Northeast Fisheries Science Center Technical Memorandum 338

Population size estimation of North Atlantic right whales from 1990-2024

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Summary

This report serves to update the population size estimate of North Atlantic right whales (*Eubalaena glacialis*; hereafter, right whales) for the most recent year of available sightings data. Using an established capture-recapture framework (Pace et al., 2017) and a new calf-integration approach (Linden, 2025), the estimated median population size at the start of 2024 was 384 whales, with a 95% credible interval ranging from 375 to 394. The sharp decrease in the population size observed from 2015-2020 appears to have slowed, although the right whale population continues to experience annual mortalities above recovery thresholds. The updated right whale population estimate will be provided to the Atlantic Scientific Review Group for consideration in the 2026 Atlantic Stock Assessment Review process.

Methods

I used a Bayesian version of a multistate Jolly-Seber capture-recapture model fit to sightings records of right whales to estimate population parameters, including annual abundance and survival. The general approach has been described in detail elsewhere (Pace et al., 2017; Pace, 2021), including a new modification to integrate known births (Linden, 2025). Here, I document the updated data and clarify modeling decisions to improve reproducibility.

Data

The New England Aquarium (NEAq), as data stewards of the North Atlantic Right Whale Consortium (NARWC), provided updated records on 8 September 2025 that included >86,000 sightings of 761 whales observed from 1990 to 2024. Individuals are identified primarily by natural markings (Hamilton et al., 2007) with additional information from genetic sampling (Frasier et al., 2007). The sightings were aggregated by individual into survey years (1 December-November 30) to align with the calving season and the seasonal distribution of survey effort (Pace et al., 2017). Annual capture histories ($y_{i,t}$) contained a binary observation (1 = seen or 2 = not seen) indicating whether an individual (i) was sighted in the given survey year (t), across a total of 35 years.

The capture histories corresponded to a matrix of true states ($z_{i,t}$) with the following definitions: 1 = not yet entered the population; 2 = alive; and 3 = dead. Individuals seen during a survey year were assigned a known alive state ($z_{i,t} = 2$), while those discovered dead were assigned a known dead state ($z_{i,t} = 3$) for the following survey year. Known alive states were also assigned for all survey years between the first and last years with sightings, including for individuals first seen prior to 1990. In addition, any adult whales seen during the 2025 calving season and not seen in 2024 were assigned a known alive state for 2024. Along with sightings of live and dead individuals, those with known birth years were assigned a known state of $z_{i,t} = 1$ for all survey years prior to birth. Any years that were missing evidence of the known state for an individual were assigned as unknown ($z_{i,t} =$ NA). For the terminal year in 2024, there were 14 calves included as potential recruits to the population.

Age and sex were known for 63% and 95% of individuals, respectively. Given a known birth year, individuals were classified each year into 1 of 6 age classes (0,1,2,3,4,5+) to accommodate modeling variation in survival for younger animals. While several options exist to handle unknown ages (Pace, 2021), including explicit modeling of age 0 entry (Hostetter et al., 2021), here I assigned the age at entry to be 5+ (adult age class) for individuals with an unknown birth year, consistent with the original approach (Pace et al., 2017).

Model fitting

The multistate Jolly-Seber capture-recapture model uses a hierarchical formulation to describe probabilities of observations conditional on true states and transitions between states over time (Kéry & Schaub, 2012; Royle & Dorazio, 2012). I used Markov chain Monte Carlo (MCMC) methods for model fitting and directly estimated the partially latent true states across time. By having at least 3 true states, the processes of recruitment and survival could be estimated, in addition to population size. Our state transition matrix was specified as follows:

$$\boldsymbol{\Omega} = \begin{array}{cc} & z_{i,t+1} \\ z_{i,t} & \begin{bmatrix} 1-\gamma_t & \gamma_t & 0 \\ 0 & \phi_{i,t} & 1-\phi_{i,t} \\ 0 & 0 & 1 \end{bmatrix} \end{array}$$

where γ_t is the probability of entry and $\phi_{i,t}$ is the probability of survival. The matrix makes clear which transitions are allowed (e.g., $z_{i,t+1} = 2$ after $z_{i,t} = 1$) and which are not allowed (e.g., $z_{i,t+1} = 2$ after $z_{i,t} = 3$). The observation matrix was defined as follows:

$$\boldsymbol{\Theta} = \begin{array}{cc} & y_{i,t} \\ z_{i,t} & \begin{bmatrix} 0 & 1 \\ p_{i,t} & 1-p_{i,t} \\ 0 & 1 \end{bmatrix} \end{array}$$

where $p_{i,t}$ is the probability of sighting individual i in year t, given the true state $z_{i,t}$.

In this formulation, entry is a removal process given that only available individuals (those not yet entered) can transition into the population (Kéry & Schaub, 2012). The entry probability is typically a nuisance parameter and not directly related to per-capita recruitment, although the realized counts of recruits (i.e., population entries) can be derived from the posterior distributions of true states. Here, I used a birth-integrated Jolly-Seber model (Linden, 2025) to improve the population estimation process and increase accuracy of the terminal year estimate. Annual calf counts (Table 1), with observed losses subtracted from the total observed births, were used to define the expected number of entries for all years $t > 1$. The γ_t entry probabilities were then a function of the expected entries. Calf mortality probability (κ), representing the probability that calves that may have survived the winter calving season but did not recruit to the population, was assumed constant.

I used parameter-expanded data augmentation as part of the MCMC approach to model fitting (Royle & Dorazio, 2012), where the capture history matrix of observed individuals is augmented with a number of additional all-zero capture histories representing potential individuals that were never sighted. Here, I added 300 additional capture histories, resulting in $M = 1061$ total individuals in the $y_{i,t}$ data.

The likelihoods of the true states and the observations conditional on true states were then specified as follows:

$$z_{i,t+1}|z_{i,t} \sim \text{categorical}\left(\Omega_{z_{i,t},1:3}\right)$$

$$y_{i,t}|z_{i,t} \sim \text{categorical}\left(\Theta_{z_{i,t},1:2}\right)$$

To facilitate convenient model fitting, I added a dummy occasion before year 1 where $\Pr\left(z_{i,t} = 1\right) = 1$ for all individuals (Kéry & Schaub, 2012), allowing γ_1 to represent the proportion of M individuals either born in 1990 or already in the population before 1990.

I accommodated individual and temporal variation in survival and sighting probabilities using logit-linear models. For survival probability:

$$\text{logit}\left(\phi_{i,t}\right) = \beta_0 + \beta_{\text{age}} \times \text{Age}_{i,t} + \beta_{\text{female}} \times \text{Sex}_i \times \text{Adult}_{i,t} + \beta_{\text{regime}}\text{I}\left(\text{year}_t > 2010\right) + \epsilon_t^{\phi}$$

Here, β_0 is the average survival probability for $\text{Age}_{i,t}$ = 0 individuals (0.5 year olds); β_{age} is the coefficient for linear change in survival with ages from 1-5; β_{female} is the coefficient of difference in survival for adult females; β_{regime} is the coefficient of difference in survival for years after 2010, representing a climate regime shift; and ϵ_t^{ϕ} is the random effect of year. For sighting probability:

$$\text{logit}\left(p_{i,t}\right) = \alpha_0 + \alpha_{\text{female}} \times \text{Sex}_i + \epsilon_t^p + \epsilon_i^p$$

Here, α_0 is the average sighting probability for males; α_{female} is the coefficient of difference in sighting for females; ϵ_t^p is the random effect of year; and ϵ_i^p is the random effect of individual.

I used vague priors for most parameters including Uniform(0,1) for intercept probabilities, Uniform(-5,5) for regression coefficients, and Uniform(0,10) for random effect standard deviations. To assign a value for individuals with unknown sex, I estimated a general sex ratio according to $\text{Bernoulli}\left(\pi_{female}\right)$ with an informed prior of Beta(5,5). Known states were provided as data during model fitting, and unknown states were initialized as $z_{i,t} = 1$ for all years prior to first sighting and $z_{i,t} = 3$ for all years following the last sighting. Augmented individuals were initialized at $z_{i,t} = 1$ for all years.

I fit the model in R (R Core Team, 2025) using MCMC with NIMBLE (de Valpine et al., 2017, 2022). The MCMC algorithm was run for 25,000 iterations over 3 chains, after a burn-in of 5,000 iterations. Convergence was assessed by examining trace plots and the potential scale reduction factor (R-hat; Brooks & Gelman (1998)), the latter indicating a value of <1.1 for all parameters. Parameter estimates are presented as the median of the posterior distribution followed by upper and lower 95% credible intervals in brackets.

Results

The birth-integrated Jolly-Seber model achieved convergence and exhibited expected patterns of variation regarding sex, age, and temporal characteristics of survival and sighting probabilities (Table 2). There was moderate evidence that females had a lower average sighting probability (α_{female} = –0.254 [–0.523, 0.021]) than males (Figure 1). There was strong evidence of reduced survival for adult females (β_{female} = –0.352 [–0.577, –0.120]) and younger whales (β_{age} = 0.129 [0.046, 0.209]) and for all individuals after 2010 (β_{regime} = –0.666 [–1.080, –0.262]). While post-

2010 survival probability was lower on average, annual fluctuations suggest recent increases in survival between 2020-2023, as compared to the low survival probabilities in 2017 and 2019 (Figure 2).

The probability of unobserved calf mortality (κ) in the first 6 months was estimated at 0.022 [0.001, 0.076]. Given that the 33 observed calf losses (Table 1) were already subtracted as potential recruits in the model, this parameter is meant to represent losses *beyond* those observed. Other model results indicated no evidence of further calf loss beyond those that were observed. Of the 471 total births during 1991-2023 that could yield a potential recruit to the population, 395 were accounted for by individuals with a known birth year in the catalog. For the remaining 76 births, there were 103 individuals first seen after 1990 with an unknown birth year and 26 of those were predicted to have been born in 1990 or earlier. Thus, all entries to the population were accounted for by observed births. Finally, the total recruits during 1991-2023 were estimated to be 473 [466, 479], matching the total observed births during that period. More work is needed to fully understand the role of κ in the birth-integrated model.

The most recent estimate of total population size in 2024 was 384 whales, with a 95% credible interval ranging from 375 to 394. The 60% credible interval, helpful for identifying Nmin as used in calculating the Potential Biological Removal, ranged from 380 to 388. While the long-term population trend continues to be in decline since 2011 (Table 3; Figure 3), the short-term trend is positive. Although some negative bias in the terminal year abundance estimate might be expected (Pace, 2021), this bias should be greatly reduced with the birth-integrated model (Linden, 2025). The initial deployment of the birth-integrated model yielded a 2023 population estimate of 372 [360, 383] right whales, while this year's revised 2023 estimate was 376 [373, 380]; the overlapping uncertainty intervals further support a reduction in bias for the terminal year estimate as a result of the new model formulation.

Given the lower survival for adult females, patterns in sex-specific abundance continue to diverge across time series (Figure 4), as originally noted by Pace et al. (2017). The 2024 estimate included 163 [157, 171] females and 221 [213, 229] males; the number of known reproductive females (with previous evidence of calving) was 72 [70, 75]. Predicted number of deaths continued to be lower from 2020-2023 compared to the highs from 2015-2019 (Table 4; Figure 5); this does not include the additional observed calf deaths (26% of observed calves in 2024), which were animals that did not survive to be included in the model. These annual mortalities are still above the Potential Biological Removal rate identified for right whales (~0.7 deaths per year; Hayes et al. (2022)).

Acknowledgments

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Tables

Table 1: *Count of observed North Atlantic right whale calving events associated with known mothers, including losses due to observed mortality events (either calf or mother) occurring in the first 6 months of the calendar year during 1990-2024.*

Year	Born	Lost
1990	12	0
1991	17	0
1992	12	0
1993	6	0
1994	9	1
1995	7	0
1996	21	2
1997	19	0
1998	5	0
1999	4	0
2000	1	0
2001	31	4
2002	21	0
2003	19	0
2004	16	1
2005	28	1
2006	19	3
2007	23	0
2008	23	2
2009	39	1
2010	19	1
2011	22	2
2012	7	1
2013	20	0
2014	11	1
2015	17	0
2016	14	2
2017	5	0
2018	0	0
2019	7	0
2020	10	2
2021	20	1
2022	15	2
2023	12	1
2024	19	5

Table 2: *Posterior summaries of main parameters from multistate capture-recapture model of North Atlantic right whales from 1990-2024. Parameters include: logit-linear coefficients for sighting probability, including the intercept (α_0) and the effect of individuals being female (α_{female}); logit-linear coefficients for survival probability, including the intercept (β_0), the linear effect of age from 0-5 (β_{age}), the effect of being an adult female (β_{female}), and the regime effect for years after 2010 (β_{regime}); the probability of a whale being female (π_{female}); the probability of calf mortality (κ); the standard deviation of individual variation in sighting probability ($\sigma^{p(i)}$); the standard deviation of temporal variation in sighting probability ($\sigma^{p(t)}$); and the standard deviation of temporal variation in survival probability ($\sigma^{\phi(t)}$).*

Parameter	mean	sd	2.5%	50%	97.5%	Rhat	n.eff
α_{female}	-0.253	0.139	-0.523	-0.254	0.021	1.00	1968
α_0	2.235	0.095	2.053	2.235	2.424	1.00	1743
β_{age}	0.129	0.042	0.046	0.129	0.209	1.00	10073
β_{female}	-0.351	0.117	-0.577	-0.352	-0.120	1.00	12000
β_{regime}	-0.668	0.208	-1.080	-0.666	-0.262	1.00	2548
β_0	3.505	0.206	3.116	3.502	3.913	1.00	6881
π_{female}	0.463	0.019	0.427	0.463	0.500	1.00	12260
κ	0.027	0.020	0.001	0.022	0.076	1.00	6763
$\sigma^{p(i)}$	1.404	0.062	1.289	1.402	1.527	1.01	1580
$\sigma^{p(t)}$	1.022	0.136	0.795	1.007	1.328	1.00	8231
$\sigma^{\phi(t)}$	0.479	0.097	0.314	0.471	0.691	1.00	2189

Table 3: *Posterior summaries of estimated population sizes from multistate capture-recapture model of North Atlantic right whales, including an integration of known calf counts, from 1990-2024.*

	Year	mean	sd	2.5%	50%	97.5%
N[1]	1990	288.88	3.17	283	289	295
N[2]	1991	297.67	3.48	291	298	304
N[3]	1992	305.34	3.22	299	305	312
N[4]	1993	298.91	3.17	293	299	305
N[5]	1994	302.68	2.74	298	303	308
N[6]	1995	304.88	2.57	300	305	310
N[7]	1996	319.63	2.74	315	320	325
N[8]	1997	329.33	2.77	324	329	335
N[9]	1998	329.04	2.59	324	329	334
N[10]	1999	327.65	2.26	324	328	332
N[11]	2000	319.38	1.92	316	319	323
N[12]	2001	346.16	1.70	343	346	350
N[13]	2002	355.40	1.46	353	355	358
N[14]	2003	364.86	1.54	362	365	368
N[15]	2004	372.38	1.61	370	372	376
N[16]	2005	396.43	1.37	394	396	399
N[17]	2006	401.25	1.41	399	401	404
N[18]	2007	413.55	1.16	412	413	416
N[19]	2008	429.71	1.23	428	430	432
N[20]	2009	465.71	1.26	464	466	468
N[21]	2010	476.11	1.82	473	476	480
N[22]	2011	482.80	1.89	479	483	487
N[23]	2012	473.38	2.48	469	473	478
N[24]	2013	481.35	3.06	476	481	488
N[25]	2014	477.01	3.06	471	477	483
N[26]	2015	472.78	4.43	465	473	482
N[27]	2016	457.24	3.64	451	457	465
N[28]	2017	433.93	2.50	430	434	439
N[29]	2018	390.50	1.53	388	390	394
N[30]	2019	380.79	1.30	379	381	384
N[31]	2020	359.12	1.40	357	359	362
N[32]	2021	371.48	1.17	370	371	374
N[33]	2022	373.74	1.40	371	374	377
N[34]	2023	376.13	1.70	373	376	380
N[35]	2024	384.27	4.91	375	384	394

Table 4: *Posterior summaries of estimated deaths from multistate capture-recapture model of North Atlantic right whales from 1990-2024. Note that these deaths do not include early calf losses (<6 months).*

	Year.range	**mean**	**sd**	**2.5%**	**50%**	**97.5%**
Nd[2]	1990-1991	5.87	1.65	2	6	9
Nd[3]	1991-1992	3.44	1.49	1	3	7
Nd[4]	1992-1993	12.89	2.17	9	13	17
Nd[5]	1993-1994	5.10	1.70	2	5	9
Nd[6]	1994-1995	3.31	1.16	2	3	6
Nd[7]	1995-1996	6.51	1.52	4	6	9
Nd[8]	1996-1997	9.26	1.75	6	9	13
Nd[9]	1997-1998	4.78	1.55	2	5	8
Nd[10]	1998-1999	9.84	1.92	6	10	14
Nd[11]	1999-2000	9.00	1.73	6	9	13
Nd[12]	2000-2001	5.91	1.19	4	6	9
Nd[13]	2001-2002	9.85	1.22	7	10	12
Nd[14]	2002-2003	10.53	1.52	7	11	13
Nd[15]	2003-2004	8.06	1.63	5	8	11
Nd[16]	2004-2005	4.68	1.35	2	5	8
Nd[17]	2005-2006	11.91	1.44	9	12	15
Nd[18]	2006-2007	8.87	1.30	7	9	12
Nd[19]	2007-2008	5.71	1.12	4	6	8
Nd[20]	2008-2009	3.19	0.93	1	3	5
Nd[21]	2009-2010	8.68	1.60	6	9	12
Nd[22]	2010-2011	13.16	1.63	10	13	16
Nd[23]	2011-2012	15.58	2.32	11	16	20
Nd[24]	2012-2013	9.71	2.57	5	10	15
Nd[25]	2013-2014	11.95	2.83	7	12	18
Nd[26]	2014-2015	17.13	4.15	9	17	25
Nd[27]	2015-2016	28.68	4.64	20	29	38
Nd[28]	2016-2017	28.48	3.67	22	28	36
Nd[29]	2017-2018	43.42	2.65	39	43	49
Nd[30]	2018-2019	16.75	1.62	14	17	20
Nd[31]	2019-2020	29.83	1.53	27	30	33
Nd[32]	2020-2021	5.66	1.15	4	6	8
Nd[33]	2021-2022	10.86	1.28	9	11	14
Nd[34]	2022-2023	6.77	1.33	4	7	9
Nd[35]	2023-2024	5.20	2.81	1	5	11

Figures

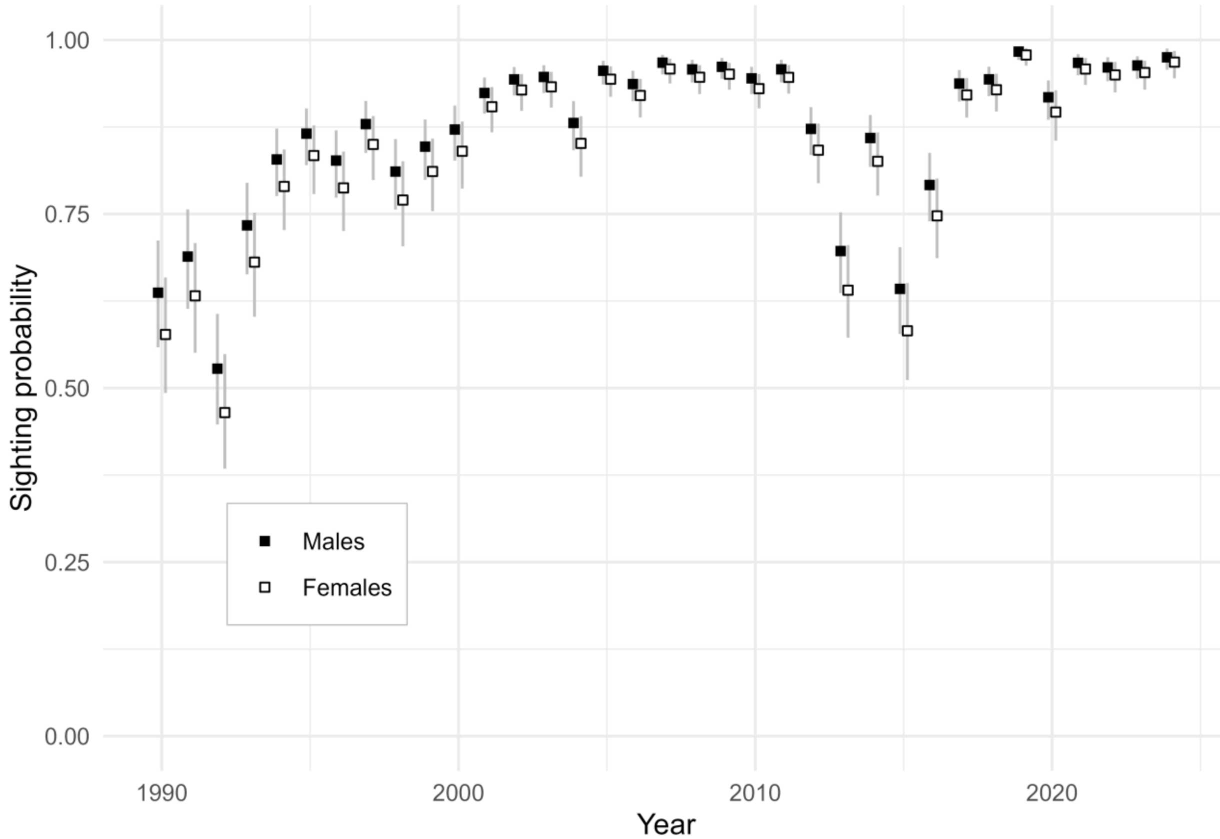

Figure 1: *Sighting probabilities for North Atlantic right whales (Eubalaena glacialis) estimated from a Bayesian capture-recapture model of sightings data from 1990–2024.*

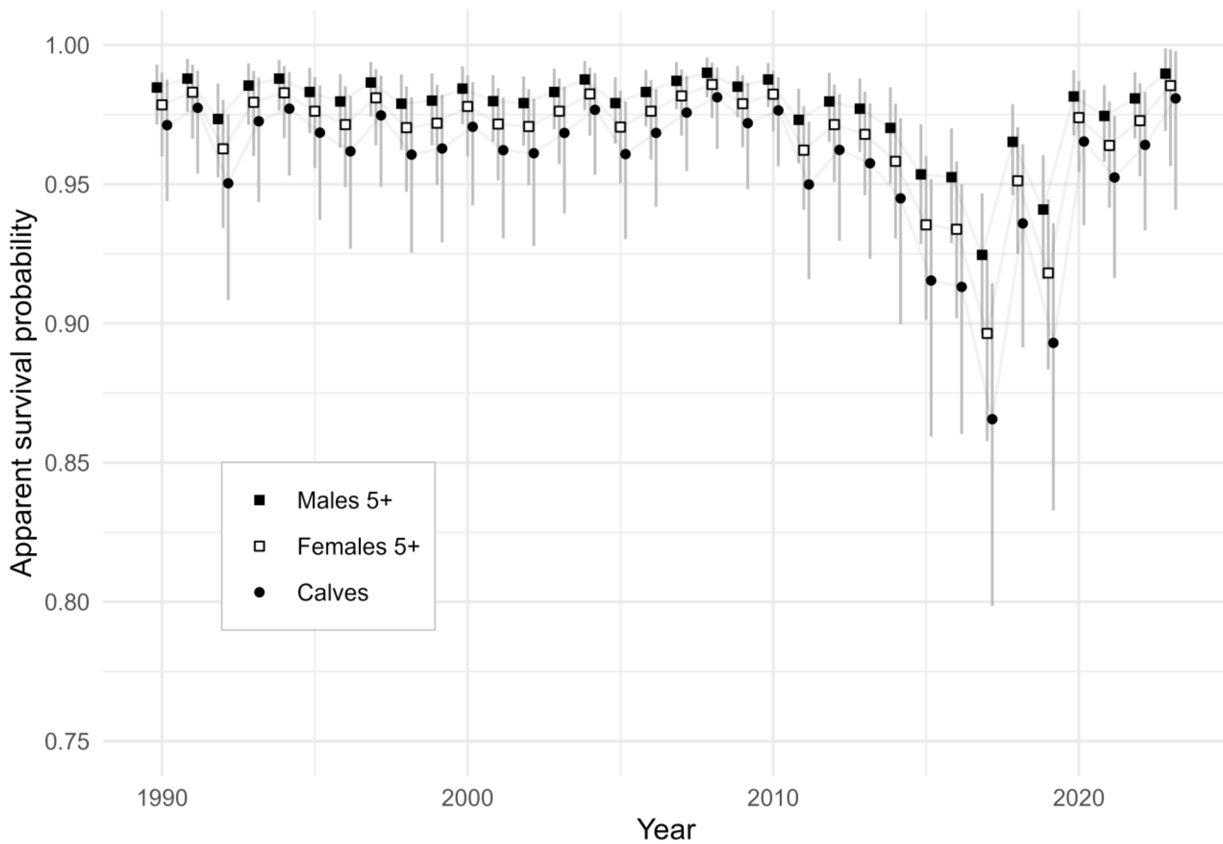

Figure 2: *Apparent survival probabilities for North Atlantic right whales (Eubalaena glacialis) estimated from a Bayesian capture-recapture model of sightings data from 1990-2024.*

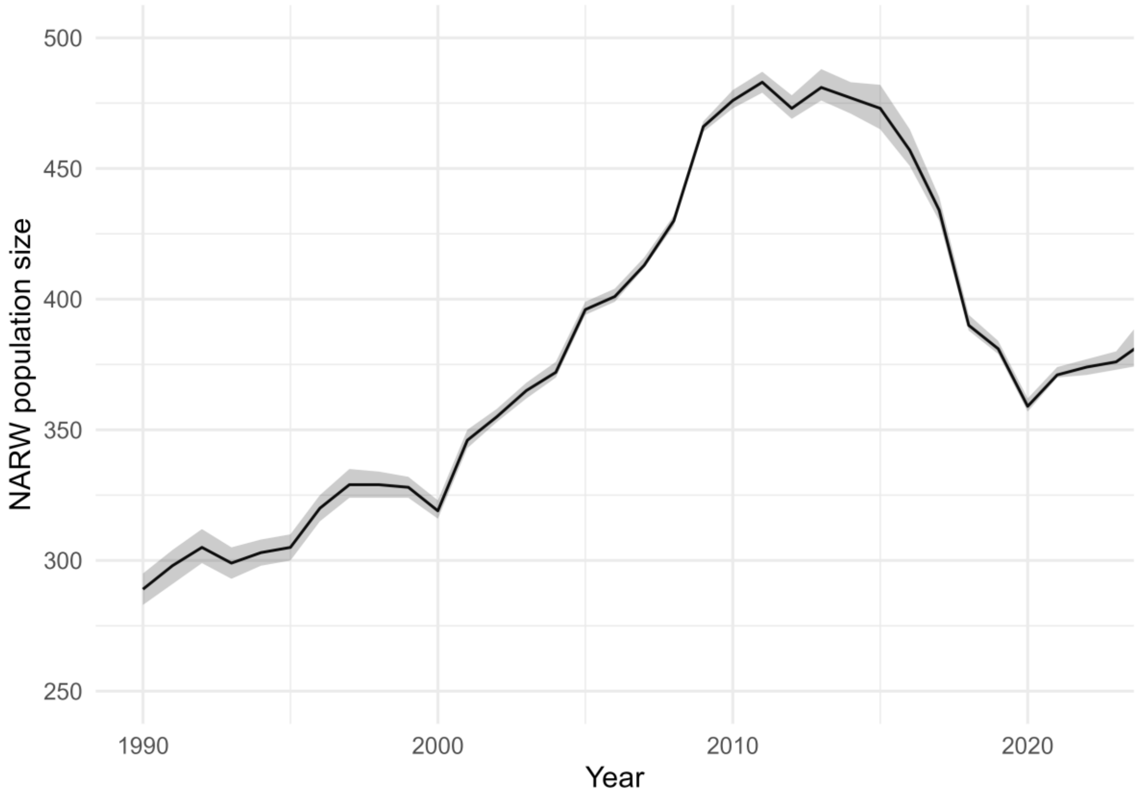

Figure 3: *Population size of North Atlantic right whales (Eubalaena glacialis) estimated from a Bayesian capture-recapture model of sightings data, including an integration of known calf counts, from 1990–2024. Solid line indicates median of posterior distribution, with shading for the 95% credible interval.*

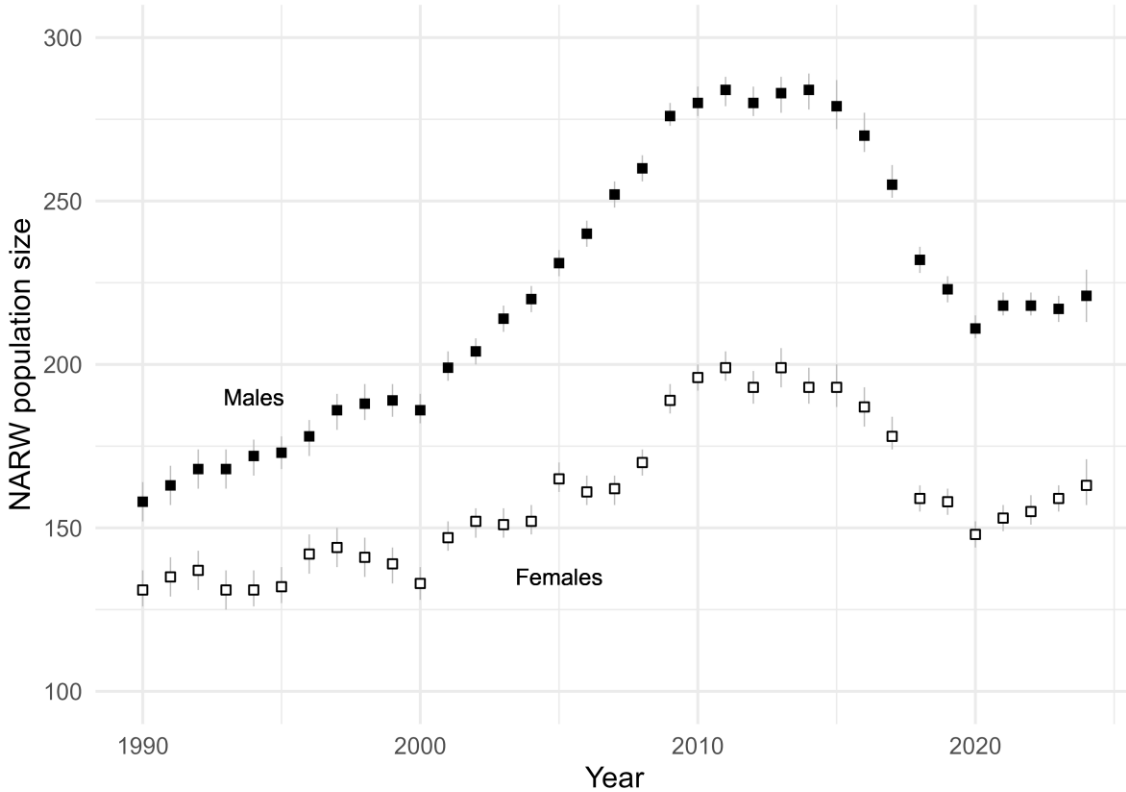

Figure 4: *Median abundance (with 95% credible intervals) of female and male North Atlantic right whales (Eubalaena glacialis) estimated from a Bayesian capture-recapture model of sightings data from 1990–2024.*

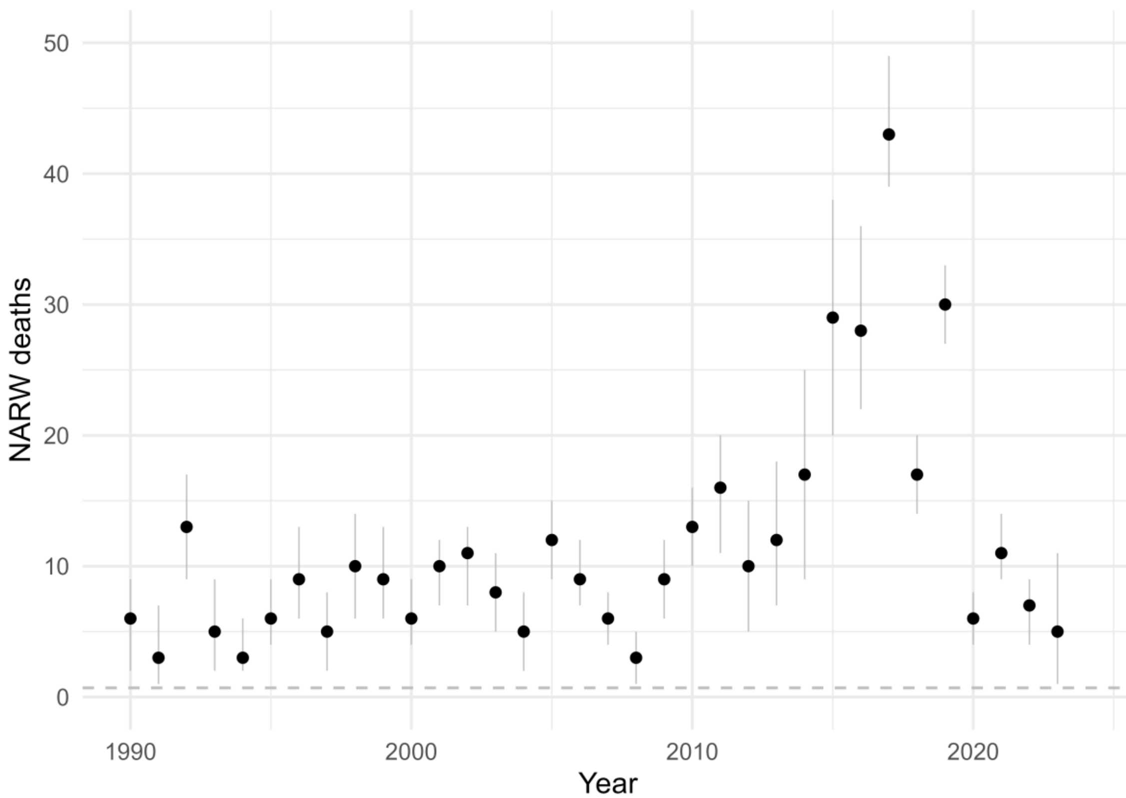

Figure 5: *Median deaths (with 95% credible intervals) of North Atlantic right whales (Eubalaena glacialis) estimated from a Bayesian capture-recapture model of sightings data from 1990–2024. Note: these deaths do not include early calf losses (< 6 months). Dashed line indicates value of Potential Biological Removal (0.7).*

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