Research article

EolPop, a R-shiny tool for quantifying the demographic impact of species exposed to fatalities: Application to bird collisions with wind turbines

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ABSTRACT

Quantifying the demographic impact of anthropogenic fatalities on animal populations is a key component of wildlife conservation. However, such quantification remains rare in environmental impact assessments (EIA) of large-infrastructure projects, partly because of the complexity of implementing demographic models. Providing user-friendly demographic tools is thus an important step to fill this gap.

We developed an application called EolPop to run demographic simulations and assess population-level impacts of fatalities. This tool, freely available online, is easy to use and requires minimal input data from the user. As an output, it provides an estimate, with associated uncertainty, of the *relative* deficit in population size at a given time horizon. Because this impact metric is relative to a baseline scenario without fatalities, it is robust to uncertainties.

We showcase the tool using examples on two species that are affected by collisions with wind turbines: Lesser kestrel (*Falco naumanni*) and Eurasian skylark (*Alauda arvensis*). After 30 years, the kestrel's population is expected to suffer a deficit of *ca.* 48%. In contrast, the impact on skylarks, which are already declining in France, is estimated to be fairly low (*ca.* 7%).

EolPop aims at providing a robust quantification of the relative impact of fatalities. This tool was originally built for windfarm EIA, with a focus on birds, but it can be used to assess the demographic consequences of any type of fatalities on any species.

1. Introduction

Human development and activities are often a direct or indirect cause of mortality towards other living creatures, hereby inducing threats to biodiversity (Jaureguiberry et al., 2022). The development of wind energy, despite being a keystone of the transition towards green energy (Teske et al., 2019), has potentially adverse effects on biodiversity (Serrano et al., 2020). These negative effects include habitat loss, displacements, as well as direct fatalities due to collisions from wind turbine blades (Drewitt and Langston, 2006). Volant vertebrates (birds and bats) are the taxa most susceptible to this latter threat (Barclay et al., 2017; De Lucas and Perrow, 2017; Thaxter et al., 2017). Assessing the risk that collisions, or any other source of direct mortality, pose to populations of protected species has become a mandatory procedure in the environmental impact assessment (EIA) carried before the authorization of a large-infrastructure project, such as the construction of a wind power plant. Typically, EIA and post-construction mortality surveys focus only on quantifying the number of animals killed or at risk of

being killed each year. The impact that these fatalities might have on a population's dynamic is rarely quantified in the context of terrestrial wind energy development (Green et al., 2016), but instead it is simply assessed verbally (qualified as 'significant' or 'not significant') based on a subjective expert judgment (Flyvbjerg, 2007). Yet, the robust quantification of population impacts should be the main focus of EIAs as their primary goal is to assess whether the focal infrastructure project is threatening the conservation status of a given set of species (May et al., 2019).

The few EIA that provide a quantitative assessment of population impacts (e.g. Bellebaum et al., 2013; Leopold et al., 2014; Busch and Garthe, 2016; NIRAS, 2016) have generally used a simplistic approach, called the Potential Biological Ratio (PBR; Wade, 1998). But there are several issues when using this method in the context of a single specific EIA. First, the PBR is designed to calculate a sustainable fatality rate that includes *all* anthropogenic sources of mortality that the population is exposed to, not just one (Dillingham and Fletcher, 2008). Nonetheless, EIA investigators apply the method using a single source of mortality (e.

g., wind turbine collision, fishery bycatch), which leads to serious mis-interpretations of the results (Green et al., 2016). Second, this method relies on several key assumptions (e.g., optimal population growth and compensatory density-dependence) that are often not verified in bird populations, and particularly in vulnerable, often declining, species of concern by EIA (Green et al., 2016; Horswill et al., 2017; O'Brien et al., 2017; Schippers et al., 2020). Third, the PBR implicitly states that the conservation objective is to maintain the population above half of its carrying capacity, accepting *de facto* potential declines of up to 50%. This implicit objective, which corresponds to a population's maximum sustainable yield (Hilborn and Walters, 1992), was indirectly inherited from fish stock management (Wade, 1998). But in the context of the conservation of non-exploited species, there is clearly no consensus that such an objective is the most appropriate (Lonergan, 2011). Moreover, the level of decline that can be induced when following such a liberal objective contradicts most countries' law regarding protected species (Green et al., 2016). Finally, the PBR provides a unique threshold value without associated uncertainties (but see Diffendorfer et al., 2021), which does not allow to fully appreciate the range of plausible demographic outcomes (Schippers et al., 2020).

Population projections based on simulations provide a more sensitive and reliable approach to assess potential demographic consequences of non-targeted anthropogenic fatalities (Green et al., 2016; Cook and Robinson, 2017). This is the method typically used in conservation when assessing a population's viability (Beissinger and McCullough, 2002). This approach alleviates most of the issues mentioned above for the PBR, except the need for some assumptions; but at least, with simulations, assumptions are explicit, controlled and easily modifiable. However, running demographic projections is not a trivial endeavor as it means building Markovian models, often with the added complexity of age-structure (matrix models) and stochasticity. This requires a high level of quantitative and coding skills which are usually not available to wildlife consultants dealing with EIA. To remedy to this problem, we developed a R-shiny user-friendly interactive dashboard, called "Eol-Pop" ("Eol" stands for "Eolien" which means "Wind Energy" in French and "Pop" stands for "Population"), that allows running demographic simulations from minimal input parameters. To explain and showcase how this tool works, we will use the context of bird collisions with wind turbines as a motivating example. Nonetheless, EolPop can be used in a similar fashion to investigate demographic impacts from any source of mortality (e.g. collisions with vehicles or obstacles, poisoning, shooting, etc.) on any taxa (bats, mammals, fish, etc.).

2. Methods

2.1. The impact metric

The primary goal of EolPop is to provide a robust quantification of the demographic impact of some source of fatalities. Because of its intended use in the context of EIA, this quantification must be done in relation to a so-called *initial state*, which here corresponds to a baseline scenario that does not include the source of mortality under scrutiny (Green et al., 2016). Therefore, what we seek to estimate with precision is not the absolute value of future population size, but the *relative* difference in population size, after some time, between two scenarios: (i) a "baseline scenario" without fatalities, and (ii) a "focal scenario" including fatalities. This *relative* metric is known as the "Counterfactual of Impacted to Unimpacted (CIU) Population" (Green et al., 2016; Cook and Robinson, 2017). The use of the CIU metric has been explicitly recommended over the use of other metrics (e.g. PBR, Acceptable Biological Change [ABC] or Decline Probability Difference [DPD]) for the assessment of the impact of anthropogenic pressures on animal populations (Green et al., 2016) for several reasons. First, unlike these other approaches (PBR, ABC, DPD), it does not possess an arbitrary built-in "acceptability" threshold (Schippers et al., 2020). Built-in thresholds should be avoided because they have no foundation in population

biology and they present the risk of unknowingly accepting adverse impacts on a population (Green et al., 2016). With CIU, the quantification of the impact remains clearly separated from the decision of whether or not a given level of impact is acceptable, as such decision should be taken by relevant state authorities and stakeholders, not wildlife biologists (Lonergan, 2011). Second, CIU is much more robust to uncertainties than these other metrics (Cook and Robinson, 2017). This is particularly important because, when dealing with wild populations, most demographic parameters cannot be known with a high degree of certainty.

In EolPop, the CIU approach is implemented by running simulations for both scenarios (baseline vs. focal) simultaneously, using a matched-run approach (Cook and Robinson, 2017). For each iteration, this provides two trajectories that are exactly equivalent except for the presence or absence of fatalities. From these, EolPop calculates the relative difference of population size (i.e. the CIU metric) at a given time horizon (e. g. 30 years).

2.2. The model

Population projections are performed using a post-breeding, discrete-time (annual) model that includes age-structure (Leslie matrix; Caswell, 2001), environmental stochasticity and demographic stochasticity (Engen et al., 1998; Lande et al., 2003). For populations that are *initially* (i.e. in absence of fatalities) growing, the model also includes negative density-dependence (Eberhardt et al., 2008). The only inputs required by EolPop are (i) the number or rate of annual fatalities, (ii) the *initial* population size, (iii) the *initial* population growth rate (λ) and (iv) the carrying capacity. This latter parameter is only used to calibrate density-dependence for growing populations (see section 2.3). A technical description of the demographic model is provided in Appendix 1. Here we only provide a general description of it.

Starting from the initial population size, the model projects population size across years based on the λ provided (baseline scenario), to which fatalities are being added each year (focal scenario). The value of λ provided by the user must thus correspond to the population's trend before the onset of fatalities, hence the term "*initially*". For instance, in the context of bird collisions with wind turbines, the λ provided should correspond to the population trend before the commissioning of the wind power plant.

Another type of input used by the model is a matrix of *generic* vital rates. These vital rate values are species-specific, but they are said "generic" because they do not correspond to a specific population. They are simply representative of the species life history strategy, i.e. where it lies along short-lived/long-lived gradient (*sensu* Stearns, 1992). To project the population dynamic forward, the model uses a Leslie matrix that is built from both this generic matrix of vital rates and the value of initial λ specified by the user. The generic vital rate matrix provides information about the focal species' life history strategy, while λ provides information on the current dynamic of the focal population. To combine both pieces of information and build the final Leslie matrix, EolPop adjusts the vital rate values to match the λ provided. Because λ corresponds to the dominant eigenvalue of the desired Leslie matrix, it is indeed possible to back-calculate the corresponding vital rate values using a numerical optimization algorithm. Here we use a quasi-Newton algorithm (L-BFGS-B; Zhu et al., 1997) in which the generic vital rates of the species are used as starting values. In addition, the optimization procedure is constrained to ensure that the relative adjustment applied to a given vital rate is inversely proportional to its demographic sensitivity (Caswell, 2001). In other words, the value of a vital rate with high sensitivity (e.g. adult survival for a long-lived species) will be less altered than that of a vital rate with low sensitivity (Sæther and Bakke, 2000; Gaillard and Yoccoz, 2003). This procedure ensures that, regardless of the λ specified, the final Leslie matrix remains consistent with the specie's life history.

In EolPop, generic vital rates have been supplied for 60 European

bird species. These are the priority species identified by the stakeholders involved in the research program, focused on windfarm impacts, that funded the development of this Shiny application. Vital rate values were obtained from an extensive search of the literature and missing values were inferred using a phylogenic imputation approach (James et al., 2021) based on the morphometric (mass) and life history characteristics (clutch size) of a species (see Appendix 1 for full details). Users can thus simply select one of the species from a dropdown menu, in which case the generic vital rate matrix is filled automatically. The user also has the option to modify these values, or even build a custom vital rates' matrix, with the desired number of age classes, by selecting "custom species" at the end of the species list.

Finally, EolPop allows incorporating uncertainty on input parameters. The user can supply parameter uncertainty either as a min-max interval, as a standard error or as a set of values obtained through expert elicitation. The program integrates this uncertainty by randomly drawing new parameter values, at each simulation, from a gamma distribution whose variance is calculated from the uncertainty values supplied by the user. A gamma distribution is used because all four parameters are positive. Environmental stochasticity is included by randomly drawing new λ values, each year, from a log-Normal distribution. Demographic stochasticity is incorporated through random draws of mortalities (both natural and anthropogenic) and reproductive events, using binomial and Poisson distributions respectively. By running many simulations, EolPop propagates these various sources of uncertainties (input parameters, stochasticity) into the final result, and therefore produces a *distribution* of possible impact values.

Three types of analyses can be performed with EolPop. First, one can assess the impact of fatalities from a *single source* (e.g., a single windfarm) by providing a unique value (with uncertainty) of annual mortality. Second, one can also quantify the *cumulated impact* of several sources of mortality (e.g. several windfarms within the same area). In that case, the user must supply a value of mortality for each source, along with their respective onset year (e.g. year of each windfarm commissioning). Third, one can simulate multiple hypothetical scenarios of mortality at once to investigate the respective impact of alternative infrastructure development strategies and facilitate their comparison.

2.3. Model assumptions

2.3.1. Fatalities

Annual fatalities are modeled stochastically, so they vary among years, but their expected value is assumed to be constant across time (i.e. no trend, no environmental variance). Annual fatalities can be provided either (1) as a number or (2) as a rate. This choice matters because it affects how the temporal consistency assumption is applied. In case (1), it is the expected *number of fatalities* that is constant over years, meaning that the mortality rate varies as population changes; this option is relevant for territorial species, as usually a fixed number of territorial pairs are in contact with the mortality source (e.g. a windfarm). In case (2), the expected *mortality rate* is constant over years, such that the number of fatalities varies as population changes; this option is relevant when the source of mortality is located in an area that is used by the whole population (e.g., common feeding grounds). In both cases, the model assumes that mortality affects both sexes and all age classes equally, except for juveniles which are assumed not to be affected by collisions. This assumption was made because for most species, sex and age cannot easily be determined from carcasses, such that EIA investigators rarely possess the required level of information to get sex- or age-specific mortality rates.

2.3.2. Population size

In EolPop, population size can be provided either (i) as a number of pairs or (ii) as a total headcount including all age classes, except juveniles. In both cases, the information is being translated in terms of age

class sizes assuming stable age distribution. The stable age distribution is derived directly from the Leslie matrix.

2.3.3. Population growth rate

Because the model includes environmental stochasticity, λ varies among years, but its expected value is assumed to be constant over time, except when density dependence is included (see section 2.3.4). Under the baseline scenario, a population's average trend is therefore assumed to be stable over time. Environmental stochasticity was set at a value of 8% inter-annual variance, based on reviews of typical values of environmental variance (between 2% and 14%) found for bird populations in the literature (Saether and Engen, 2002; Sæther et al., 2005).

2.3.4. Density dependence

For populations that are initially stable or declining, we chose to exclude density-dependence (i) to avoid over-optimistic predictions due to compensatory mechanisms (Péron et al., 2012; Horswill et al., 2017; O'Brien et al., 2017), and (ii) because density-dependence parameters can only be inferred empirically if the current $\lambda > 1$. Indeed, density-dependence relies on the assumption that a population would be continually growing, at a progressively slowing pace, until it reaches its carrying capacity K. This does not mean that declining population cannot experience density-dependence effects, but from an inferential perspective, we cannot empirically back-calculate relevant density-dependence parameters from a declining population. For growing populations, we included a negative density-dependence effect on λ using a theta-logistic model (Eberhardt et al., 2008), assuming a linear relationship between λ and population size. To avoid unrealistically high values of λ, EolPop uses the theoretical λ_{max} value of the species, calculated using the demographic invariants approach (Niel and Lebreton, 2005), as an upper limit.

3. Case study

To showcase the use of EolPop, we use two case studies that are very contrasted in terms of spatial extent, population size and uncertainty associated with population estimates. The first one concerns a small and well-studied population of Lesser kestrels (*Falco naumanni*) that breeds in Southern France and suffers collision fatalities from a single windfarm located nearby the kestrel colonies (Duriez et al., 2022). The second case study is an application of EolPop on Eurasian skylark (*Alauda arvensis*) windfarm collisions at the French national scale. In the Eurasian skylark example, the spatial scale and the uncertainties are much larger that in the Lesser Kestrel case study.

3.1. Lesser kestrel

The population of Lesser kestrels breeding in central Hérault, France is one of only three French populations of that species (Duriez et al., 2022). Started from a few immigrated pairs in 1992, it has known a steady growth due to good breeding success and regular immigration (Duriez et al., 2022). This kestrel population has been exposed to collisions since the commissioning of a local windfarm in 2006. Since 2013, when the windfarm reached its full capacity, an average of 5.4 kestrel carcasses per year (SD = 1.7) have been found on site. After correction for detection biases (Huso, 2011), the true number of fatalities was estimated at 19.4 (SE = 2.9) death per year, which is equivalent to a 4.9% (SE = 0.7%) annual mortality rate. Over that same 7-year period, the population has grown at a rate of *ca.* 7.0% annually, from 148 to 254 pairs. After a simple correction using the collision rate of 4.9%, we can infer that, without these collisions, the population would currently be growing at an annual rate of *ca.* 11.0% (SE = 1.0%).

To implement the impact analysis in EolPop, we used the following inputs (Fig. 1): (i) annual fatality rate = 4.9% (SE = 0.7%); here, we used a constant mortality rate because collisions occur at one of the main foraging sites that is used by the entire population; (ii) current
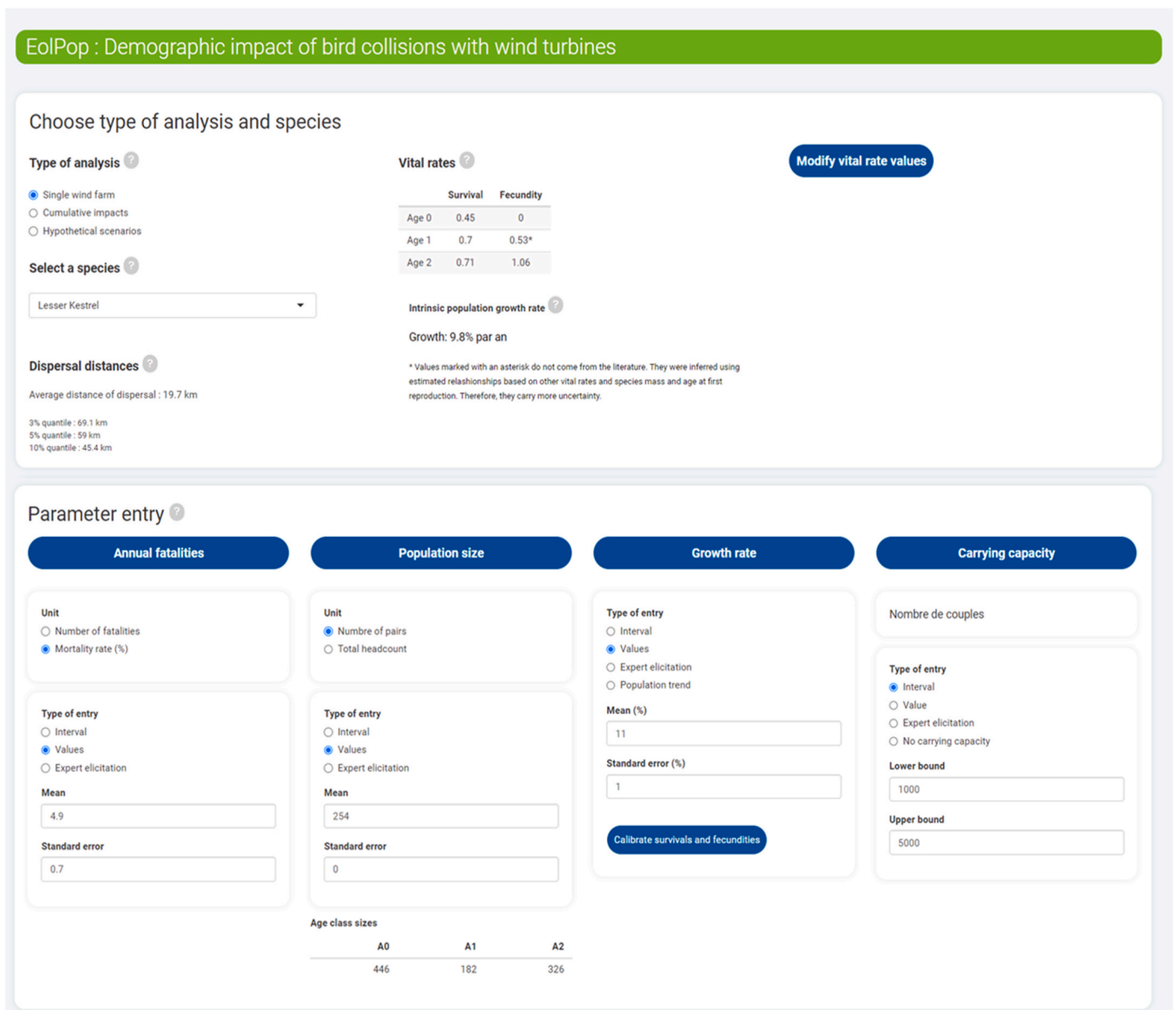
Fig. 1. EolPop interface showing input values used for the Lesser kestrel example.

population size = 254 pairs (SE = 0); and (iii) population growth rate (without collisions) = 1.11 (SE = 0.01). The vital rates for that species are available in EolPop: juvenile survival probability = 0.45; subadult survival probability = 0.70; adult survival probability = 0.71; subadult fecundity = 0.53; adult fecundity = 1.06. Finally, because the population is currently growing ($\lambda = 1.11$), we also needed a carrying capacity. To obtain this information, we asked three experts to provide their best estimate of that parameter. They respectively answered 1,000, 2000 and 5000 pairs. There is necessarily some subjectivity in their responses and while these values might not necessarily be an accurate reflection of true carrying capacity, they represent relevant conservation objectives. We thus parameterized the carrying capacity using a min-max interval between 1000 and 5000 pairs. We ran 1000 simulations over a time horizon of 30 years.

With the current rate of *ca.* 4.9% annual mortality from collisions, this population of Lesser kestrels is still expected to grow, but at a much slower pace than it would without these collisions (Fig. 2A). As shown on Fig. 2B, the relative impact is expected to keep cumulating for about 20 years, and then stabilize thereafter due to compensatory density dependence effects. After 30 years, the relative deficit in terms of

population size is expected to be *ca.* 48% (95% C.I. = 32%–66%).

To assess the robustness of population predictions provided by Eol-Pop we also ran a retrospective analysis for the 2014–2020 period, based on this well-documented Lesser kestrel case study. We used the same parameter inputs as described above, except for initial population size, which was equal to 173 pairs in 2014. We projected population trajectories until 2020 under both scenarios and compared them to known population size values over the 2014–2020 period. Prediction from the scenario with windfarm fatalities was very close to the real population growth (Fig. S1), which confirms the accuracy of EolPop at predicting population trajectories when reliable parameter estimates are available.

3.2. Eurasian skylark

In France, the Eurasian skylark is the species most frequently found in windfarm carcass searches during the breeding season (Marx, 2017). Based on national summary statistics, it has been estimated that Eurasian skylarks represent *ca.* 5.4% of all birds killed on French windfarms (Marx, 2017), which amounts to *ca.* 0.38 skylarks killed each year by every wind turbine. With a total of 8500 turbines in France (as of
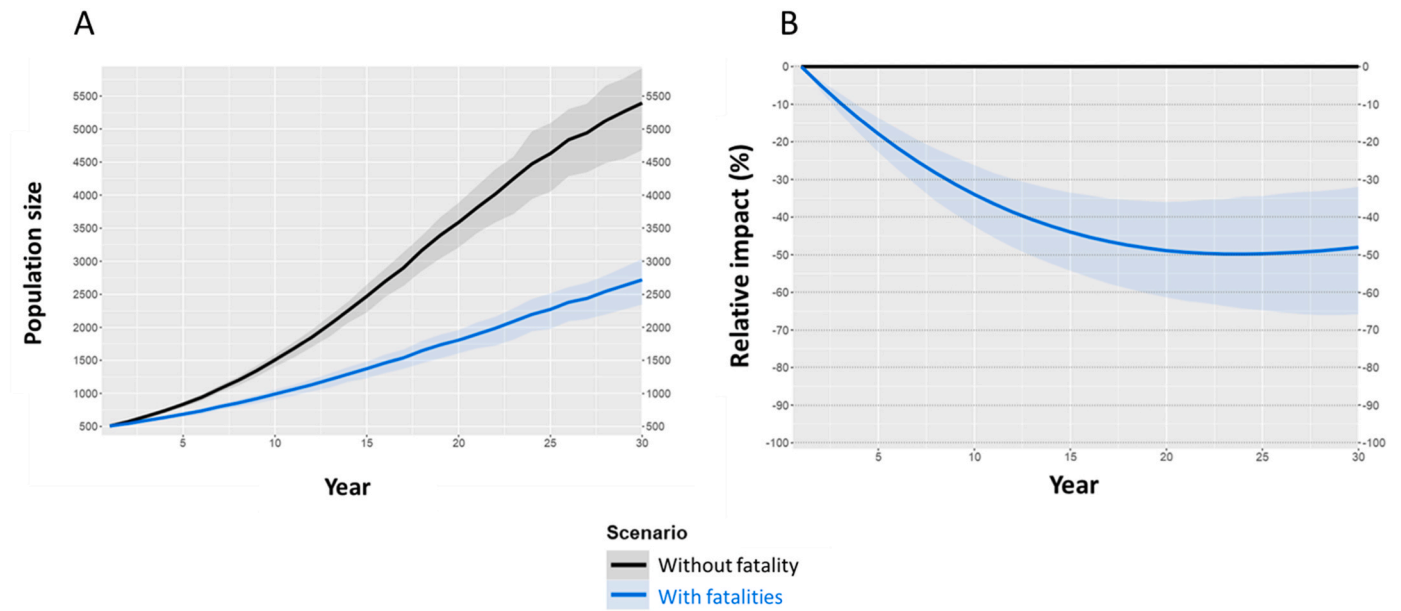
Fig. 2. Results of the Lesser kestrel analysis. (A) Predicted population trajectories over 30 years. (B) Relative impact of collision fatalities, across years. The impact scenario (blue) is relative to the baseline scenario (black).

2021), this means that about 3200 skylarks are being directly killed each year by the wind energy sector. Because this a very gross estimate, which ignores spatial variability and other complicating factors, we applied an uncertainty factor of 2 around this value. This gave us a credible interval between 1600 (3200/2) and 6400 (3200 * 2) fatalities. Given that the national population size of Eurasian skylarks is estimated between 1.3 and 2.0 million breeding pairs (Comolet-Tirman et al., 2015), this amounts to a mortality rate interval of 0.10%–0.39%. In terms of national trend, Eurasian skylarks have been declining steadily at a rate between −1,28% and −1,37%, annually (Comolet-Tirman et al., 2015). Because the species is in decline, there was no need to provide a carrying capacity for that analysis. Generic values of vital rates are also available in EolPop for that species, which only has two age classes (juvenile, adult): juvenile survival probability = 0.30; adult survival probability =

0.66; adult fecundity = 1.43. We ran 1000 simulations over a time horizon of 30 years.

Using these parameter values, the relative impact of wind turbine collisions is estimated to incur a national population size deficit of *ca.* 7% (95% C.I. = 4%–10%) after 30 years. As can been seen on Fig. 3, this impact is relatively small in comparison to the overall declining trend that the species is facing. This result clearly contrasts with that of the Lesser kestrel population, which happens to be strongly impacted locally. This contrast is partly due to the difference in spatial scale between the two analyses.

4. Discussion

EolPop is a R-Shiny interactive dashboard that allows running
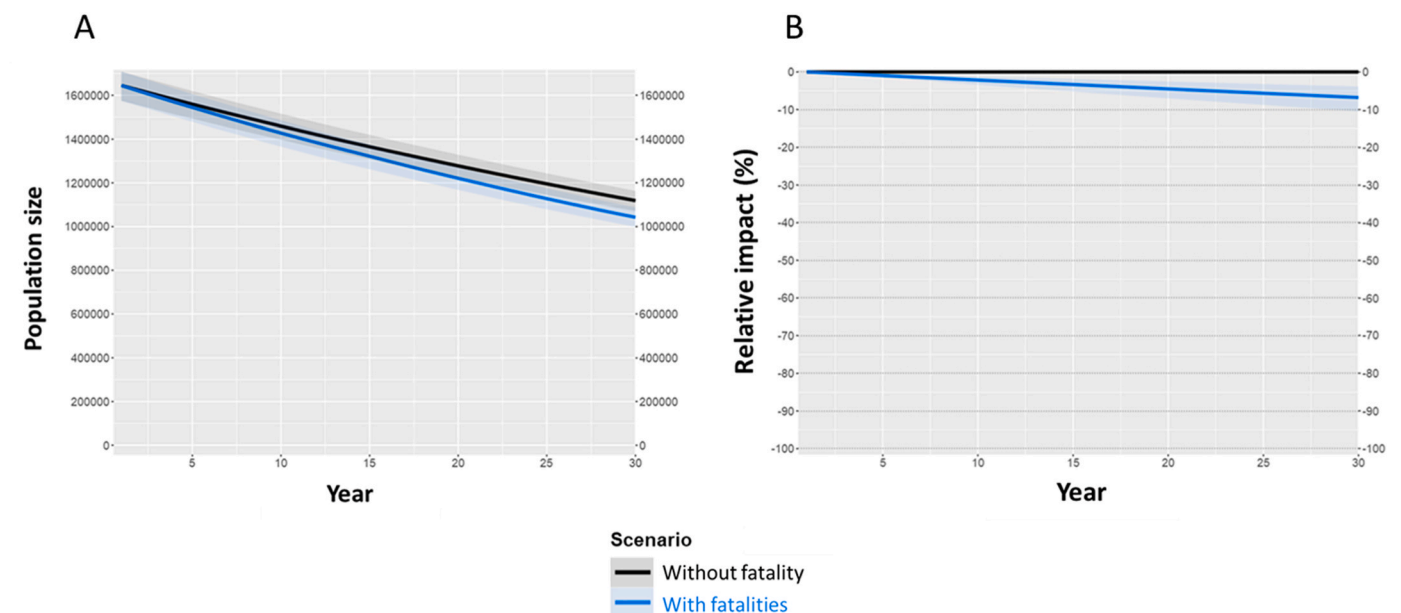

Fig. 3. Results of the Eurasian skylark analysis. (A) Predicted population trajectories over 30 years. (B) Relative impact of collision fatalities, across years. The impact scenario (blue) is relative to the baseline scenario (black).

population projections to quantify the demographic impact of additional (non-natural) fatalities without the requirement of technical skills to build Markovian population models. It is freely available online, both in English (https://shiny.cefe.cnrs.fr/en_eolpop/) and in French (https://shiny.cefe.cnrs.fr/eolpop/). The application can also be downloaded on a computer and launched from R locally (follow instructions here: https://human-animal-interactions.github.io/html/EolTools_Page.htm). This tool is primarily intended for non-academic professionals that are involved in the process of environmental impact assessments (EIA). This includes people working at environmental consulting firms, environmental NGOs, as well as state authorities. With this tool, EIA could experience a major improvement in quality by formally and objectively quantifying the expected impacts of a project at the population level (May et al., 2019), instead of relying on subjective expert's opinions to decide whether or not the impact of some level of fatalities will be "significant" (Flyvbjerg, 2007). This latter approach, which has unfortunately become common practice in terrestrial wind energy development, often leads to decision biases and encourages corruption practices (Williams and Dupuy, 2017; Enríquez-de-Salamanca, 2018). This is clearly detrimental to the protection of biodiversity (Green et al., 2016; Williams and Dupuy, 2017).

EolPop is not a research-oriented PVA tool. Therefore, its purpose is not to provide highly accurate predictions of a population's true trajectory into the future, which would require much more information than is typically available in the context of EIA. The main goal of EolPop is to allow non-academic professionals, who lack the quantitative skills required to build complex population models on their own, to easily get an objective quantification of the *relative* demographic impact generated by some level of fatalities. Because it aims at being operational, EolPop necessarily comes with simplifying assumptions (see section 2.3). All assumptions that are made were deemed to be the best trade-off between realism and functionality, but nonetheless some caution is warranted when interpreting the outputs. One assumption that could lead to over-optimistic results is the homogeneity of mortality rate among sex and age classes. Unequal collision mortality rates between sexes has for instance been found in Common terns (*Sterna hirundo*), where males were more impacted than females (Stienen et al., 2008). In the case of a long-lived species, if adults are more exposed to the focal source of fatalities than youngers individuals, the model will underestimate the demographic impact. Similarly, in most cases if females are more impacted than males, we expect an underestimation of impact. This assumption was made for the sake of functionality, because in every EIA we have consulted, there never was nearly enough information to quantify sex- or age-specific mortalities. Accurately quantifying the total number of fatalities for a given species is already very challenging (Huso, 2019; Conkling et al., 2021), so expecting to collect sex- or age-specific mortalities seems unrealistic.

Another assumption we made was to include density-dependence for growing populations only. Again, this choice achieves the best trade-off between realism and functionality. Ignoring density-dependence for growing populations can lead to irrelevant demographic explosions, so it appeared necessary to include it in order to produce realistic population projections and impact estimates. The drawback of this choice is that the user must provide a value for carrying capacity (K), a parameter that is rarely known and can vary over time. In absence of data to inform this parameter, one approach consists of using expert elicitation as we did in our Lesser Kestrel example. Even if the value obtained does not necessarily match the true (unknown) environmental carrying capacity, it should at least represent a meaningful conservation objective ("what population size do we want?"). Alternatively, a conservative approach is simply to ignore density-dependence by checking the "no carrying capacity" option in EolPop. In this case, the estimated population impact will be at its maximum potential, such that the risk of underestimating it is minimal. Regarding declining populations, there was two important reasons to exclude density-dependence. First, as explained in section 2.3.4, density-dependence parameters can only be inferred empirically if

the current $\lambda > 1$. More importantly, because density-dependence is a mechanism through which fatalities are partially compensated (Rose et al., 2001; Péron et al., 2012), we decided to adopt a precautionary approach for populations that already declining. This cautionary stance is in full accordance with the relevant literature on this topic (Green et al., 2016; Horswill et al., 2017). Along the same lines, we decided to include demographic and environmental stochasticity, not only for the sake of realism, but because ignoring these processes could lead to underestimate the extinction risk of small populations (Lande, 1993; Beissinger and McCullough, 2002).

All other assumptions (see section 2.3) are neither unusual nor overly restrictive compared to the assumptions that are typically made in population dynamics analyses. Overall, we tried to build as many safeguards as possible in EolPop to avoid leading users towards the production of erroneous results. First, by providing a relative metric of impact (i.e. the counterfactual approach; see section 2.1), we ensure the highest degree of robustness to parameter, process, and structural uncertainties (Green et al., 2016; Cook and Robinson, 2017). Second, by providing the user with three alternative ways to supply parameter uncertainty (see section 2.2), we hope to maximize the chances that uncertainty will in fact be fully considered and integrated into the analysis. EolPop then automatically carries all uncertainties forward, which are thus fully reflected in the impact estimate. In addition, we encourage users to carry sensitivity analyses, by running multiple simulations using slightly different parameter values, to fully apprehend the consequences of uncertainties prevailing in their study cases.

Another choice we made for the sake of functionality was to provide some generic values of vital rates for 60 European bird species. As explained in section 2.2 and Appendix 1, these values were gathered from the literature and, when missing, they were imputed using a phylogenic imputation approach (James et al., 2021). We know that these values will not always be representative of the real vital rates of a specific population. First, because inter-population variation in vital rates exists (Frederiksen et al., 2005), values found in the literature, which come from a few populations at best, cannot be representative of all populations of a given species. In addition, even within the same population, vital rates can fluctuate over time (Coulson et al., 2001). Second, we acknowledge that the imputed values only provide a crude approximation of real vital rates. But none of these issues are really relevant because, as explained in section 2.2, the Leslie matrix used to make demographic projections is internally adjusted to match the local population growth rate λ provided by the user. Vital rate values are simply used as a reference frame that must be representative of the species' life history strategy. What really matters here are not the absolute values of vital rates, but the relative values of age-specific survivals and fecundities in relation to each other (see demonstration of this claim in Appendix 3). In terms of population projection accuracy, the most important piece of information is thus the value of λ supplied by the user. It is therefore their responsibility to ensure that they provide a reliable λ. If they don't, the absolute values of projected population size will be inexact, but the CIU impact metric will remain fairly reliable because it is not highly sensitive to uncertainties on λ. This, of course, is only true to some extent, i.e. as long as the λ provided is not too far from reality.

Ultimately, the quality and reliability of the results can only be as good as that of the inputs themselves. So, despite all the safeguards included in EolPop, it remains the responsibility of the users to ensure that they use reliable information to parameterize the model. If inputs are accurate and representative of the target population, the relative impact metric provided by EolPop will also be accurate. It is also the responsibility of the user to quantify and supply uncertainties on input parameters. We remind that, for decision making purposes (Maris et al., 2018), it is crucial to not only interpret the average impact estimated by EolPop but also its confidence interval, which reflects the level of uncertainty surrounding that result. Eolpop users should also be aware that population projection results are necessarily conditional on the current

state of knowledge (i.e. accuracy of the inputs provided) and on the stability of current conditions (e.g. constancy of the current population trend under the baseline scenario). Because no one can predict how environmental conditions are going to change over the next decades, it is impossible to anticipate with great confidence a population's true trajectory over such a long time (see Maris et al., 2018). We thus caution against the over-interpretation of absolute values of populations size at a given time horizon, and recommend that users limit their interpretation to the relative metric (CIU) of impact provided by EolPop.

Finally, the validity of the results delivered by EolPop strongly depends on an adequate delineation of the population being impacted by fatalities. When the mortality occurring at a given site primarily concerns individuals that are only passing through during their seasonal migration, their population of origin is generally unknown, except in rare specific cases with high migratory connectivity and limited breeding range (e.g. arctic geese such as *Anser brachyrhynchus;* Madsen et al., 2014). We therefore advise against the use of EolPop in most cases of migratory species. Currently, there is no easy solution to this issue and it remains very difficult to assess the demographic consequences of fatalities occurring along migratory pathways (De Lucas and Perrow, 2017). EolPop is better suited to cases where individuals exposed to fatalities are non-transient and thus belong to a well-defined local population. This includes year-round resident species, but it can also be applied to the breeding and wintering areas of a migratory species. For instance, in our Lesser kestrel example, the analysis concerned a well-identified breeding population that is only present in the area from March to September.

The availability of EolPop constitutes an important first step, which can still be perfected, to improve the quality and objectivity of demographic impacts assessments of wind energy and other types of large infrastructure projects. As data become more available, it will be possible to further generalize the tool and relax some assumptions. Although EolPop was originally conceived to assess the demographic impact of bird fatalities caused by collisions with wind turbines, it can be used to assess the impact of any sources of additional mortality, such as hunting, electrocution on power lines, collisions with cars, illegal poisoning. Similarly, it is not restricted to birds and can be used for any taxon (using the "custom species" option), as long as reliable input parameters (mainly population size and trend) are available.

Credit author statement

Thierry Chambert: Conceptualization, Tool Development – Coding & Data Aggregation, Writing - Original Draft Preparation, Writing - Review & Editing. Mathilde Deleaux: Contribution Tool Development – Data collection. Olivier Duriez: Conceptualization, Writing - Review & Editing. Aurélien Besnard: Conceptualization, Writing - Review & Editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118923.

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