Northeast Fisheries Science Center Technical Memorandum 337

Update to a management-focused population viability analysis for North Atlantic right whales

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Editorial Notes

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OVERVIEW

We provide an update to the recently published population viability analysis for North Atlantic right whales (*Eubalaena glacialis*). The update includes improvements to the reproduction modeling and also shares additional context given evidence of reduced mortality indicated by recent population monitoring. Projections from the analysis are used to quantify simulated population sizes across 100 years and resulting quasi-extinction probabilities (falling below 50 mature females that have proven ability to reproduce) to compare hypothetical scenarios related to management of threats and changing environmental conditions. Under a status quo scenario reflecting conditions of 2019, prior to the enactment of new regulations by the U.S. and Canada, the North Atlantic right whale population would be expected to continue to fall, with a median decline of 88 percent (95% projection interval, –98 percent to –45 percent change) and a probability of falling below 50 proven females (i.e., quasi-extinction) of 0.988 at 100 years. In hypothetical scenarios that fully remove each of the three primary threats to right whales one at a time, removal of the entanglement threat alone reduces the probability of falling below 50 proven females in 100 years to 0.070; removal of the vessel strike threat alone reduces it to 0.522; and a return to historical prey abundance patterns (pre-2010), but with both human-related threats still in place, reduces it to 0.524. Although additional baseline scenarios were explored to examine the potential effects of recent regulations, we found that the most up-to-date mortality rates (2020–2022) are similar to those simulated under a 70% reduction in severe entanglement injury compared to rates estimated during 2013–2019. If management measures implemented in the U.S. and Canada continue to reduce mortality, the estimated probability of falling below 50 proven females in 100 years is 0.234. Our model continues to provide a tool for assessing North Atlantic right whale recovery.

INTRODUCTION

A population viability analysis (PVA) for North Atlantic right whales (NARW; *Eubalaena glacialis*) was recently developed to quantify extinction risk for this endangered species (Runge et al., 2023). The analysis was designed to assess the current population status, evaluate the contributions of various threats to the risk of extinction, and explore the management interventions needed to achieve recovery. An individual-based model was designed to represent NARW population dynamics and account for age- and stage-specific survival and reproductive rates, the effects of severe injury from anthropogenic interactions, and future changes in prey availability and accessibility. Demographic parameters to inform the projection model were derived from retrospective analyses of mortality (Linden et al., 2024a) and reproduction (Linden et al., 2024b) using NARW sightings from 1990–2019. A representation of status quo conditions prior to 2019 provided a baseline scenario for comparison with various proposals representing expected changes (i.e., due to recently enacted regulations) and hypothetical mitigation measures that reduced major threats by varying degrees. Simulation was then used to explore the range of population trajectories under each scenario while thoroughly accounting for uncertainty.

Here, we provide updated projections using the original model structure with some revised parameter estimates of demographic rates from 1990–2019 and additional context using new information collected since 2020. The purpose of this report is to provide a refinement of the results from Runge et al. (2023) with the acknowledgment that considerable uncertainty remains regarding the future population trajectory of NARW.

Differences from original PVA

The original PVA report (Runge et al., 2023) presented several hypotheses about regime shifts to justify changepoints in demographic parameters. The changepoints represented years where the characteristics (e.g., mean, trend) of the time series changed significantly. Runge et al. (2023) explored changepoints that reflected population-level responses to two recent events: 1) a major ecosystem shift in the western Atlantic in 2010 (Sorochan et al., 2019); accompanied by 2) a shift in spatial distribution of NARW after 2013 (Simard et al., 2019; Meyer-Gutbrod et al., 2023). Runge et al. (2023) used the 2010 regime shift to explain changes in prey availability, while the retrospective analyses used the 2013 distributional shift to explain differences in injury/mortality rates and calving probabilities that were manifested in the baseline population projections. Evidence suggested that following the distributional shift after 2013, NARW experienced increased rates of severe injury due to vessel strike and entanglement (Linden et al., 2024a) and decreased probabilities of calving (Linden et al., 2024b).

After publication, it was determined that most projections in Runge et al. (2023) had been simulated using the 1990–2012 period for average probability of calving when the intent was to illustrate population dynamics under conditions consistent with 2013–2019. This misspecification resulted in an average probability of calving for waiting females (individuals mature enough and ready to have a calf) that was much higher than intended (27% vs 11%). Extinction probabilities were therefore underestimated in the baseline projections and for most other scenarios under the assumptions that were stated in the original report (e.g., post-2013 conditions would persist into the future).

Additionally, revisions to Linden et al. (2024b), made in response to further peer review, changed how prey availability was represented and provided an improved model specification to accommodate patterns in the data. Prey availability indices were originally defined as a log-scale average biomass of *Calanus spp.* calculated for year *t* using the previous 3 years (*t*–1, *t*–2, and *t*–3); a substantial improvement in predictive power resulted from instead defining the average biomass by the years *t*, *t*–1, and *t*–2 (Linden et al., 2025). We also switched the changepoint in calving probability to reflect the 2010 regime shift in ecosystem dynamics of the western North Atlantic (more directly relevant to prey) rather than the 2013 regime shift in whale distribution. Crucially, an interaction between the 2010 regime shift and the linear relationship with the eastern Gulf of Maine prey index was also included (Linden et al., 2025). The resulting model structure better reflected realized patterns in calving across the time series (Figure 1).

The baseline projections presented here used the patterns in reproduction consistent with those estimated for 2011–2019, where average probability of calving for waiting females was ~14% and the eastern Gulf of Maine prey index no longer explained variation in calving (Linden et al., 2025). Estimates of mortality in the baseline projections were consistent with those used in the original report (Runge et al., 2023) and reported in Linden et al. (2024a).

Comparison with new demographic data

In addition to the updates regarding variation in NARW calving, we also sought to explore the implications of recent evidence for decreased mortality since 2019 as indicated by the most current population estimates (Linden, 2024). The apparent decrease may be attributed to management measures in place since 2020 that have reduced mortality risk for NARW in both the U.S. and Canada, a possibility that was discussed in Runge et al. (2023). To illustrate the magnitude of mitigation from the baseline scenario (2013–2019) necessary to match the realized mortality rates from 2020–2022, we identified the entanglement reduction scenario and resulting projections that had the closest mortality schedule. Although mitigation has likely addressed risk from both entanglement and vessel strike, the simulated scenario provides an approximation for how the population would fare under reduced mortality (all other things being equal).

METHODS

We refer readers to the original PVA report for the literature review, model description, parameter estimation, and scenario design used for projections (Runge et al., 2023). Briefly, we designed an individual-based model where simulated whales transition between stages as dictated by NARW life history and demographic parameters estimated from retrospective analyses. Our choice of parameters represented assumptions about how current conditions may be representative of potential future conditions and how hypothetical mitigation or environmental change could affect population trajectories. We used a "baseline and scenarios" approach (Runge et al., 2017; Williams et al., 2021) to provide best estimates of the current status and scenarios that deviate from the baseline to provide "what if" conditions that would be relevant to management and conservation considerations. The basic construct of the original analysis was repeated here with the only differences coming from the estimates of reproductive rates.

Here, our baseline used NARW demographic rates from the recent past, including reproductive rates from 2011–2019 (Linden et al., 2025) and injury/mortality rates from 2013–2019 (Linden et al., 2024a). We assumed that vessel strike injury rates would remain constant (i.e., no mitigation or changes in vessel traffic) and the lower prey availability observed from 2010–2019 would continue indefinitely. Note, the representative years for average calving probability (2011–2019) and prey index values (2010–2019) slightly differ because of how the reproduction model uses the preceding 3-year average of prey index values. Entanglement injury rate presented a challenge given that efforts to address entanglement risk were implemented in 2020 and beyond in both the U.S. (NMFS, 2021) and Canada (SCFO, 2023). We therefore constructed three alternative baselines to represent uncertainty regarding the effectiveness of impending management measures. Baseline 1 represented the "status quo", assuming no change in entanglement injury rate from that observed during 2013–2019, while baselines 2 and 3 represented situations where entanglement injury rates were reduced by 25% and 50%, respectively. The baselines were intended to provide a status assessment for the species and illustrate various metrics for understanding the future prospects of the population, including extinction probability, expected minimum population (EMP) size, and probabilities of population change.

The hypothetical scenarios included a threats analysis to examine how the removal of each threat entirely would affect extinction probabilities, and management scenarios where mitigation or environmental change was implemented to varying degrees. We conducted a sensitivity analysis to determine which model parameters had the largest effects on projection outputs, specifically with regards to EMP size. We structure and describe the results here in the same format as the original report while accommodating interpretation of new estimates and differences in outcomes; finally, the comparison of new demographic data (2020–2022) to hypothetical threat mitigation is presented.

RESULTS

The results of the projections from the individual-based model show the outcomes expected from each scenario. We begin with the results from the baseline scenarios, using a variety of metrics, to establish the expected future dynamics under our current understanding of the threats. Then, we present the results from the threats analysis and management scenarios, with a focus on the probability of quasi-extinction and how it differs across scenarios. Finally, we present the results of the sensitivity analysis, to understand the role that uncertainty in the parameters is playing in the results.

Baseline Scenarios

The baseline scenarios project the trajectory of the NARW population and account for uncertainty. These scenarios incorporate the best available scientific and commercial information about NARW and the primary threats they face. As noted above, there are three baseline scenarios that represent different assumptions about the efficacy of recently enacted regulations designed to reduce entanglement risk. In the sections that follow, several different metrics are displayed for the baseline scenarios, including population projections, quasi-extinction rates, the expected minimum population size, and metrics concerning rates of increase or decline.

Baseline population projections

Under the baseline 1 scenario (the "status quo" scenario), the total NARW population size is expected to decline steadily over the next 100 years, with a median decline of about 88 percent (Figure 2A). The 95-percent projection interval, however, is wide, and includes trajectories that show a 98-percent decrease as well as a 45-percent decrease.

The baseline 2 scenario (25% entanglement reduction) indicated a steady, slightly decreasing population on average, with a median population that is 72-percent smaller after 100 years (Figure 2B). Again, there was considerable uncertainty, with the 95-percent projection interval including a 95-percent decrease and an 18-percent increase. Finally, baseline 3 scenario (50% entanglement reduction) resulted in a slightly decreasing population for most projections, with a median decrease of 30 percent (Figure 2C). The highest projection in the 95-percent interval indicated a 206-percent increase whereas the lowest indicated a 91-percent decrease.

As in any population, the long-term population growth rate for NARWs is a function of the per-capita birth and death rates, with a stable population (growth rate $\lambda = 1.00$) occurring when the birth and death rates are equal (Figure 3). By plotting the realized birth and death rates for the baseline scenarios on this same graph, the transition from negative to positive average growth is apparent (Figure 3). In addition to the expected differences among baseline scenarios in death rate due to reduced entanglement, there are also differences in birth rate due to marginally higher probabilities of reproduction when entanglement rates are reduced.

Probability of quasi-extinction

To understand the risks posed by the threats to NARWs, we calculated the probability of quasi-extinction (PQE), specifically, the probability that the number of proven females (individuals that had previously calved) would fall below thresholds of 1, 10, 50, or 100 animals by any point in time (Figure 4). A quasi-extinction threshold of 100 proven females was not informative, because the population was already below this value at the start. A quasi-extinction threshold of 10 mature females was also not very informative, because the probability was uniformly low for all scenarios and time points. At a threshold of 50 proven females, the probability of quasi-extinction for the baseline 1 scenario increased quickly to 0.964 at 50 years and 0.988 at 100 years (Figure 4*A*). The other baseline scenarios had lower probabilities of quasi-extinction; baseline 2 was estimated to be 0.772 at 50 years and 0.904 at 100 years (Figure 4*B*), whereas baseline 3 was estimated to be 0.36 at 50 years and 0.526 at 100 years (Figure 4*C*). In comparison to the first baseline, the reduction of entanglement risk by 25% reduced the probability of quasi-extinction at 100 years from 0.988 to 0.904 and the reduction of entanglement risk by 50% reduced the probability of quasi-extinction from 0.988 to 0.526.

Expected minimum population size

The expected minimum population size provides another measure of the risk of decline. In this approach, the minimum population size is determined for each replicate up to a given point in time and the average is calculated across replicates. This roughly answers the question of how small, on average, the population size could fall before any point in time. This metric necessarily decreases (or at least does not increase) over time. The expected minimum population size is fairly sensitive to the differences in the three baseline scenarios, with values of 55, 119, and 226 individuals, respectively, at 100 years (Figure 5).

Probability of population decline or increase

The probabilities of population change, whether measures of decline (e.g., IUCN metrics) or increase (e.g., potential recovery criteria), reflected the same patterns across the three baselines as the other metrics presented (Table 1). The baseline 1 scenario (status quo) had higher probabilities of decline and lower probabilities of increase compared to the other baselines. The median time to surpass 1,000 mature individuals was >100 years for all three baselines. For the baseline 2 and baseline 3 scenarios, when the population reached 1,000 mature individuals the total population size was N = 1,540 on average.

Threats Analysis

For the remainder of the results (except the sensitivity analysis), we focus on the probability of quasi-extinction for proven females, a metric that is both based on the intent of the federal conservation laws and has a sufficient ability to discern differences among scenarios. To examine the contributions of the three primary threats (entanglement, vessel strike, prey loss) to long-term risk for NARWs, we compare the probability that the number of proven females falls below 50 individuals in 100 years under various removals of threats (Table 2). The presence of all threats (e.g., entanglement and vessel strike risk, and post-2010 prey availability) is the baseline 1 scenario (note the value of 0.988 matches that in Figure 4*A*). If prey availability were to follow the historic patterns (1990–2009) compared to the post-2010 conditions, the probability of quasi-extinction reduces by almost half (to 0.524). The full removal of the vessel strike risk alone reduces the probability of quasi-extinction to 0.522, and the full removal of the entanglement risk alone reduces it to 0.070. Thus, although all threats contribute substantially to the overall risk of quasi-extinction, the entanglement threat had a stronger individual effect than the risks from vessel strike and prey reduction.

Management Scenarios

Entanglement

The influence of entanglement mortality on population trajectories is apparent in Figure 6 where incremental reductions correspond to reduced probabilities of quasi-extinction for proven females. With 0% entanglement reduction (equivalent to baseline 1 scenario), the probability of falling below 50 proven females at 100 years was 0.988 (as reported above). The probability of quasi-extinction decreased by almost half at 50% entanglement reduction (PQE = 0.526). Weak rope implementation was less effective than full entanglement risk reduction, as expected (Figure 7), given that weak rope measures represent a partial risk reduction for entanglement (Knowlton et al., 2016; Runge et al., 2023). The probabilities of quasi-extinction were still high at a 50% implementation, with full entanglement at 0.526 and weak rope at 0.826.

Vessel strike

The scenarios exploring changes in vessel strike risk (via rates of severe injury and mortality) indicated that speed restrictions that reduce the collision risk can lower the probabilities of quasi-extinction, although long-term trends in vessel traffic would modulate the effectiveness of such mitigation (Figure 8). In the absence of a new speed restriction, the probabilities of falling below 50 proven females in 100 years were 0.982, 239 0.988, and 0.994, for long-term changes in vessel traffic at annual rates of –0.3, 0, and 0.7%, 240 respectively. With a speed restriction resulting in a 25% reduction in vessel strike risk, those probabilities decreased to 0.944, 0.964, and 0.986, for annual rates of –0.3, 0, and 242 0.7%, respectively.

Considering vessel strike and entanglement risk reduction in combination, the probabilities of falling below 50 proven females in 100 years were 0.862, 0.904, and 0.956, for long-term changes in vessel traffic at annual rates of –0.3, 0, and 0.7%, respectively, when the entanglement risk is also reduced by 25% (Figure 9). A speed restriction that reduces vessel strike risk by 25% combined with entanglement risk reduction of 25% results in a probability of quasi-extinction of 0.766 when the annual rate of vessel traffic remains constant.

Prey availability

Under a scenario where vessel strike and entanglement risks are maintained as in the baseline 1 scenario, but where prey distribution and abundance follow historical patterns as observed from 1990–2009 (the "steady" scenario; Runge et al., 2023), the probability of quasi-extinction (at N=50 proven females) increases slowly with a maximum at 0.524 over the next 100 years (Figure 10). However, under post-2010 prey conditions (baseline 1 scenario), the PQE increases more steeply to 0.988 in 100 years (Figure 10).

Prey accessibility

Changes in prey accessibility (i.e., a scaling of observed prey availability from 2010–2019) with reference to the baseline 1 scenario had a minor influence on the probabilities of quasi-extinction (Figure 11), with results that were not immediately intuitive. The expected relationship with the eastern Gulf of Maine prey index after 2010 suggested greater variance with higher potential probabilities at prey index values above and below the mean (Figure 1); this resulted in lower extinction probabilities when availability was both increased and decreased by greater degrees. At 70% accessibility compared to the current levels of prey availability (labeled 100% in Figure 11), the probability of falling below 50 proven females was 0.892 after 100 years. At 130% accessibility, the probability of falling below 50 proven females was 0.852 after 100 years. Smaller changes in accessibility were more similar to the baseline.

Sensitivity Analysis

There were several parameters for which the EMP size exhibited sensitivity (Figure 12 and Figure 13; Table S1). For parameters governing mortality, the average injury rates due to both entanglement (α_0^{iE}) and vessel strike (α_0^{iV}) (1) had regression coefficients with notable relationships (as measured by a p-value of ≤0.05) and (2) showed relatively large differences in EMP size between extreme values. Other mortality rate parameters had notable relationships that were all negative (Figure 12), but differences in expected minimum population size were relatively small (Figure 13). All parameters associated with age-specific reproduction (i.e., the "beta" parameters) also had notable relationships and relatively large differences in EMP size.

Projections approximating 2020-2022 mortality rates

The average realized per-capita mortality rate for NARW from 2020–2022 (Linden, 2024) was 0.024 [95% credible interval (CI): 0.00, 0.041]. The scenario that most closely approximated this rate involved a 70% reduction in the rate of severe injury due to entanglement compared to that from 2013–2019, which had a realized per-capita mortality of 0.025 [95% CI: 0.008, 0.063]. Under this scenario, the projected population size increased over 100 years on average (Figure 14) though uncertainty was considerable. At a threshold of 50 proven females, the probability of quasi-extinction for this scenario was 0.234 at 100 years (Figure 15).

DISCUSSION

Our tool was built to illustrate the potential population trajectories given a model of NARW population dynamics and demographic parameter distributions that represent hypotheses about future conditions. The projections presented here are an improvement from those originally published (Runge et al., 2023) and more accurately portray the potential consequences of threats to the species, and our update also provided an opportunity to examine recent evidence of successful management efforts. There are numerous reasons why the predictions made by our projections could turn out to be more or less accurate and they fall into one of two general categories: 1) our representation of the system; and 2) differences between realized and expected conditions or outcomes. We represented the system using an extensive knowledge base of NARW ecology and decades of empirical observations, though changes to specific model structures or assumptions can dictate the simulated population dynamics. Likewise, even if our system representations were completely accurate, future conditions could follow unexpected patterns and cause realized dynamics to fall outside of our predictions. The updated projections in this report were an attempt to improve our representation of the system and to also acknowledge potential evidence for a change in conditions.

The biggest changes between the methods used to make projections in Runge et al. (2023) and those that were used here derive from the representation of NARW calving probability. The average calving probability of waiting females used in Runge et al. (2023) (27%) was higher than originally intended to represent expectations going forward, and here the expected value (14%) better reflects the reduced calving that has been apparent since 2011 (Linden et al., 2025). Other research has indicated a similar unexplained decrease in calving probability in recent years (Pirotta et al., 2023; Reed et al., 2022) for reasons that are unclear though likely related to climate effects on prey availability and resulting nutritional deficiencies as well as severe entanglements resulting in decreased body size (Pirotta et al., 2024; Stewart et al., 2021). In addition to average calving probability, the projections here also reflect a change in the relationship with prey index values for the eastern Gulf of Maine after 2010 as indicated in Figure 1. Thus, both the average calving probability and fluctuations due to prey availability were depressed in the simulations of NARW reproduction used in the baseline projections presented here. Conversely, historical prey conditions indicated a calving probability that was both higher on average and linked more closely to fluctuations in prey availability.

The results of these changes to expected calving were an increase in quasi-extinction probabilities for most scenarios (including the baselines) and a larger difference between the scenarios exploring current vs. historical prey availability. Under the status quo conditions of 2019, the probability of quasi-extinction (i.e., falling below 50 proven females) increased from 0.934 (original projections; Runge et al., 2023) to 0.988 (updated). The other baselines showed similar increases, from 0.705 (original) to 0.904 (updated) for the 25% entanglement reduction scenario, and from 0.349 (original) to 0.526 (updated) for the 50% entanglement reduction scenario. Under historical prey availability, the updated projections had a much lower extinction probability (0.524) than in the original report (0.875). Additionally, reduced prey availability was identified as a more significant threat (Table 2), similar to vessel strike in the degree of reduced extinction probability when removed.

Despite the updated projections suggesting a more negative outlook for North Atlantic right whales, the recent evidence of a reduction in mortality rates post-2020 suggests that the status quo baseline may be too pessimistic. Management actions implemented after 2019 in Canada (SCFO, 2023) and the U.S. (NMFS, 2021) appear to have reduced the high mortality rates that were observed during 2013–2019. By comparing the mortality rates observed during 2020–2022 with those that were simulated across various projection scenarios, the scenario with the closest mortality profile was one where the baseline entanglement rate was reduced by 70%. The average projected population trajectory matches the slow increase in population size observed during 2020–2023 (Linden, 2024) and suggests a quasi-extinction probability (0.234) that is much lower than the updated baseline scenarios. Although this additional perspective is optimistic, the projections rely on the persistence of conditions that allow for lower mortality rates. If the management actions implemented by the U.S. and Canada are responsible for reduced NARW mortality, those actions would need to continue indefinitely or be successfully adapted (i.e., to accommodate change) in order for the projections to accurately reflect the future. Additionally, the increased observations of serious injuries from 2023–2024[1] could result in subsequent mortality rates that are estimated to be higher than those from 2020–2022, warranting caution when interpreting the aforementioned comparison.

The NARW PVA was designed to be a tool that can be continually refined to improve inferences on NARW population recovery. Our update to the PVA improves our representation of the system but does not directly incorporate new data. New data could incrementally improve the accuracy of projections, particularly if those data provide evidence of a change in expected conditions. Any such benefits will be tempered by the potential for increased uncertainty induced by low sample sizes (e.g., small number of additional monitoring years). Changes to the model structure to incorporate new knowledge or additional complexity are also possible (Runge et al., 2023), and all modifications to the NARW PVA will continue to be documented to allow for transparency and reproducibility (Linden et al., 2023).

ACKNOWLEDGEMENTS

Both the original report (Runge et al., 2023) and the update presented here were made possible with the help of collaborators across multiple organizations. We thank Kevin Sorochan (DFO, Maritimes) and Stéphane Plourde (DFO, Qc) for sharing their knowledge on *Calanus* ecology and future trends, and for kindly processing and providing both published and unpublished *Calanus* data. We would also like to acknowledge the following data curators of the AZMP (DFO) swGSL-June mackerel egg survey and EcoMon (NOAA) survey who kindly provided the *Calanus* data: David Bélanger (DFO, NL), Benoit Casault (DFO, NL), Caroline Lehoux (DFO, Qc), and Harvey Walsh (NOAA). We appreciate NMFS, DFO, and Transport Canada staff, as well as the U.S. Regional Implementation Teams (NEIT, SEIT) and the Atlantic Scientific Review Group for their early input. The efforts of many collaborators working through the North Atlantic Right Whale Consortium allowed for the right whale analysis presented here. The Florida Fish and Wildlife Conservation Commission's Fish and Wildlife Research Institute

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[1] https://www.fisheries.noaa.gov/national/marine-life-distress/2017-2025-north-atlantic-right-whale-unusual-mortality-event

supported one of the authors (JAH) during an early stage of this project. We are grateful to Wayne Getz, Trevor Branch, Andrew Read, and Evan Cooch for constructive reviews of the original report; and to Leah Crowe and Conor McGowan for constructive reviews of this report. We would like to take this occasion to note the extraordinary lifetime contribution of Stéphane Plourde to our ecological understanding of right whales and *Calanus*; his passing in March 2025 was a tremendous loss to his family, friends, and colleagues.

FIGURES

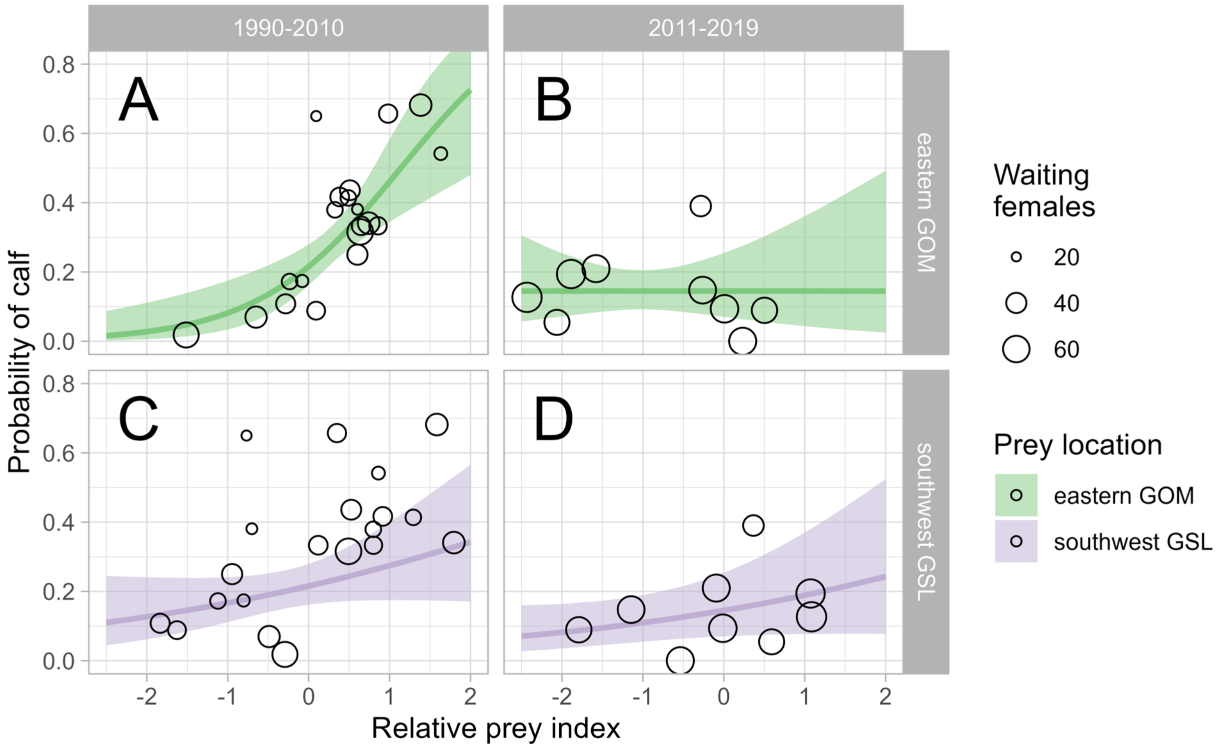
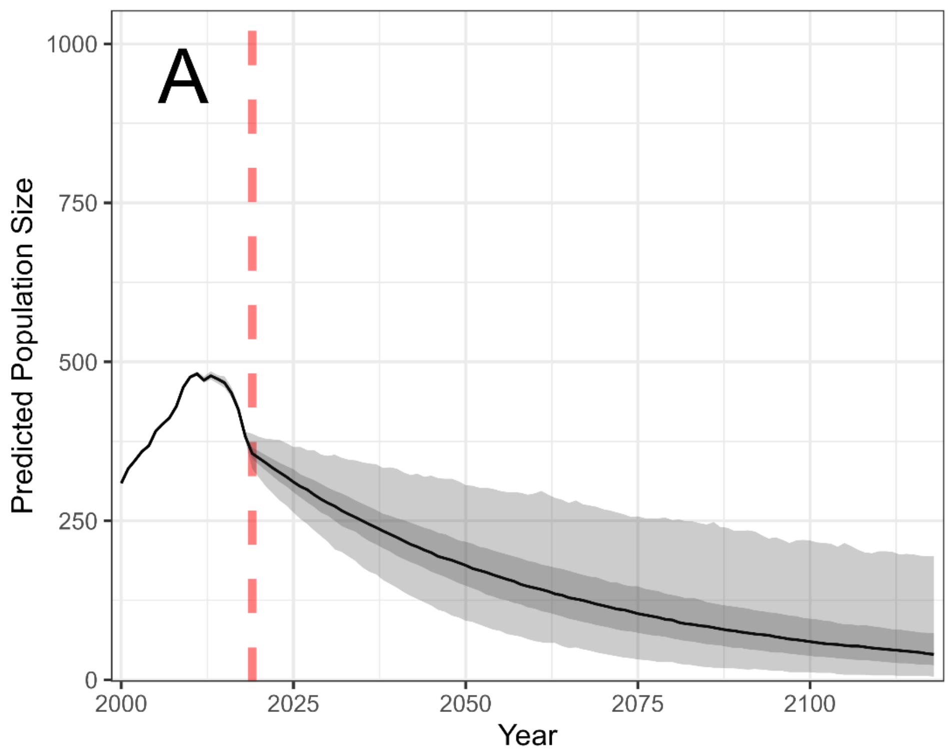
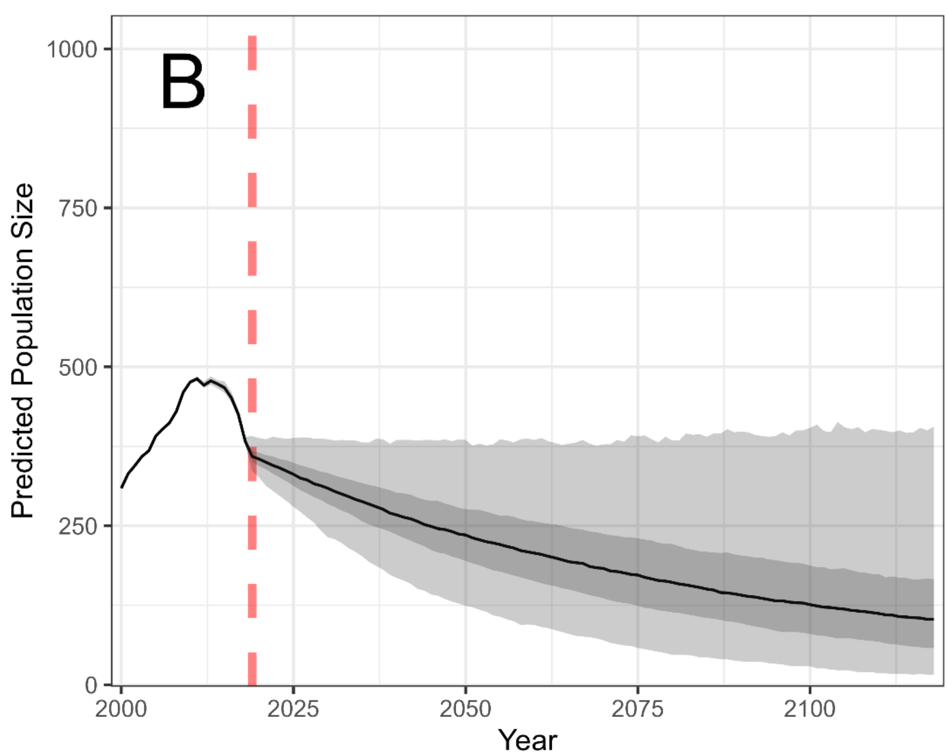


Figure 1: Observed and predicted annual probabilities of calving by North Atlantic right whales (*Eubalaena glacialis*) across relative prey index values for the eastern Gulf of Maine (A, B) and the southwest Gulf of St. Lawrence (C, D), further separated by temporal regime. Observed values (circles) and predictions (lines) are for proven females without severe injuries. Median estimate with 95% credible intervals presented for predictions; circle sizes represent the relative sample sizes for the proportion of observed waiting females that had a calf. Reproduced from Linden et al. (2025).


A
Predicted Population Size
1000
750
500
250
0
2000
2025
2050
2075
2100
Year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Predicted Population Size
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750
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2000
2025
2050
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2100
Year

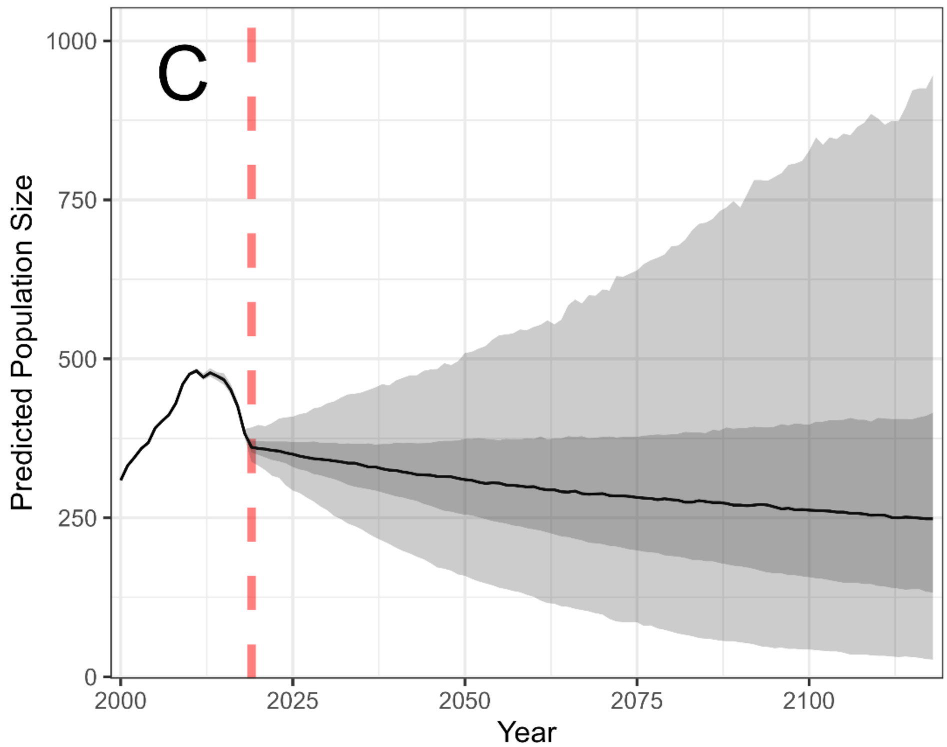


Figure 2: Historical and projected total North Atlantic right whale (NARW; *Eubalaena glacialis*) population size over time, 2001-2119. (A) Baseline 1 scenario (status quo). (B) Baseline 2 scenario (25% entanglement reduction). (C) Baseline 3 scenario (50% entanglement reduction). The period before 2019 (vertical dashed line) shows the historical estimates for the NARW population size; the period after 2019 shows the projections from the population projection model. The bold line shows the median value; the light gray shaded area encompasses the 2.5% and 97.5% quantiles (thus the 95% projection interval) and the dark gray area encompasses the 25% and 75% quantiles (thus the 50% projection interval).

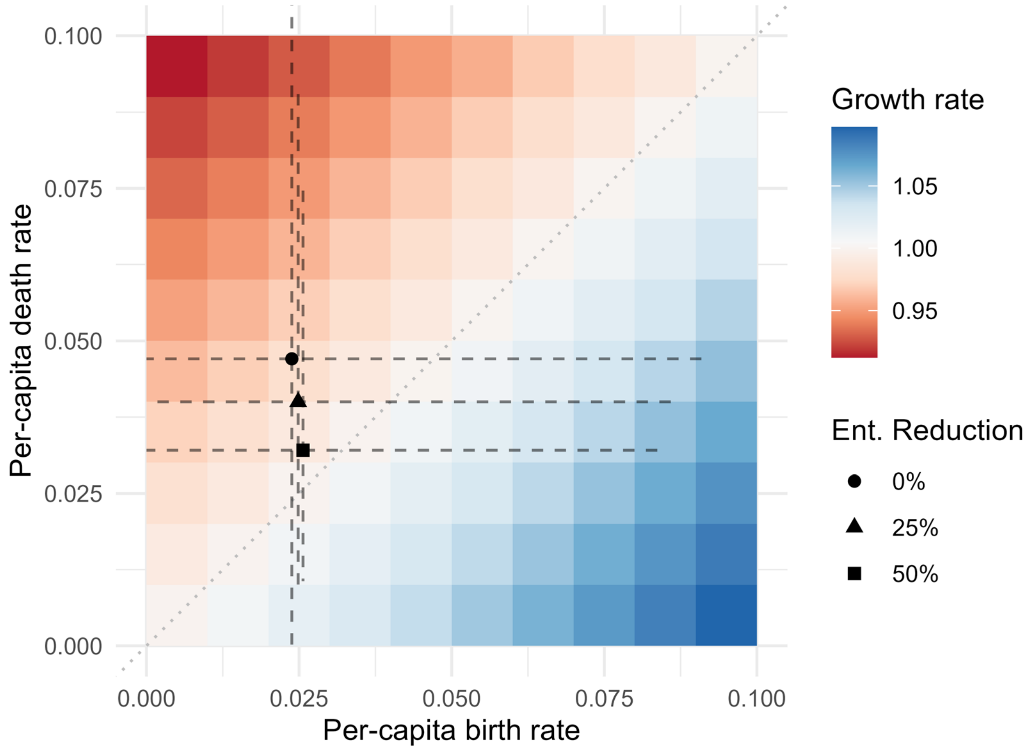
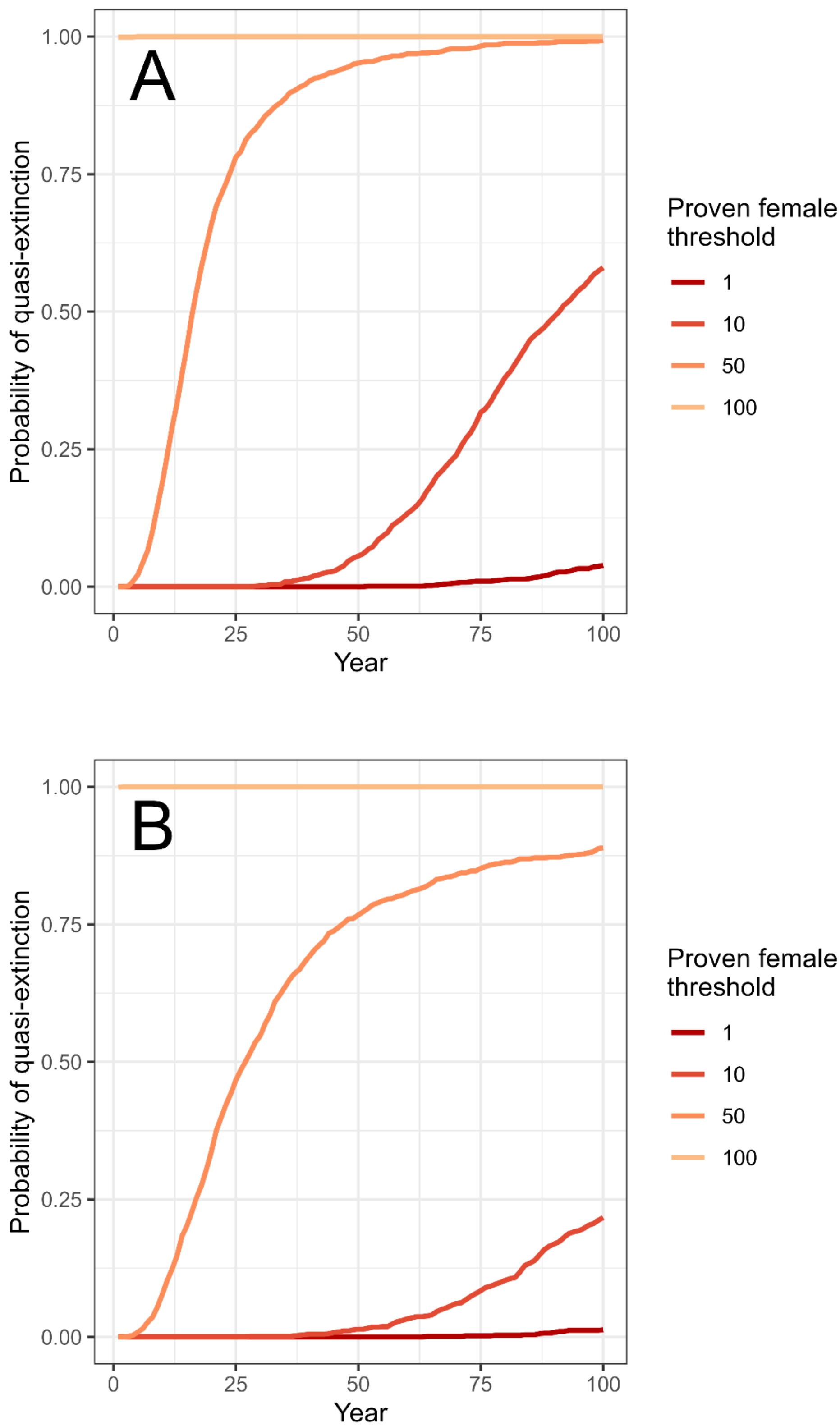


Figure 3: Realized per-capita rates of birth and death for the North Atlantic right whale (*Eubalaena glacialis*), with the resulting growth rates, for each baseline, as represented by the amount of entanglement reduction: baseline 1 (0%), baseline 2 (25%), and baseline 3 (50%). Dashed lines indicate 95-percent credible intervals. Dotted line indicates a growth rate of 1, when birth and death rates are equal.


A
B
Probability of quasi-extinction
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0.75
0.50
0.25
0.00
0
25
50
75
100
Year
Proven female threshold
1
10
50
100

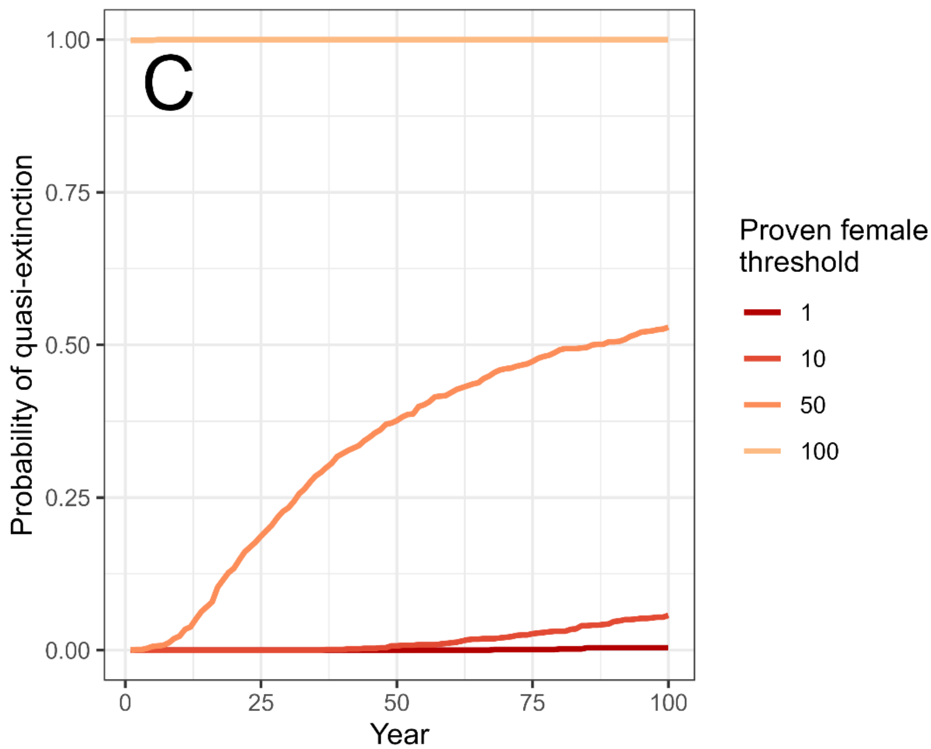

Figure 4: Probabilities of quasi-extinction for proven North Atlantic right whale (*Eubalaena glacialis*) females (individuals known to have produced calves) under various thresholds during the 100-year forward projection. (A) Baseline 1 scenario (status quo). (B) Baseline 2 scenario (25% entanglement reduction). (C) Baseline 3 scenario (50% entanglement reduction).

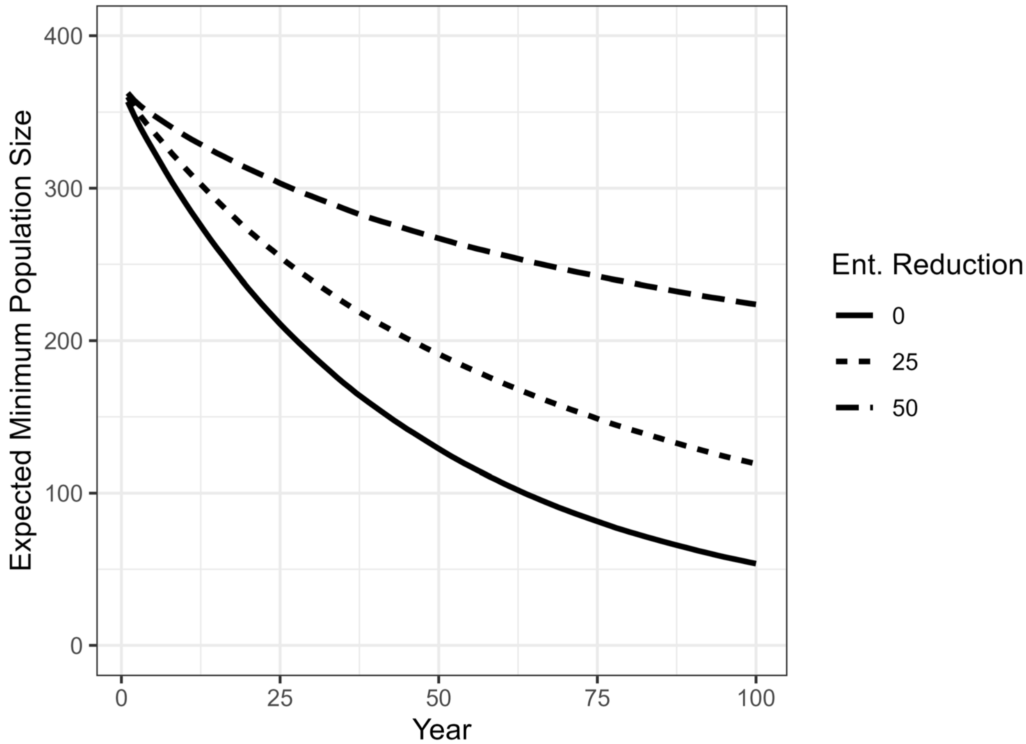

Figure 5: Expected minimum population size for North Atlantic right whales (*Eubalaena glacialis*) females during the 100-year forward projection for each baseline, as represented by the amount of entanglement reduction (Ent. Reduction): Baseline 1 scenario (status quo); Baseline 2 scenario (25% reduction); and Baseline 3 scenario (50% reduction).

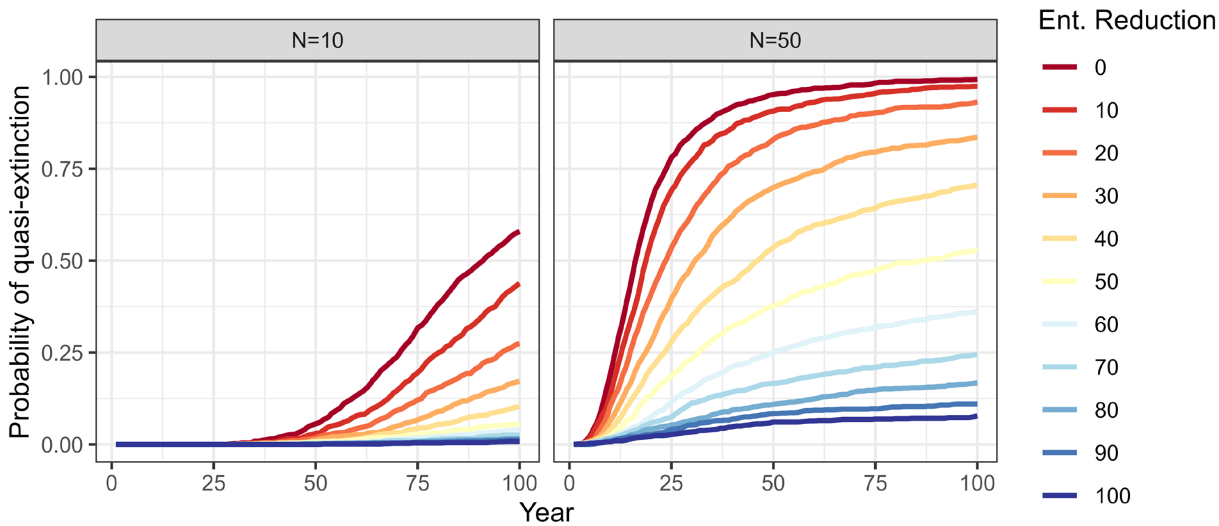

Figure 6: Probabilities of quasi-extinction for proven North Atlantic right whale (*Eubalaena glacialis*) females (individuals known to have produced calves) at thresholds of N=10 and N=50 individuals under various reductions in total entanglement risk.

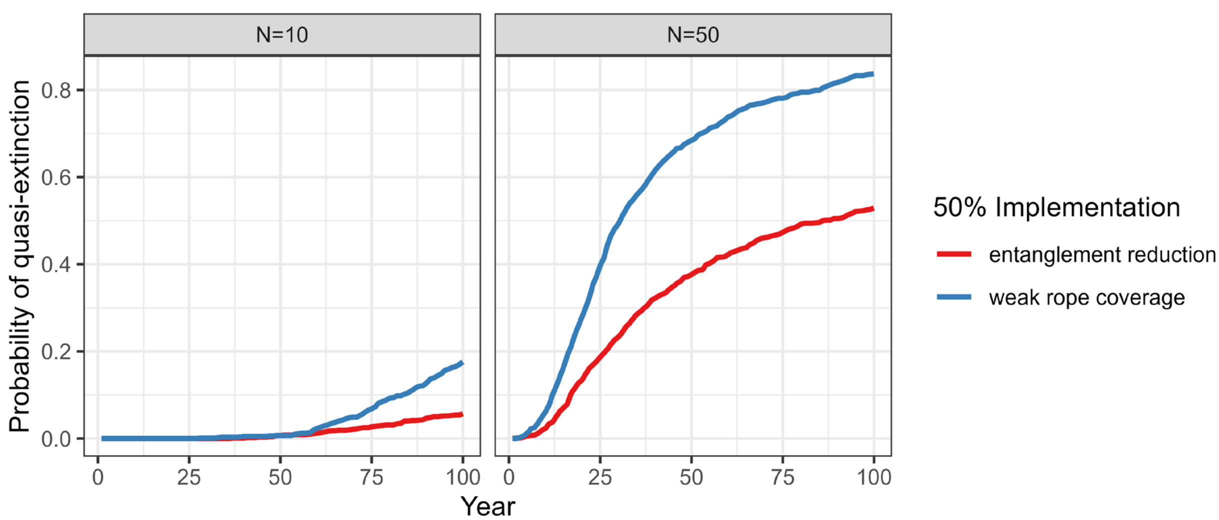

Figure 7: Probabilities of quasi-extinction for proven North Atlantic right whale (*Eubalaena glacialis*) females (individuals known to have produced calves) at thresholds of N=10 and N=50 individuals under a 50% implementation of weak rope coverage or full entanglement risk reduction.

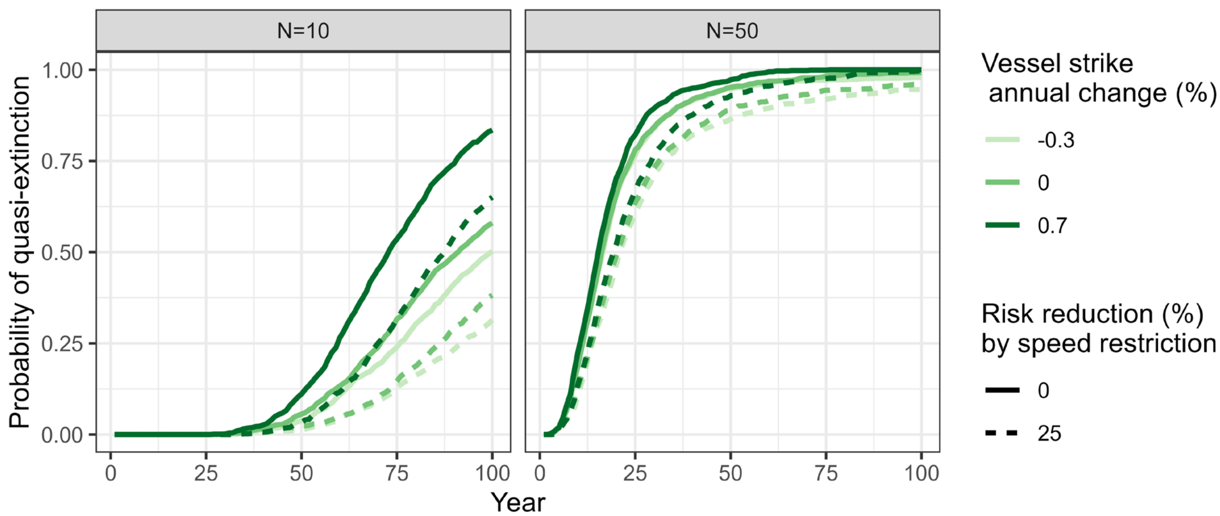

Figure 8: Probabilities of quasi-extinction for proven North Atlantic right whale (*Eubalaena glacialis*) females (individuals known to have produced calves) at thresholds of N=10 and N=50 individuals as a function of the annual rate of change in vessel strike risk and implementation of a speed restriction resulting in 25% reduction in risk, without any reduction of entanglement risk (thus, compare to baseline 1).

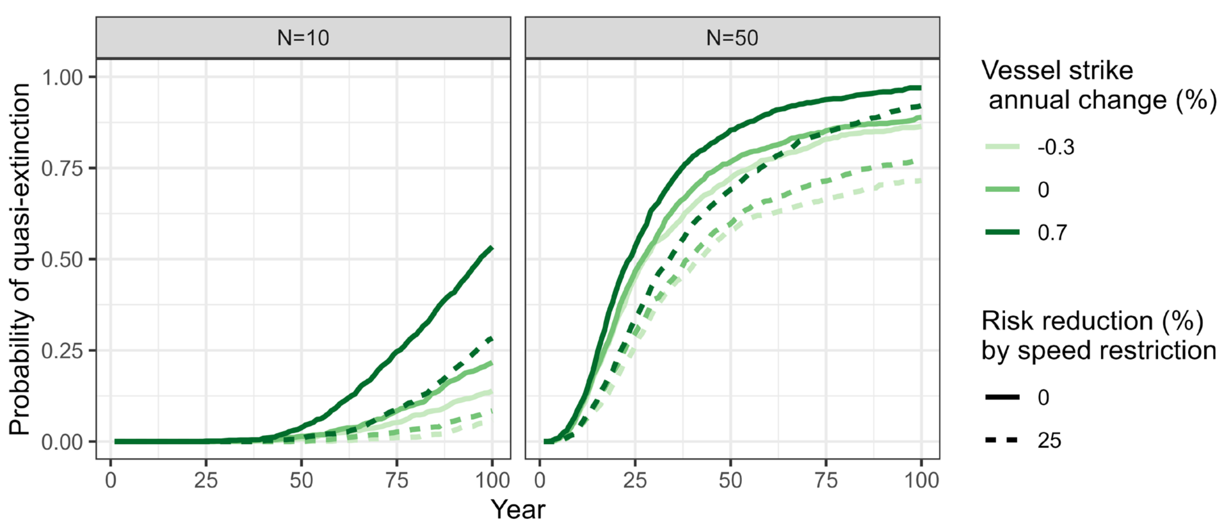

Figure 9: Probabilities of quasi-extinction for proven North Atlantic right whale (*Eubalaena glacialis*) females (individuals known to have produced calves) at thresholds of N=10 and N=50 individuals as a function of the annual rate of change in vessel strike risk and implementation of a speed restriction resulting in 25% reduction in risk, along with a 25% reduction in entanglement risk (thus, compare to baseline 2).

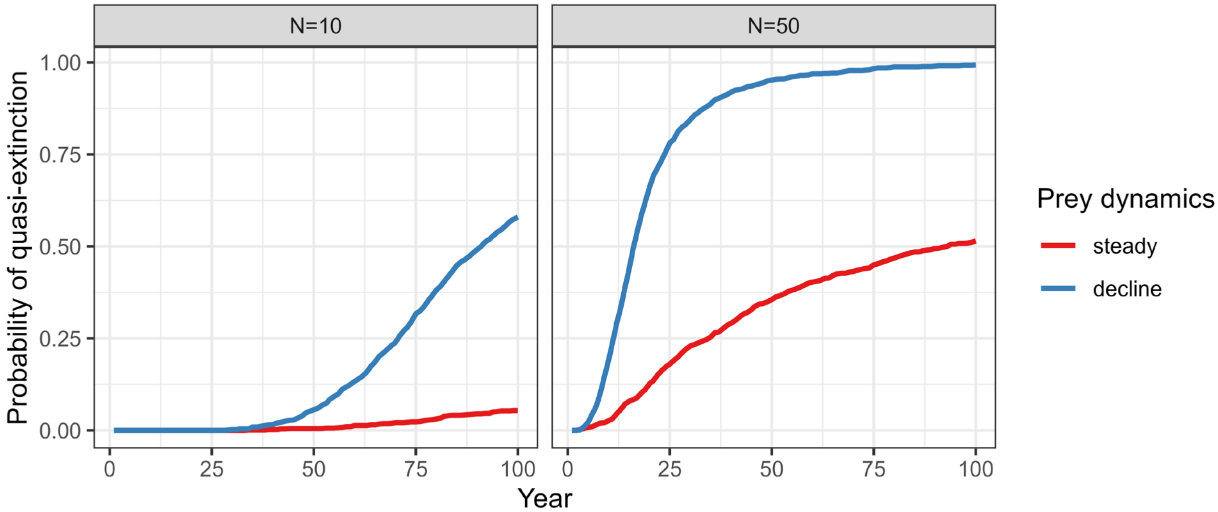

Figure 10: Probabilities of quasi-extinction for proven North Atlantic right whale (*Eubalaena glacialis*) females (individuals known to have produced calves) at thresholds of N=10 and N=50 individuals under two regimes of prey availability dynamics: steady, following historical patterns (1990-2009); and decline, representing post-2010 conditions.

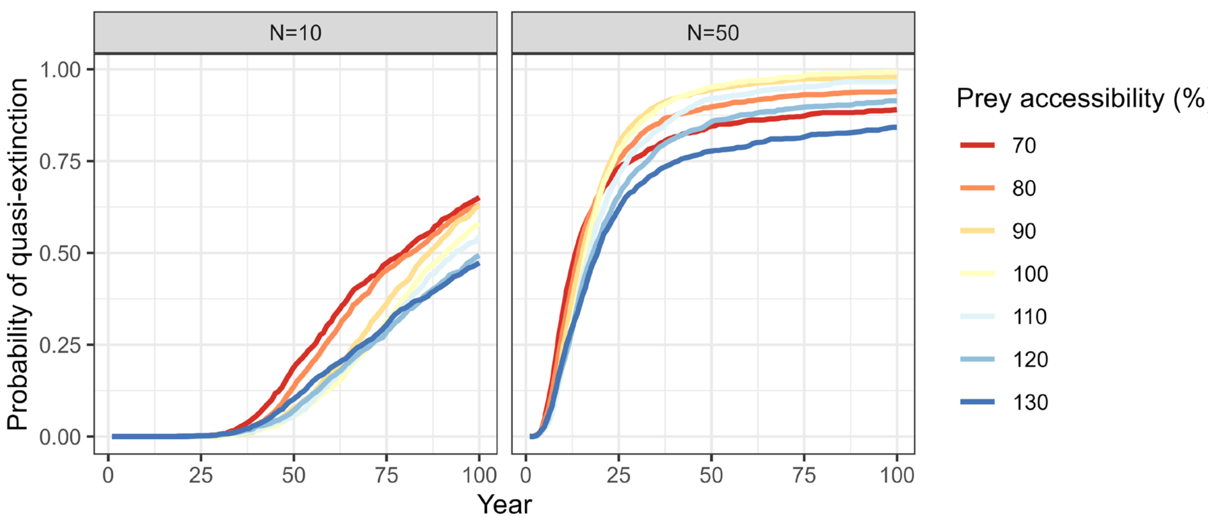

Figure 11: Probabilities of quasi-extinction for proven North Atlantic right whale (*Eubalaena glacialis*) females (individuals known to have produced calves) at thresholds of N=10 and N=50 individuals under various changes in prey accessibility compared to the baseline 1 scenario.

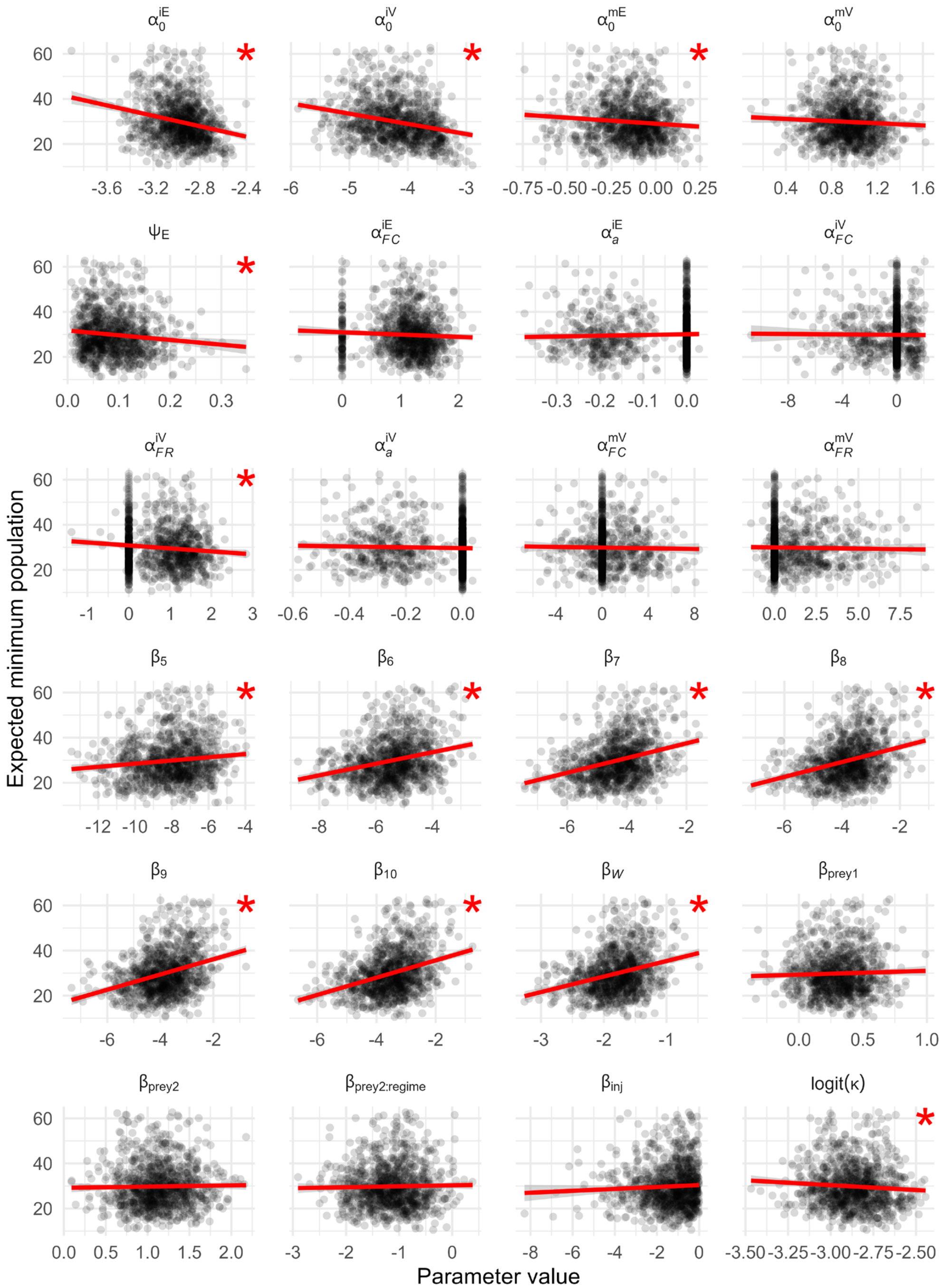

Figure 12: Expected minimum population size for North Atlantic right whales (*Eubalaena glacialis*) as a function of the value of an individual parameter, for each of 1,000 replicates. Red lines represent the estimated regression lines, and red stars indicate regression coefficients deemed notable (p-value ≤ 0.05). Parameter descriptions in Table S1.

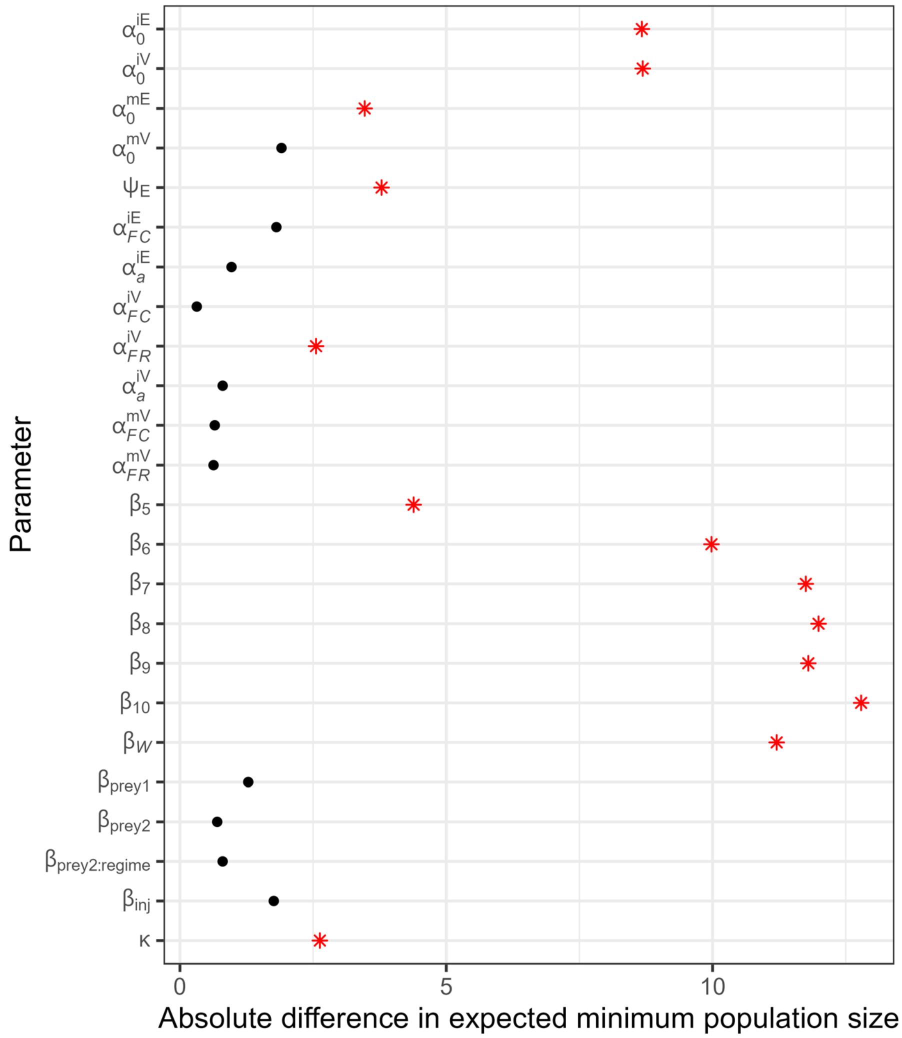

Figure 13: Absolute difference in expected minimum population size for North Atlantic right whales (*Eubalaena glacialis*) between lower and upper 95-percent values for each parameter in the population projection model. Red stars indicate regression coefficients deemed notable (p-value ≤ 0.05). Parameter descriptions in Table S1.

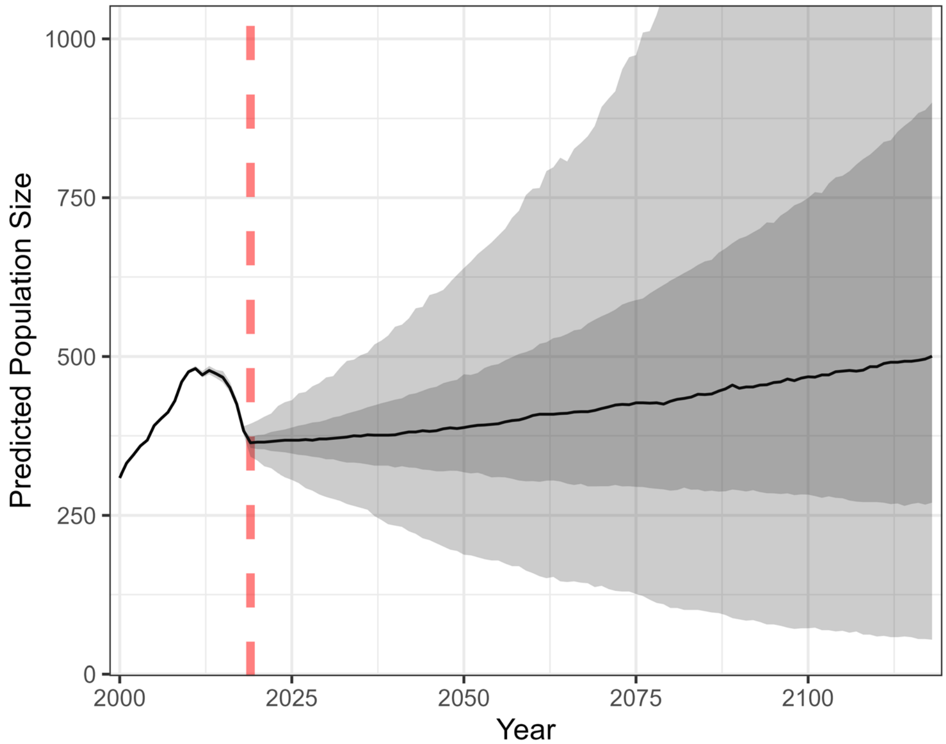

Figure 14: Historical and projected total North Atlantic right whale (NARW; *Eubalaena glacialis*) population size over time, 2001-2119, under a scenario where the rate of severe injury due to entanglement has been reduced by 70% compared to that experienced from 2013-2019. This scenario most closely matches the realized NARW mortality rates experienced from 2020-2022 (Linden, 2024). The bold line shows the median value; the light gray shaded area encompasses the 2.5% and 97.5% quantiles (thus the 95% projection interval) whereas the dark gray area encompasses the 25% and 75% quantiles (thus the 50% projection interval).

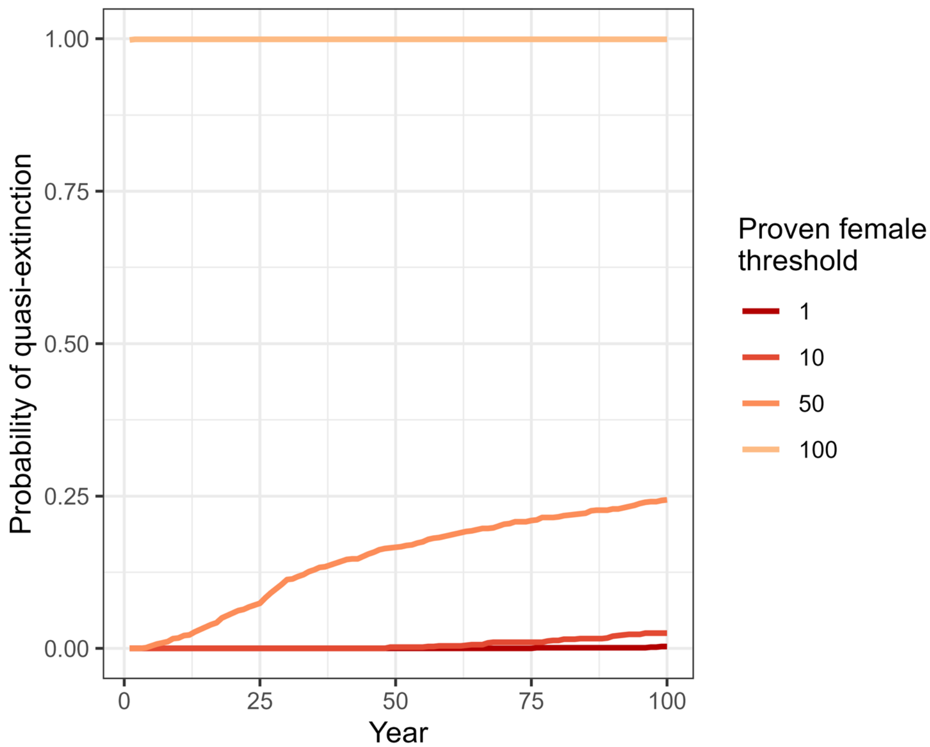

Figure 15: Probabilities of quasi-extinction for proven North Atlantic right whale (NARW; *Eubalaena glacialis*) females (individuals known to have produced calves) under various thresholds during the 100-year forward projection where the rate of severe injury due to entanglement has been reduced by 70% compared to that experienced from 2013-2019. This scenario most closely matches the realized NARW mortality rates experienced from 2020-2022 (Linden, 2024).

TABLES

Table 1. Probabilities of population decline or increase of various magnitudes for North Atlantic right whales (*Eubalaena glacialis*) for each baseline scenario. The first three statistics correspond to metrics used by the International Union for the Conservation of Nature (probability [Pr] of the total population size declining by 30%, 50%, or 80% in 100 years). Also shown are the probability that the population size doubles within 35 years and the probability that the number of mature animals exceeds 1,000 within 100 years.

	Pr(decline over 100 yrs)				
Scenario	30%	50%	80%	Pr(doubling in 35 yrs)	Pr(>1,000 in <100 yrs)
Baseline 1	0.990	0.972	0.762	<0.001	<0.001
Baseline 2	0.922	0.788	0.356	<0.001	0.002
Baseline 3	0.544	0.370	0.088	<0.001	0.004

Table 2. Probabilities (Pr) of quasi-extinction for proven North Atlantic right whale (*Eubalaena glacialis*) females after 100 years at a threshold of 50 individuals under removal of the primary threats to the population.

Threat present?			
Low Prey	Entanglement	Vessel Strike	Pr(Quasi-Extinction)
Present	Present	Present	0.988
Absent	Present	Present	0.524
Present	Absent	Present	0.070
Present	Present	Absent	0.522
Absent	Absent	Present	0.008
Present	Absent	Absent	<0.001
Absent	Present	Absent	0.034
Absent	Absent	Absent	<0.001

REFERENCES

Knowlton A. R., Robbins, J., Landry, S., McKenna, H. A., Kraus, S.D., and Werner, T.B. (2016). Effects of fishing rope strength on the severity of large whale entanglements. Conservation Biology 30:318-328.

Linden, D. W. (2024). *Population size estimation of North Atlantic right whales from 1990–2023.* NOAA Tech Memo NMFS-NE 324. https://doi.org/10.25923/bjn8-kx95

Linden, D. W., Hostetler, J. A., Pace III, R. M., Garrison, L. P., Knowlton, A. R., Lesage, V., Williams, R., and Runge, M. C. (2024a). Quantifying uncertainty in anthropogenic causes of injury and mortality for an endangered baleen whale. *Ecosphere*, *15*(12), e70086. https://doi.org/10.1002/ecs2.70086

Linden, D. W., Pace III, R. M., Garrison, L. P., Hostetler, J. A., Knowlton, A. R., Lesage, V., Williams, R., and Runge, M. C. (2024b). A multistate capture-recapture model to estimate reproduction of North Atlantic right whales. *bioRxiv*. https://doi.org/10.1101/2024.04.13.589367

Linden, D. W., Pace III, R. M., Garrison, L. P., Hostetler, J. A., Knowlton, A. R., Lesage, V., Williams, R., and Runge, M. C. (2025). A multistate capture-recapture model to estimate reproduction of North Atlantic right whales. *Endangered Species Research*. https://doi.org/10.3354/esr01406

Linden, D., Hostetler, J., Pace, R., Garrison, L., Knowlton, A., Lesage, V., Williams, R., and Runge, M. (2023). *NARW population viability analysis* (Version v1.0.1) [Computer software]. Zenodo. https://doi.org/10.5281/zenodo.14945490

Meyer-Gutbrod, E. L., Davies, K. T., Johnson, C. L., Plourde, S., Sorochan, K. A., Kenney, R. D., Ramp, C., Gosselin, J.-F., Lawson, J. W., and Greene, C. H. (2023). Redefining North Atlantic right whale habitat-use patterns under climate change. *Limnology and Oceanography*, *68*, S71–S86.

[NMFS] National Marine Fisheries Service. (2021). *Taking of marine mammals incidental to commercial fishing operations; Atlantic Large Whale Take Reduction Plan regulations; Atlantic Coastal Fisheries Cooperative Management Act provisions; American lobster fishery*. Fed Regist. 86:51970-52024.

Pirotta, E., Schick, R. S., Hamilton, P. K., Harris, C. M., Hewitt, J., Knowlton, A. R., Kraus, S. D., Meyer-Gutbrod, E., Moore, M. J., Pettis, H. M., et al. (2023). Estimating the effects of stressors on the health, survival and reproduction of a critically endangered, long-lived species. *Oikos*, e09801.

Pirotta, E., Tyack, P. L., Durban, J. W., Fearnbach, H., Hamilton, P. K., Harris, C. M., Knowlton, A. R., Kraus, S. D., Miller, C. A., Moore, M. J., et al. (2024). Decreasing body size is associated with reduced calving probability in critically endangered North Atlantic right whales. *Royal Society Open Science*, *11*(2), 240050.

Reed, J., New, L., Corkeron, P., and Harcourt, R. (2022). Multi-event modeling of true reproductive states of individual female right whales provides new insights into their decline. *Frontiers in Marine Science*, *9*, 994481.

Runge, M. C., Linden, D. W., Hostetler, J. A., Borggaard, D. L., Garrison, L. P., Knowlton, A. R., Lesage, V., Williams, R., and Pace III, R. M. (2023). *A management-focused population viability analysis for north atlantic right whales*. NOAA Tech Memo NMFS-NE-304. https://doi.org/10.25923/dqp2-2r71

Runge, M. C., Sanders-Reed, C., Langtimm, C., Hostetler, J., Martin, J., Deutsch, C., Ward-Geiger, L., and Mahon, G. (2017). *Status and Threats Analysis for the Florida Manatee (Trichechus manatus latirostris), 2016*. Scientific Investigations Report 2017-5030. Reston (VA): U.S. Geological Survey. https://doi.org/10.3133/sir20175030

[SCFO] Standing Committee on Fisheries and Oceans. (2023). *Tenth Report: Protection and coexistence of the North Atlantic Right Whale in Canada*. 44th Parliament, 1st Session. Ottawa (Canada): House of Commons. https://www.ourcommons.ca/DocumentViewer/en/44-1/FOPO/report-10

Simard, Y., Roy, N., Giard, S., Aulanier, F. (2019). North Atlantic right whale shift to the Gulf of St. Lawrence in 2015, revealed by long-term passive acoustics. Endangered Species Research 40:271-284.

Sorochan, K., Plourde, S., Morse, R., Pepin, P., Runge, J., Thompson, C., and Johnson, C. (2019). North Atlantic right whale (*Eubalaena glacialis*) and its food:(II) interannual variations in biomass of Calanus spp. On western North Atlantic shelves. *Journal of Plankton Research*, *41*(5), 687–708.

Stewart, J. D., Durban, J. W., Knowlton, A. R., Lynn, M. S., Fearnbach, H., Barbaro, J., Perryman, W. L., Miller, C. A., and Moore, M. J. (2021). Decreasing body lengths in North Atlantic right whales. *Current Biology*, *31*(14), 3174–3179.

Williams, R., Lacy, R. C., Ashe, E., Hall, A., Plourde, S., McQuinn, I. H., and Lesage, V. (2021) Climate change complicates efforts to ensure survival and recovery of St. Lawrence Estuary beluga. *Marine Pollution Bulletin*, *173*, 113096.

APPENDIX

Table S1. Parameters estimated from the retrospective analyses of North Atlantic right whale (*Eubalaena glacialis*) reproduction and mortality that were included in the projection model sensitivity analysis.

Parameter	Description
α_0^{iE}	Log baseline hazard rate for entanglement injury
α_0^{iV}	Log baseline hazard rate for vessel strike injury
α_0^{mE}	Log baseline hazard rate for entanglement mortality
α_0^{mV}	Log baseline hazard rate for vessel strike mortality
ψ_E	Probability of retaining a severe entanglement injury
α_a^{iE}	Coefficient for effect of age on log-scale hazard rate for injury due to entanglement
α_a^{iV}	Coefficient for effect of age on log-scale hazard rate for injury due to vessel strike
α_{FC}^{iE}	Coefficient for effect of being a female with calf on log-scale hazard rate for injury due to entanglement
α_{FC}^{iV}	Coefficient for effect of being a female with calf on log-scale hazard rate for injury due to vessel strike
α_{FR}^{iE}	Coefficient for effect of being a resting female on log-scale hazard rate for injury due to entanglement
α_{FR}^{iV}	Coefficient for effect of being a resting female on log-scale hazard rate for injury due to vessel strike
α_{FC}^{mE}	Coefficient for effect of being a female with calf on log-scale hazard rate for mortality due to entanglement
α_{FC}^{mV}	Coefficient for effect of being a female with calf on log-scale hazard rate for mortality due to vessel strike
α_{FR}^{mV}	Coefficient for effect of being a resting female on log-scale hazard rate for mortality due to vessel strike
β_5	Logit-scale intercept for age 5 calving probability
β_6	Logit-scale intercept for age 6 calving probability
β_7	Logit-scale intercept for age 7 calving probability
β_8	Logit-scale intercept for age 8 calving probability
β_9	Logit-scale intercept for age 9 calving probability
β_{10}	Logit-scale intercept for age 10+ calving probability
β_W	Logit-scale intercept for waiting female calving probability
β_{prey1}	Coefficient for effect of prey index in southwest Gulf of St. Lawrence on calving probability

Parameter	Description
β_{prey2}	Coefficient for effect of prey index in eastern Gulf of Maine on calving probability
$\beta_{prey2:regime}$	Coefficient for interaction effect between the prey index in eastern Gulf of Maine and regime shift in 2010 on calving probability
β_{inj}	Coefficient for effect of severe injury on calving probability
κ	Probability of calf loss in the roughly 6 months between birth and the anniversary date of the model (July 1st)

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