficiently during the migration. Mortality rates can be higher during migration compared to the rest of the annual cycle (Klaassen et al., 2014; Thorstad et al., 2012), and spatially explicit anthropogenic pressures can increase the mortality risk during these obligate migratory periods (Hüppop et al., 2006; Newton, 2006, 2010; Măntoiu et al., 2020; Moore et al., 2023; Dean et al., 2023). In order to understand what mitigation and compensation measures can effectively halt or reduce migrant population declines, it is important to assess which migratory species are most vulnerable to these pressures, and what aspects of their migratory ecology contribute to these vulnerabilities. Understanding how, when and where anthropogenic pressures impact species whilst on migration is the first step to implementing effective conservation measures.

Vulnerability assessments are a tool commonly used to identify which species are most at risk from identified pressures, and often form the starting point of mitigation and compensation decisions during the planning process (Croll et al., 2022). Vulnerability assessments have been used to identify species that are vulnerable to impacts created by a range of pressures, including climate change (Burthe et al., 2014; Hakkinen et al., 2022), offshore windfarms (Furness et al., 2013; Garthe and Hüppop, 2004; Kelsey et al., 2018), shipping (Fliessbach et al., 2019), powerlines (Biasotto et al., 2022), agriculture (Buchan et al., 2022; Stork et al., 2009; Vijay et al., 2016) and buildings (Sabo et al., 2016). It is understood that vulnerability assessments require a measure of (1) exposure to a pressure, and (2) the sensitivity to that pressure when exposed to it (Furness et al., 2013; Stoddard and Hovorka, 2019). However, vulnerability assessments are constructed and implemented in many different ways using various different terminologies and processes, which makes it challenging to evaluate their utility and compare the outputs directly with one another. This in turn can hinder the identification of which species are consistently vulnerable to pressures caused by anthropogenic activities. Therefore, stakeholders will find it challenging to take a holistic view of human activities which wildlife can be vulnerable to and implement strategic mitigation and compensation measures to combat this. This is particularly relevant as regulators are increasingly seeking consistent methods to assess cumulative impacts of anthropogenic activities (Natural England, 2024; Tyack et al., 2022).

Given the scale of pressures being created by humans globally, there is an increasing need to assess and understand how these may impact the other species that utilise the planet, even if that utilisation is very brief within each year. Here we present a vulnerability assessment framework that can be flexibly adapted to any species group in need of assessment during migration, and an identified spatially explicit pressure that could be caused by a diverse range of anthropogenic activities. We demonstrate the use of the framework using Anatidae species migrating over UK waters that may be exposed to collision pressure from offshore wind farms. The process of implementing this framework for other assessment groups and pressures is outlined, and a method of evaluating knowledge uncertainty within the constituent metric data is given.

To avoid linguistic uncertainty (Masden et al., 2015) in this proposed framework, we use the same definitions for pressure, activity and impact as in Natural England (2024), and other definitions for categories (see section 2.2) and the concept of vulnerability as outlined in Croll et al. (2022).

2. Framework

2.1. Screening of main assessment criteria

The first step in the vulnerability assessment process is screening to determine which vulnerabilities will be assessed. The anthropogenic pressure (2.1.1), assessment group (2.1.2), and spatial assessment area (2.1.3) must be identified before the search for relevant data to include within the assessment can begin (2.2).

2.1.1. Anthropogenic pressure

A single type of spatially explicit pressure that has the potential to impact the assessment group (2.1.2) whilst on migration must be identified. The pressure could be generated by one or several anthropogenic activities. Examples of spatially explicit anthropogenic pressures could be barriers to movement, collision risk, noise, or visual disturbance (Natural England, 2024), and can be created by a range of structures such as wind farms (onshore or offshore), buildings, powerlines, roads, unexploded ordnance, tidal turbines, tidal barrages, mobile masts, hunters' traps, fences, hedges or farming areas. The location of the pressure must be known, or at least be accurately estimated, in order to identify the spatial assessment area (2.1.3) and calculate the exposure score (2.3).

2.1.2. Assessment group

This should be a migratory taxonomic group (species and/or populations) that share comparatively similar behavioural and morphological traits (2.2.1), so that reasonable scoring systems for the two categories that create the sensitivity index (2.2) can be produced. Most migratory species within a single taxonomic Family should fit these criteria, but with careful expert judgement it may be possible to assess species that span multiple Families, or even Orders (Furness et al., 2013; Garthe and Hüppop, 2004). It is unlikely that this framework would be suitable for comparisons between species from different Classes.

Examples of suitable migratory taxonomic groups which share comparatively similar behavioural and morphological traits could be:

- Anatidae exposed to collision risk whilst passing offshore wind farms (section 3).
- Bovidae exposed to barrier effects whilst passing fenced areas (members of the Cervidae and Giraffidae could reasonably be included) (Liu et al., 2024).
- Charadriiformes exposed to starvation risk at stopover sites following unregulated extraction of horseshoe crabs (Niles et al., 2009).
- Cetacea exposed to entanglement, or secondary entanglement, whilst passing floating wind farm cables.
- Ranidae (frogs) and Bufonidae (toads) exposed to barrier effects whilst crossing roads or passing fences (Hill et al., 2019).
- Salmonidae and other fish species exposed to barrier effects whilst passing weirs and dams in rivers (Garcia de Leaniz, 2008).
- Passerines exposed to mortality risk from hunters' traps (Raine et al., 2016).

2.1.3. Spatial assessment area

The spatial assessment area in which the impacts of the pressure on the assessment group can be experienced must be clearly defined, so that the method used to calculate the exposure score (2.4) can have spatial confines. The assessment group must migrate through the identified spatial assessment area. This area can be on any scale, from a local recreational park to an entire migratory flyway. It must be possible to find suitable data for the chosen category metrics within this area (2.2) and the spatial location of the identified anthropogenic pressure (2.1.1). Ideally all assessments should be conducted at the scale of the populations' entire migratory distribution, but it is acknowledged that this is not always practical to achieve (e.g. section 3).

Once the main assessment criteria have been selected, the framework can be implemented as outlined in Fig. 1 and within the methods described below.

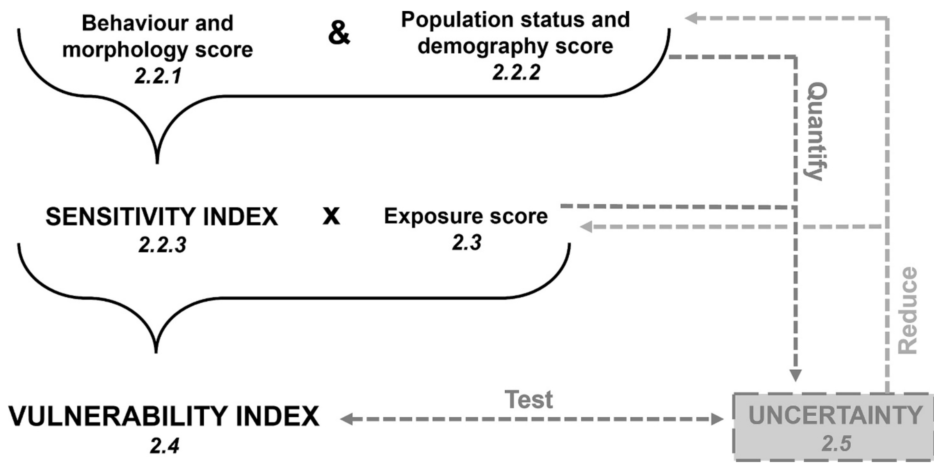

Fig. 1. Vulnerability assessment framework for species which may be exposed to a spatially explicit anthropogenic pressure whilst on migration. Numbers under each heading refer to the relevant section in the main text.

2.2. Sensitivity index

This framework defines sensitivity through combination of the two category terminologies (Behaviour and morphology score [2.2.1] and Population status and demography score [2.2.2]) proposed for similar assessments by Croll et al. (2022). However, other studies have used alternative terminologies for similar quantities. The inconsistent use of these terminologies can make it challenging for regulators and stakeholders to directly compare the outputs of different vulnerability assessments. Using these terminologies more consistently will improve the comparability of vulnerability assessments.

The availability of suitable data for all species within the assessment group will need to be considered. If data for 'ideal' category metrics are not available then suitable proxy data may be needed. For example, leg length could be a proxy for walking speed. Data with high uncertainty can be included, as the consequence of the uncertainty on the vulnerability ranking can be quantified (2.5).

Once all the data for the chosen metrics within each category are compiled, they should be converted into values on a comparative scale. Ideally, the complete metric data range should be split into five evenly sized bins, and each bin assigned a value from 1 to 5 accordingly (see section 3 for worked example). The lowest value of the scale should be assigned to the data least likely to create vulnerability to the pressure (e.g. species has Least Concern IUCN threat status), and the highest to the data most likely to create vulnerability (e.g. species is Critically Endangered). There are numerous approaches to how metric values could be assigned. For example, they could use empirical data extracted directly from peer reviewed or other literature, be assigned by suitably-informed assessor(s) (e.g. Furness et al., 2013; Garthe and Hüppop, 2004) or agreed through a formalised expert elicitation process (e.g. Martin et al., 2012).

To produce the overall category score, the individual metric values for each species within the assessment group must be combined in a manner deemed appropriate by the assessor (see section 2.2.3). In the worked example below (section 3) this is calculated by adding all the values together. Other similar assessments combine the metric values within each category differently, according to the relative weighted importance that each metric is assumed to have on the vulnerability of the species (e.g. Furness et al., 2013; Garthe and Hüppop, 2004).

2.2.1. Behaviour and morphology score

This category should be composed of species metrics that contribute to vulnerability during interaction with the defined pressure (2.1.1) and encapsulates resistance to the pressure and its impact. These metrics may be generic for the species in its entire global range during migration, but may also vary spatially (Allen, 1877), temporally (e.g. butterflies in different generational stages), or for different demographic groups (e.g. male, female, adult, immature). The metrics included must be considered on a case-by-case basis depending on the assessment being conducted, and the criteria selected in section 2.1.

Examples of behaviour and morphology metrics could be:

- Flight speed (e.g. bird migrating in relation to wind farms)
- Walking speed (e.g. small mammal migrating over a road)
- Flight manoeuvrability (e.g. bat ability to manoeuvre around a powerline)
- Flight altitude (e.g. butterfly flight height in relation to buildings)
- Percentage of migration conducted at night (e.g. insects passing buildings or lamp posts and getting attracted to light)
- Landing frequency (e.g. small passerine migrating through areas with glue traps)

Other terminologies used to cover this category in the literature include 'Resistance' (Natural England, 2024), and 'flight behaviour' and 'general behaviour' (Furness et al., 2013; Garthe and Hüppop, 2004).

2.2.2. Population status and demography score

This category should encapsulate species metrics that contribute to population status and demographic vulnerability when exposed to the pressure, within the spatial assessment area and migratory temporal period being considered. This category encapsulates the likely capacity of a population size to increase or maintain growth when exposed to a pressure and impact. The metrics included must be considered on a case-by-case basis depending on the assessment being conducted, and the criteria selected in section 2.1.

Examples of population status and demography metrics could be:

- Percentage of biogeographic population that migrates through exposure area (e.g. percentage of swan population migrating over North Sea)
- Adult survival rate (e.g. relevant elephant population migrating through farmland)
- Threat status (e.g. regional status of dolphin population in area with tidal turbines)
- Reproductive rate (e.g. dragonfly productivity in relation to pond development)
- Local population size (e.g. Bighorn sheep migrating up and down particular mountains)

Other terminologies used to cover this category in the literature include 'Resilience' (Natural England, 2024), 'status' (Garthe and Hüppop, 2004) and 'conservation status' (Furness et al., 2013).

2.2.3. Calculation of sensitivity index

This is a combination of the behaviour and morphology score (2.2.1) and the population status and demography score (2.2.2). If the constituent metrics used to produce each score are deemed to contribute equally to the potential severity of interaction when exposed to the pressure, then they may simply be added together to produce the sensitivity index (see 3.2 Worked Example: Sensitivity Index). However, if each metric value or category score is not thought to be evenly weighted in its contribution, then further consideration will need to be made. How the calculation of the sensitivity index is achieved will depend on the specific metrics that are included, the number of these metrics within each category, and the perceived importance of each metric and category score to the severity of interaction with the pressure. This must be decided by the expert(s) conducting the assessment. For examples of where this study-specific approach has been necessary, compare the worked example (section 3) with Garthe and Hüppop (2004) and Furness et al. (2013).

2.3. Exposure score

The exposure score should give a quantitative score to indicate the likely probability or frequency that each individual within a population within the assessment group (2.1.2) will interact with the chosen pressure (2.1.1), whilst on migration through the defined spatial assessment area (2.1.3). A method for empirically measuring, modelling or estimating the likelihood of the assessment group interacting with the pressure on migration within this spatial area should be identified. As with the sensitivity score, the exact process by which values are arrived at could vary between assessments, but the method selected must be applied consistently to the whole assessment group, so that the calculated exposure score is on an indicative and relative scale for all species being assessed. This method should be able to predict the probability or rate of interactions each individual or group of individuals may have with the pressure. Individual components of the spatially mapped pressure could be weighted unevenly if they are deemed to contribute differently to the exposure score.

The following studies and tools have methods for quantifying exposure, which could be adapted to other migratory groups and spatial areas as necessary:

- The Avian Migration Collision Risk tool (mCRM, 2023) has an adaptable method and code for generating migration route simulations and calculating how often these simulated tracks interact with spatially explicit structures within the migratory corridor. It gives an indicative score for the likely collision rate with these structures. It is currently designed for simulating UK migrant bird interactions with offshore wind farms, within the UK Exclusive Economic Zone, but the principles may be applied to any combination of migratory species, spatial areas, and spatially explicit structures likely to cause collision risk.
- The 'Vulnerability Map' modelling method described in Garthe and Hüppop (2004) allows assessment of seabird exposure to offshore wind farms.
- The 'Exposure assessment' method outlined in Natural England (2024) was used effectively for seabirds.
- The empirical method outlined by Sabo et al. (2016) allowed data collection of window strike rate by birds.
- The methods presented by Buchan et al. (2022) using remote sensing data.
- The 'biodiversity assessment for vulnerable forest areas' methods described by Vijay et al. (2016) demonstrate how to use remote sensing to map objects that might cause pressures, in areas that are otherwise inaccessible.
- Animal borne tracking devices provide empirical data to assess interaction rates with chosen anthropogenic pressures (Gauld et al., 2022; Kramer et al., 2023; O'Hanlon et al., 2024).

2.4. Vulnerability index

This is calculated by multiplying the sensitivity index (section 2.3) by the exposure score (section 2.4). Multiplying these together ensures that those species with a high sensitivity index *and* a high exposure score are identified as most vulnerable. This also ensures that even if a species has the highest sensitivity index but an exposure score of zero, it will have a vulnerability index of zero; if it is never exposed to the pressure, then it cannot be vulnerable to it, even if it would be sensitive were an interaction to occur. This is particularly relevant for assessments of new spatially restricted pressures being introduced to migratory pathways.

2.5. Uncertainty testing

There are many types of uncertainty involved in vulnerability assessments (Masden et al., 2015). Here we propose a method for testing knowledge uncertainty in the data and parameters used to assign the metric values, and the impact of this uncertainty on the resultant vulnerability index rankings.

Once the initial vulnerability index has been calculated, and the assessment group ranked from most to least vulnerable, the impact of data uncertainty within the category metrics on this final ranking should be assessed. Each species and metric combination will have been assigned a single value (likely between 1 and 5) to calculate the category scores and sensitivity index. To assess the impacts of uncertainty on the final vulnerability ranking, firstly the highest and lowest potential values should be identified for each species and metric during the metric assignment process (section 2.2). Secondly, the vulnerability index should be recalculated for each species and metric combination by drawing randomly with equal or otherwise defined probability from between these lower and upper potential values through multiple iterations (typically 1000, or until no new rank positions are identified with continued iterations). The vulnerability index ranking should be recalculated for each of these iterations, and the new rank position for each species or population recorded. Finally, the distribution of the changes in rank position for each species and metric combination can be inspected, thus identifying the impact of data uncertainty on the final rank position of each species or population within the assessment group. These steps are outlined more thoroughly in the Supplementary Materials.

3. Implementation of framework for migrating Anatidae and offshore wind farms

3.1. Worked example: main assessment criteria

In order to demonstrate the framework via a worked example, the 29 distinct migratory populations of Anatidae (assessment group; Supplementary Materials Appendix A) that may be exposed to collision risk from offshore wind farms (OWF; anthropogenic pressure) within the UK Exclusive Economic Zone (UK EEZ; Fig. 2; spatial assessment area) were assessed. These populations were placed into five taxonomic groups: swans ($n = 2$), geese ($n = 10$), ducks (n = 10), sea ducks ($n = 5$) and sawbills (n = 2). The UK was chosen as it has 119 Special Protection Areas (SPAs) with Anatidae species as named features (excluding waterbird assemblages), where development impacts must be assessed (JNCC, 2022), and as the migratory pathways of these populations have recently been mapped (Woodward et al., 2023). Migrants must cross seas to reach UK shores, and approximately 2.5 million Anatidae migrate across UK waters annually (Wetlands International, 2021; Woodward et al., 2020). The UK is the second largest global market for offshore wind, with 45 operational OWFs (Fig. 2) in 2023, and targets to

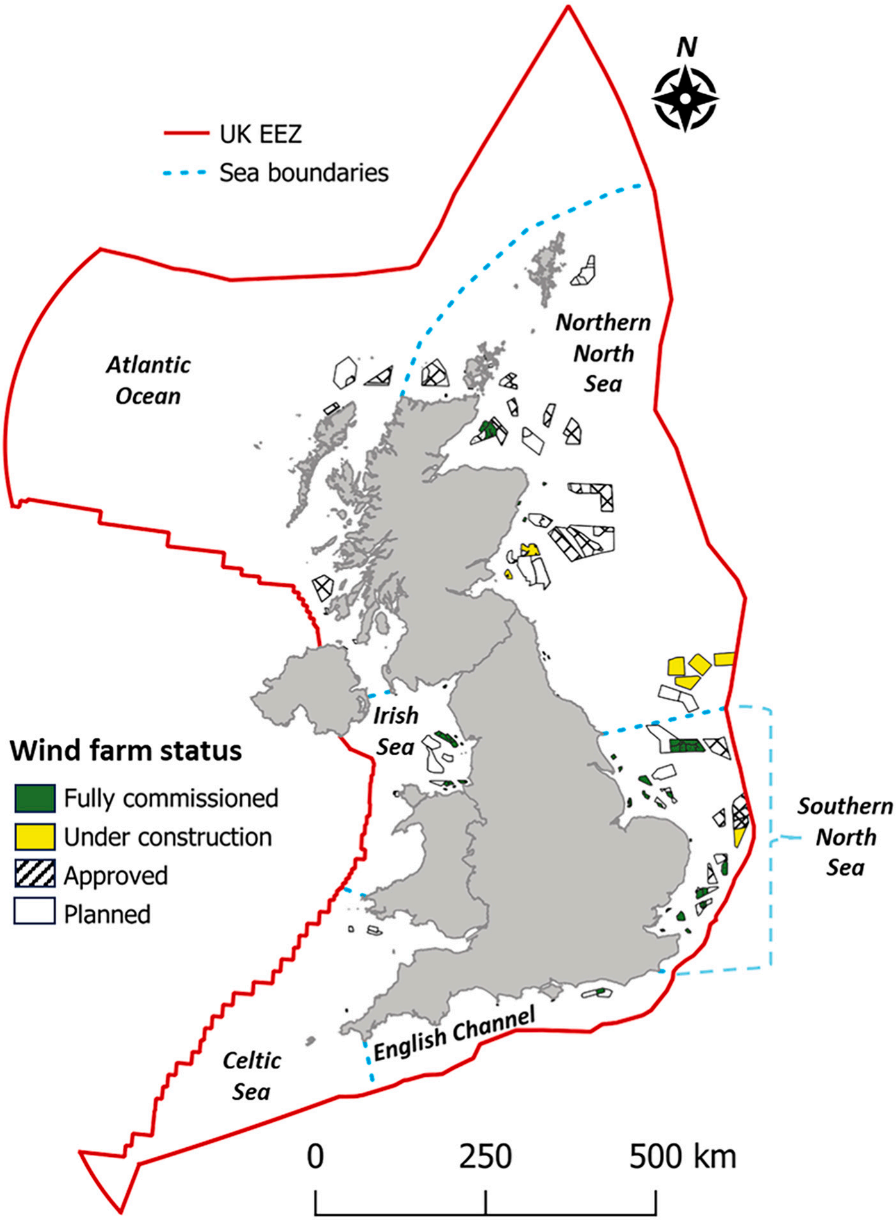

Fig. 2. The spatial assessment area covered within the worked example, displaying the UK Exclusive Economic Zone (EEZ; solid red outline), relevant sea boundaries (light blue dotted lines), and offshore wind farm footprints (filled by operational status; Oct 2023; (EMODnet., 2023).

quadruple this generation capacity by 2030 (HM Government, 2022). This assessment was conducted by the authors, who consulted the best available empirical data (e.g. Eaton et al., 2015; Stanbury et al., 2021; Tobias et al., 2022; Woodward et al., 2023) and agreed through discussion and consensus on the metrics used, assignment of each metric value for each species, combination of metrics into the two scores and the combination of the two scores into the sensitivity index.

3.2. Worked example: Sensitivity index

3.2.1. Worked example: Behaviour and morphology score

Four metrics were selected for calculating the behaviour and morphology score - (*a*) flight manoeuvrability; (b) flight altitude; (*c*) nocturnal flight activity; and (*d*) avoidance rate. The detailed justification for the selection of these metrics is given in Supplementary Materials Appendix B; in summary, these are key metrics for determining collision risk, and are utilised frequently within models for estimating collisions risk (Cook et al., 2025). Each of the 29 distinct migratory populations of Anatidae were assigned a metric value between 1 and 5, within each of the four chosen metrics. These can be found in Supplementary Materials Appendix C. Each of the metrics was deemed to be evenly weighted in its contribution to this score, so each metric value was added together to produce the score as follows:

$$\text{Behaviour and morphology score} = a + b + c + d \qquad (1)$$

The relative ranking for the behaviour and morphology score (Table 1) demonstrated that no single group consistently ranked more highly than another, though the mean rank for the sawbills (both 1.0) and ducks (7.7 ± 4.9) was higher than for sea ducks (14.4 ± 9.4), geese (15.9 ± 9.5) and swans (both 17.0). Overall, the variation in the scores was low, ranging from 11 to 15 on a possible scale of 4–20. This small range was largely driven by uncertainty in the values for flight altitude, nocturnal flight activity and avoidance rate (Supplementary Materials Appendix D), which are often generalised for the group rather than being specific to each migratory population (see Supplementary Materials Appendix C).

Table 1
Metric values used to calculate the behaviour and morphology score. Species are presented in rank order.

Group	Migratory population	Flight manoeuvrability (*a*)	Flight altitude (*b*)	Nocturnal flight activity (*c*)	Avoidance rate (*d*)	Behaviour and morphology score (1)	Relative rank
Geese	White-fronted goose (Greenland)	4	5	5	1	15	1
Sea ducks	Velvet scoter	4	5	4	2	15	1
Ducks	Scaup	3	5	5	2	15	1
Sawbills	Goosander	3	5	5	2	15	1
Sawbills	Red-breasted merganser	3	5	5	2	15	1
Geese	Taiga bean goose	4	5	4	1	14	6
Geese	White-fronted goose (European)	4	5	4	1	14	6
Geese	Barnacle goose (Svalbard)	3	5	5	1	14	6
Sea ducks	Common scoter	3	5	4	2	14	6
Ducks	Shoveler	2	5	5	2	14	6
Ducks	Wigeon	2	5	5	2	14	6
Ducks	Mallard	2	5	5	2	14	6
Ducks	Pintail	2	5	5	2	14	6
Ducks	Pochard	2	5	5	2	14	6
Ducks	Tufted duck	2	5	5	2	14	6
Ducks	Gadwall	2	5	5	2	14	6
Swans	Bewick's swan	5	3	3	2	13	17
Swans	Whooper swan	5	3	3	2	13	17
Geese	Barnacle goose (Greenland)	3	5	4	1	13	17
Ducks	Shelduck	3	3	5	2	13	17
Sea ducks	Goldeneye	2	5	4	2	13	17
Ducks	Teal	1	5	5	2	13	17
Geese	Greylag goose (Icelandic)	5	3	3	1	12	23
Sea ducks	Long-tailed duck	2	5	3	2	12	23
Geese	Pink-footed goose	4	3	3	1	11	25
Sea ducks	Eider	4	2	3	2	11	25
Geese	Brent goose (east Atlantic light-bellied)	3	3	4	1	11	25
Geese	Brent goose (Nearctic Atlantic light-bellied)	3	3	4	1	11	25
Geese	Brent goose (dark-bellied)	3	3	4	1	11	25

3.2.2. Worked example: Population status and demography

Four metrics were also selected for the population status and demography score – (*e*) percentage of biogeographic population that passes through UK EEZ on migration; (*f*) adult survival rate (the average proportion of adult birds (i.e. of at least breeding age) which survive each year); (*g*) UK threat status; (*h*) birds directive status (Birds Directive for Europe (2009/147/EC)). The detailed justification for the selection of these metrics is given in Supplementary Materials Appendix B; in summary these are all metrics that would impact, or be impacted by fatal collisions with offshore wind turbines. Again, each of the populations in the assessment group were assigned a metric value between 1 and 5, within each of these four metrics. These can be found in Supplementary Materials Appendix C. Each of the metrics was deemed to be evenly weighted in its contribution to this score, so each metric value was added together to produce the score as follows:

$$\text{Population status and demography score} = e + f + g + h \tag{2}$$

The mean population status and demography ranking for swans (6.5 ± 1.5) and geese (7.2 ± 5.6) was higher than for sea ducks (13.0 ± 2.3), ducks (20.5 ± 5.0) and sawbills (both 21.0) (Table 2). Generally, the swan and goose populations had higher values for all metrics due to the percentage of their populations migrating to the spatial assessment area, their higher adult survival rate, and protections given by Annex 1 of the Birds Directive for Europe (2009/147/EC) (birds directive status [*h*]). There was greater variation in the population status and demography scores (range 5–19) than for the behaviour and morphology scores (11–15) (Table 1).

3.2.3. Worked example: calculation of sensitivity index

The importance of each category score was deemed by our assessment team to be evenly weighted in its contribution to the sensitivity index. Therefore, the two scores were simply added together:

$$\begin{aligned}\text{Sensitivity index} &= \text{Behaviour and morphology score (1)} \\ &\quad + \text{Population status and demography score (2)}\end{aligned} \tag{3}$$

The variation in the resulting sensitivity index was driven more by the variation in the population status and demography score (5–19) than by the behaviour and morphology score (11–15) (Fig. 3). Consequently, the mean sensitivity index for the swans (29.0 ± 1.0) and geese (28.1 ± 3.0) was higher than for the sea ducks (24.6 ± 1.6), sawbills (both 24.0) and ducks (22.9 ± 1.5). Accordingly, the mean sensitivity index rank for swans (5.5 ± 1.5) and geese (7.4 ± 4.8) was higher than for the sea ducks (14.8 ± 6.5), sawbills (both 15.0) and ducks (20.8 ± 5.1). Reducing the uncertainty in the data for flight altitude, nocturnal flight activity and avoidance rate may increase the variability in the behaviour and morphology scores, and consequently the mean ranks for these groups may change, but the overall group order is unlikely to change substantially (Supplementary Materials Appendix D).

3.3. Worked example: exposure score

For each migratory population of Anatidae all OWF footprints (polygons) within the UK EEZ of the migratory flyway as defined by Woodward et al. (2023) were selected using mCRM v0.3.0 (see web references; mCRM, 2023), and OWF scenarios were generated. An OWF footprint was identified as a suitable proxy for the identified collision risk pressure. For each populations migratory flyway 10,000 tracks were simulated, and 1000 random draws of these were sampled with replacement 1000 times. The average proportion of sampled lines overlapping with each OWF was used to calculate the percentage of each population that might interact with OWFs during migration. This percentage was converted into a raw number of individuals based on the size of the population (Woodward et al., 2023), and an output was generated for each individual OWF within the migratory flyway. The number of predicted interactions with each OWF were then summed for

Table 2
Metric values used to calculate the population status and demography score. Species are presented in rank order.

Group	Migratory population	% Biogeographic population at risk (*e*)	Adult survival (*f*)	UK threat status (*g*)	Birds directive (*h*)	Total score (2)	Relative rank
Geese	Barnacle goose (Greenland)	5	5	4	5	19	1
Geese	Barnacle goose (Svalbard)	5	5	4	5	19	1
Geese	Brent goose (east Atlantic light-bellied)	5	5	4	4	18	3
Geese	Brent goose (Nearctic Atlantic light-bellied)	5	5	4	4	18	3
Swans	Whooper swan	5	3	4	5	17	5
Geese	Brent goose (dark-bellied)	3	5	4	4	16	6
Geese	White-fronted goose (Greenland)	5	1	5	5	16	6
Swans	Bewick's swan	2	3	5	5	15	8
Geese	Pink-footed goose	5	3	4	3	15	8
Sea ducks	Eider	1	5	4	4	14	10
Geese	Greylag goose (Icelandic)	5	3	4	2	14	10
Sea ducks	Velvet scoter	1	3	5	3	12	12
Sea ducks	Common scoter	1	2	5	3	11	13
Sea ducks	Goldeneye	1	2	5	3	11	13
Ducks	Shelduck	2	4	4	1	11	13
Ducks	Teal	4	1	4	2	11	13
Sea ducks	Long-tailed duck	1	1	5	3	10	17
Ducks	Scaup	1	1	5	3	10	17
Geese	Taiga bean goose	1	2	5	2	10	17
Geese	White-fronted goose (European)	1	1	5	3	10	17
Ducks	Gadwall	2	1	4	2	9	21
Sawbills	Goosander	1	3	1	4	9	21
Ducks	Pintail	2	1	4	2	9	21
Ducks	Pochard	1	1	5	2	9	21
Sawbills	Red-breasted merganser	1	1	3	4	9	21
Ducks	Shoveler	2	1	4	2	9	21
Ducks	Wigeon	2	1	4	2	9	21
Ducks	Mallard	1	1	4	2	8	28
Ducks	Tufted duck	1	1	1	2	5	29

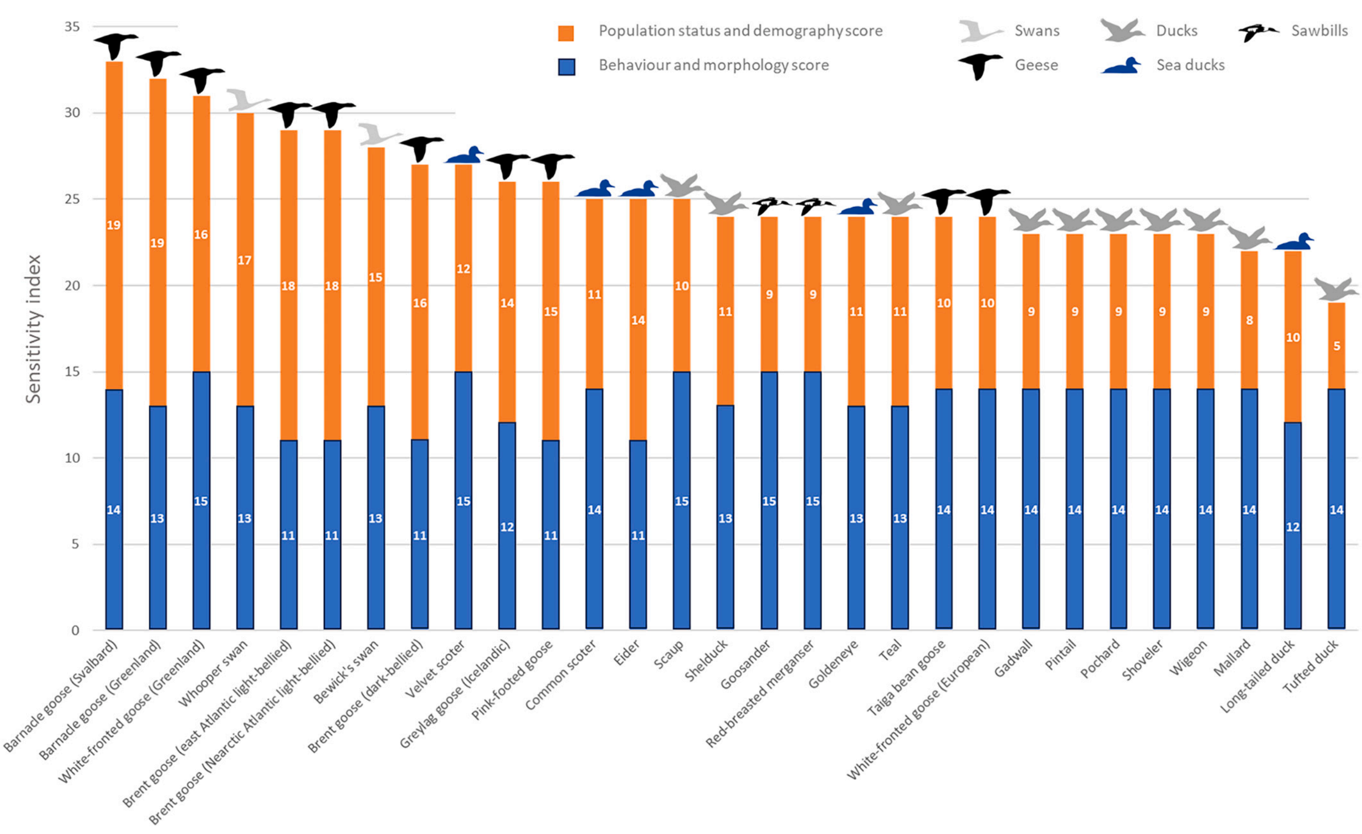

Fig. 3. Sensitivity index, displaying the constituent behaviour and morphology score (blue outlined bottom sections) and population status and demography score (orange open top sections) separately. Symbols indicate which group each migratory population belongs to.

each population, to give a total number of estimated interactions during migration through the UK EEZ. This value was then divided by the total number of birds within the population to give a predicted rate of interactions per individual. For this worked example, it was assumed that no interaction was fatal, thus any individual could interact with multiple OWFs during migration. The total number of predicted interactions gives an indicative measure of exposure within the UK EEZ, on a relative scale for all populations assessed.

3.4. Worked example: vulnerability index

The sensitivity index was then multiplied by the exposure score (i) to produce the vulnerability index:

$$\text{Vulnerability index} = \text{Sensitivity index } (3) \times \text{Exposure score } (i) \quad (4)$$

The vulnerability index indicated that no single group was consistently more vulnerable than another, though the mean rank for sawbills (6.0 ± 4.0) and sea ducks (7.8 ± 2.3) was higher than for swans (10.0 ± 5.0), geese (17.8 ± 10.5) and ducks (18.6 ± 3.7) (Table 3).

The exposure score (i) was the metric that influenced the vulnerability ranking the most. Most individual Anatidae migrating across the North Sea now have a high probability ($i > 0.90$) of interacting with at least one OWF during a straight-line migration through the UK EEZ. Overall, those populations which migrate almost exclusively across the North Sea currently have a greater risk of exposure than those migrating exclusively across the Atlantic Ocean. It should be noted that the exposure score only includes OWF interactions within the UK EEZ. Exposure scores for populations crossing the North Sea will be an underestimate as these do not include interactions with OWFs in French, Belgium, Dutch, German, Danish or Norwegian waters. Given the accessible tools and data at the time of this assessment it was not possible to include the OWFs of these countries, but the spatial assessment area could be expanded in future should the accessibility status of suitable data change (see section 2.1.3).

3.5. Worked example: uncertainty testing

The uncertainty within the constituent metrics and exposure score was quantified, and the effects of this uncertainty on the final vulnerability ranking were assessed. The lowest and highest potential value for each migratory population within each metric and exposure score was calculated (Supplementary Materials Appendix C) using available data and expert opinions provided through Woodward et al. (2023) and following the processes outlined within Furness et al. (2013). The vulnerability index (Eq. 4) was then recalculated for each migratory population and metric combination by drawing randomly (with equal probability) from within these lower and upper potential values 1000 times. The vulnerability index ranking for all species was then recalculated for each of these 1000 iterations, and the new rank number for each migratory population was recorded. The distribution of these rank position changes for each metric and migratory population combination was then inspected to identify the robustness of the assessment to uncertainty in different metrics (Supplementary Materials Appendix D). A step-by-step explanation of this process is also provided in Supplementary Materials Appendix D.

The uncertainty analysis demonstrated that even when uncertainty within the metric values (a – i) was accounted for, the same five migratory populations are always ranked as the five most vulnerable populations, and those ranked in the bottom eight positions are always ranked there (Table 3). The results of this analysis are in Supplementary Materials Appendix D. This demonstrates that even if uncertainties are reduced, particularly within the flight altitude (b), nocturnal flight activity (c) and avoidance rate (d) metrics, the overall vulnerability rankings will remain relatively stable for the most and least vulnerable Anatidae migratory populations.

Table 3
The sensitivity index and exposure scores used to calculate the vulnerability index. Migratory populations are displayed in rank order, from most vulnerable to least vulnerable. The seas that each population migrates over are coded as follows: N (North Sea); E (English Channel); C (Celtic Sea); I (Irish Sea); A (Atlantic Ocean); c (coastal) ≤12 miles offshore; n (northern), s (southern), w (western).

Group	Species	Sensitivity index (3)	Exposure score (i)	Vulnerability index (4)	Relative rank	Seas migrating over
Geese	Taiga bean goose	24	1.71	40.95	1	N
Sawbills	Goosander	24	1.55	37.22	2	N, Ac
Geese	Barnacle goose (Svalbard)	33	1.12	36.80	3	Nn
Sea ducks	Velvet scoter	27	1.28	34.65	4	N, E, C, I
Swans	Bewick's swan	28	1.02	28.68	5	Ns, I
Geese	Brent goose (dark-bellied)	27	1.00	26.90	6	Ns, E
Sea ducks	Eider	25	1.06	26.44	7	All seas
Sea ducks	Goldeneye	24	1.05	25.22	8	All seas
Sea ducks	Long-tailed duck	22	1.06	23.43	9	All seas
Sawbills	Red-breasted merganser	24	0.97	23.18	10	All seas
Sea ducks	Common scoter	25	0.91	22.69	11	All seas
Geese	White-fronted goose (European)	24	0.94	22.45	12	Ns, E
Ducks	Wigeon	23	0.96	22.11	13	All seas
Ducks	Shelduck	24	0.91	21.82	14	All seas
Swans	Whooper swan	30	0.72	21.71	15	N, I, A
Ducks	Pintail	23	0.94	21.52	16	All seas
Ducks	Scaup	25	0.86	21.50	17	N, C, I, A
Ducks	Mallard	22	0.97	21.35	18	N, E, C, I, Ac
Ducks	Shoveler	23	0.89	20.57	19	All seas
Ducks	Gadwall	23	0.86	19.72	20	All seas
Ducks	Tufted duck	19	0.94	17.80	21	All seas
Ducks	Teal	24	0.59	14.10	22	All seas
Geese	Pink-footed goose	26	0.50	12.95	23	A, I, Nc
Geese	Brent goose (east Atlantic light-bellied)	29	0.36	10.52	24	Nn
Geese	White-fronted goose (Greenland)	31	0.30	9.40	25	I, A
Ducks	Pochard	23	0.40	9.10	26	N, E, C, I, Ac
Geese	Greylag goose (Icelandic)	26	0.34	8.96	27	A, Nnw
Geese	Brent goose (Nearctic Atlantic light-bellied)	29	0.27	7.74	28	A, C, I
Geese	Barnacle goose (Greenland)	32	0.24	7.68	29	A

4. Discussion

Migratory animals are at increasing risk of exposure to spatially explicit pressures created by anthropogenic activities, even though the period of exposure to these pressures may be brief within the context of their entire annual cycle (UNEP-WCMC., 2024). Here we have presented and demonstrated a framework for assessing the vulnerability of migrant groups to an identified spatially explicit pressure. We show that the framework can be implemented for a group of migrating birds exposed to collision pressure and use it to identify the most and least vulnerable migratory populations. Exploration of knowledge uncertainty has also shown that key uncertainties can be identified, and their impact on the vulnerability ranking assessed. This can help identify key areas to focus future research and conservation efforts.

Our approach builds off vulnerability assessments that use variations of our framework structure (e.g. Croll et al. (2022), Furness et al. (2013), Garthe and Hüppop (2004)), but the terminologies used previously for the metrics, categories and indices have varied, creating linguistic uncertainty (Masden et al., 2015) and reducing the ease with which the outputs can be compared. For example Fauchald et al. (2024), Furness et al. (2013) and Garthe and Hüppop (2004) have all assessed the vulnerability of seabirds to offshore wind farms, Gauld et al. (2022) assessed avian species vulnerability to energy infrastructure, Pereira et al. (2004) and Stork et al. (2009) use vulnerability assessments to understand the impacts of land-use change, and Blom et al. (2005) used a similar process to identify that large mammals were vulnerable to roads and poachers traps. However, all of these assessments used different terminologies and methods, which makes comparing their outputs challenging. These assessments have all been valuable in driving research and conservation efforts within their specific field, but the lack of consistent approach and terminologies reduces regulators' ability to identify which species groups are consistently vulnerable in all periods of their annual cycle, and which pressures create vulnerabilities in the greatest number of species groups. Our approach builds off these previous assessments, and introduces accepted terminology from the spatial planning lexicon (Natural England, 2024; Robinson et al., 2014) and a consistent structure that effectively allows assessment of activity-pressure-impact chains, with specific anthropogenic pressures, spatial areas and assessment groups identified. Vulnerability assessments often form the first step in mitigating and compensating for the impacts of anthropogenic developments (Croll et al., 2022), and so conducting these assessments using a standardised process may help regulators more easily make strategic planning decisions across migrant taxa and anthropogenic pressures.

Importantly, the outputs from an assessment following our protocol are particularly valuable as an assessment of a specified assessment group to a specified anthropogenic pressure in a specified spatial assessment area can be compared directly to: (a) the same assessment group facing the same anthropogenic pressure in a different spatial assessment area and/or (b) a different assessment group facing the same anthropogenic pressure in the same specified spatial assessment area and/or (c) the same assessment group facing a different anthropogenic pressure in the same specified spatial assessment area. In this way, our approach can also be used to address the most gnarly of challenges around assessing 'multiple pressures' on assessment groups (Curren et al., 2022; Hodgson et al., 2019). Rankings from parallel or subsequent assessments of different anthropogenic pressures can identify taxonomic groups within the assessment group that are consistently vulnerable to different kinds of anthropogenic pressure. Similarly, they could identify whether or not a novel anthropogenic pressure is likely or not to make things worse for a species group that has been identified as vulnerable to an existing anthropogenic pressure. To take our worked example, hunting during migratory passage could be assessed separately on the same species groups of Anatidae within the UK EEZ and the rankings compared. Completing and comparing the outputs of multiple assessments on different pressure and assessment group combinations can then provide an evidence base for regulating new anthropogenic pressures within a given spatial area, and facilitate conservation, policy and planning decisions to prioritise and reduce species vulnerabilities. It could also provide an evidence base for regulators and policy makers to ascertain species that will be cumulatively impacted by essential anthropogenic activities, and so where conservation action may no longer be valuable or cost-effective.

Any comprehensive assessment is likely to have limitations, often through limitations in available data or information and it is important to acknowledge these limitations in any assessment (Ann Wilson, 2010; Curren et al., 2022; Hodgson et al., 2019). To illustrate this, in our worked example, the spatial assessment area was geographically restricted due to the tools available to calculate the exposure score. Ideally the exposure score would have been conducted at the scale of the flyway and would have included all offshore wind farms likely to be encountered during the migration. As noted in section 2.1.3 we recommend that all future assessments using this framework are conducted at the largest ecological spatial scale appropriate to the assessment group, wherever possible. Where data availability prevents this, the limitations of the assessment should be highlighted as we do with our worked example (section 3.4). For other assessments, limitations might include a lack of empirical evidence and/or an over-dependence on expert elicitation for sensitivity and exposure components. Sometimes relevant data do exist but are not in an accessible format for assessments of this nature, either as they are commercially sensitive or have not been analysed and published into the public domain (Kettel et al., 2022). These limitations can then propagate through to 'multiple pressure' assessments as highlighted by Hodgson et al. (2019). We acknowledge that any assessor using this framework will need to produce their own assessment appropriate metric scoring system, and method for calculating the sensitivity index and exposure score, but the consistent approach to reporting the vulnerability index as a rank scale that is relative for all species within the assessment group should make comparisons across different assessments more straightforward for regulators. It is important to acknowledge the limitations in data, methods and outputs of any individual assessment to aid the process of comparison between these in future.

This framework is specifically designed to assess the vulnerability of migrant species to identified anthropogenic pressures. Recent studies have highlighted the scale of mortality over large spatial areas for migrant birds (Newton, 2024; Serratosa et al., 2024), and demonstrated that a large proportion of the assessed species are vulnerable to spatially explicit anthropogenic pressures within their flyways. Migrants are at increasing risk of extinction due to the cumulative impacts of anthropogenic activities (UNEP-WCMC., 2024), so there is increasing urgency to assess which species are most vulnerable to which pressures, and implement conservation and management strategies to combat these identified vulnerabilities (Curren et al., 2022; Hodgson et al., 2019). Vulnerability assessments often form the first stage in this long process, and so conducting them consistently may increase the efficiency with which strategic planning decisions can be made. Anthropogenic development and infrastructure are necessary for economic and social stability, but they fragment natural environments, so practitioners will be better placed to implement effective wildlife conservation measures if standardised methods are used for conducting all initial vulnerability assessments. If combined with other standardised frameworks (e.g. Somveille and Ellis-Soto, 2022), this could create powerful regulatory methods for protecting migrant animals in the future, or identifying species that can no longer be conserved.

For the Anatidae worked example, the exposure score is currently the most influential metric for driving vulnerability index separation between migratory populations. While inevitably this is in part a function of the structure of Eq. 4, the driving influence here is 7-fold variation in likelihood of exposure to OWFs, with those populations crossing the North Sea having particularly high exposure scores. Within the North Sea UK EEZ there are currently >40 operational OWFs, and in the North

Sea overall there are at least 80 operational OWFs. European governments have recently pledged to increase the generation capacity of OWFs by eight times current levels before 2050 (Communication from the Commission to the European Parliment et al., 2023), which means that migrant exposure, and hence vulnerability, to OWFs will increase over the coming decades. We could have accounted for this by increasing the weighted contribution of North Sea OWFs within the exposure score, but this was not feasible given the capabilities of the mCRM tool. Further, of all the species groups assessed within Birds of Conservation Concern 5 (Stanbury et al., 2021), ducks, swans and geese are the group with the second highest percentage of species listed as red or amber (89.3 %), second only to buntings and longspurs. This is largely driven by winter population declines; if these continue into the future, this may impact the percentage of the biogeographic population of these species that pass through the UK EEZ on migration each year, which may consequently impact the vulnerability rankings presented here. Given the data used within this assessment are changing rapidly, regular reassessments (at least every decade) are recommended. Ideally these reassessments would be conducted at an expanded spatial scale of ecological relevance (e.g. the whole North Sea), rather than being restricted to human borders (e.g. UK EEZ).

Our method for assessing the impact of knowledge uncertainty (section 2.5) on the resultant vulnerability rankings is a novel approach within vulnerability assessments, as far as we can tell. It allows rapid assessment of the key traits leading to vulnerability and identification of those species that are consistently vulnerable, or not vulnerable, to given pressures. This should help regulators target further research more effectively and maximise the impact of limited funding resources. Milner-Gulland and Shea (2017) highlighted that it is important to (i) understand how likely it is that new information would change a previous regulatory decision, and (ii) identify what new information would lead to this change in decision. In the worked example for Anatidae and offshore wind farms, we demonstrate that this framework can be used to identify where knowledge uncertainty within the metrics could impact the vulnerability ranking within the assessment group, and demonstrate where reductions in this uncertainty will not result in a change in vulnerability ranking. For instance, there is reasonable knowledge uncertainty within the flight altitude data for Anatidae, but reductions in this uncertainty will not impact which species are most or least vulnerable to collisions with offshore wind turbines. This process can help justify the implementation of conservation measures without the need for further research to reduce uncertainties.

5. Conclusion

Species are increasingly vulnerable to anthropogenic pressures during migration (UNEP-WCMC., 2024), and individuals and organisations have a responsibility to assess the impacts of these and mitigate population declines as rapidly and effectively as possible (e.g. Niles et al., 2009). Vulnerability assessments are an essential first step in this process (Croll et al., 2022), but their inconsistent terminology and application to a range of species and pressure combinations has made it challenging for regulators to use their outputs efficiently to inform spatial planning.

This framework builds off previous works, provides a standardised process and terminologies, and a method of assessing the impacts of knowledge uncertainty on the outputs. It can be flexibly adapted to assess the vulnerability of any migratory species group to any single identified spatially explicit pressure caused by anthropogenic activities. Repeated assessments to alternative anthropogenic pressures create an opportunity to assess multiple pressures. Uncertainty within the constituent data can be quantified, and its impact on the final vulnerability ranking can be assessed. This process can be used to target research efforts effectively, or to gain confidence that conservation measures can begin, even if uncertainty in data remains.

CRediT authorship contribution statement

Ros M.W. Green: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation. **Niall H.K. Burton:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Aonghais S.C.P. Cook:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Samantha E. Franks:** Writing – review & editing, Supervision, Methodology. **Jonathan A. Green:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendices. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2025.111118.

Data availability

Data will be made available on request.

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