Assessing the effects of the historical use of implantable tags on North Atlantic right whale health, survival, and reproduction

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Objective

The objective of this effort was to assess the occurrence and magnitude of the effects of implantable tags deployed in the past on the health, survival, and reproduction of individual North Atlantic right whales (NARW; *Eubalaena glacialis*), using an existing model for the Population Consequences of Multiple Stressors (PCoMS) for this species. These analyses were requested by the U.S. Marine Mammal Commission, following a NARW tagging workshop sponsored by the U.S. Marine Mammal Commission, National Marine Fisheries Service, Office of Naval Research, and the Canadian Department of Fisheries and Oceans (September 2023; Marine Mammal Commission (2024)).

Methodology

The analysis was based on the existing PCoMS model for NARW (Pirotta *et al.*, 2023). Briefly, this is a Bayesian state-space model for the survival and calving probability of individual whales as a function of their health status at a three-month time scale. A set of intrinsic (lactation and juvenile status) and extrinsic (occurrence of vessel strike or entanglement, and a proxy for prey abundance) variables are modelled to affect underlying health. The model is informed using 1970-2019 data provided by the NARW Consortium (www.narwc.org/narwc-databases.html), comprising individual sightings, health scores from a visual health assessment, known deaths, information on sex, age class and calving, and records of anthropogenic traumas. Recently, the model has been extended to include a component for individual length, informed by photogrammetric length measurements from drones and affecting female calving probability (Pirotta *et al.*, 2024).

Here, we incorporated information on the deployments of two types of implantable tags (type A and type C) from the late 1980s until 2001 on specific individuals in the NARW photo-identification catalogue. The data were compiled and provided by Dr Amy Knowlton at the New England Aquarium, using information derived from the NARW Consortium database. The two tag types are described in Kraus *et al.* (2000), Mate *et al.* (2007), and Mate *et al.* (1997), and each corresponds to a range of tag designs (also described in those publications). Details of the tag type and design for each deployment included in this work were provided in the spreadsheet received from the New England Aquarium and are reported in the Appendix to this report.

We modelled the effect of tag deployment on underlying health at the time of implantation, in addition to the other stressors already included in the model (model v1). We then investigated whether this effect depended on tag type, because of the differences in tag design and potential impact between the two types (model v2). Given the uncertainty on the duration of tag attachment (because satellite transmission can stop before the tag detaches from the body of the animal), we only modelled the effect of tagging on the individual's health state in the time step where deployment occurred. However, the coarse temporal resolution of the model (three months) implies that any effect could be protracted over that time window. Moreover, underlying health is autocorrelated over time, i.e., health in one time step depends on health in the previous time step. As a result, an individual may take multiple time steps to recover from a decline in its health. Finally, if the tag had a continued, detectable effect on health throughout the duration of the deployment, this would be reflected in a stronger estimated effect at deployment (as evidenced by previous analysis of the effects of entanglements and vessel strikes).

In the model, survival probability emerges from a direct transformation of health; therefore, any effect on health is converted into the corresponding change in survival probability at a three-month and annual scale (see Pirotta *et al.* (2023) for details). Calving probability in a year when a female is available to reproduce also depends in the model on the female's health. However, Pirotta *et al.* (2023) showed that only approximately 20% of the variation in calving probability is explained by the health metric in the model, while Pirotta *et al.* (2024) demonstrated that the majority of its variation can be captured by including an effect of body length on calving probability. Therefore, we also tested whether tagging had a direct effect on calving probability that was not mediated by a change in the health metric. First, we assessed the effect of any tagging prior to a potential calving opportunity on the asymptote of the sigmoid relationship between a female's health and her calving probability (i.e., the effect of tagging on her maximum calving probability; see Pirotta *et al.* (2023) and Pirotta *et al.* (2024) for details of this implementation; model v3). Next, we investigated whether having been tagged in the year immediately prior to a potential calving opportunity had any effect on the probability of calving in that year (model v4). These two analyses were also repeated by tag type (model v5 and v6).

It should be noted that the model currently cannot be used to evaluate the interactive effects of multiple stressors on health or vital rates. Therefore, the present analysis could only assess the occurrence of any additive effect of tagging. Moreover, this analysis was by nature retrospective, i.e., it investigated the occurrence of any effects of past deployments (using the tags available at that time) but could not provide predictions of the effects of future deployments. The analytical approach underpinning this investigation was discussed with researchers at the New England Aquarium and the Marine Mammal Commission Scientific Program Director prior to running any analysis; standard model diagnostics were used to ensure that the model mixed and converged appropriately (please refer to details in Pirotta *et al.* (2023)).

Analyses of observational data, such as those used here, are subject to potential confounding factors—for example, if there was a general decline in individual health during the time the tags were deployed, then this could incorrectly be interpreted as a tag effect. To assess the potential for confounding we undertook a set of exploratory analyses.

We first created three simulated datasets, where tagging events were allocated to alternative individuals in the population that matched the characteristics of tagged animals. Specifically, for each tagged individual, we selected three separate control individuals of the same sex and age class (adult, juvenile, or calf), and allocated a simulated tagging event within ±2 years of the real tag deployment (constrained between 1988 and 2001, i.e., the first and last year of tagging). The three resulting datasets were completely independent, i.e., no control individual was shared among them. We also made sure that the number of individuals tagged multiple times was the same as in the real dataset. In these simulated datasets, true tagged individuals were considered non-tagged. With each of these three simulated datasets, we repeated the analysis investigating the effect of tagging on health (models v1 and v2). If an effect is detected on the real datatset but not on the simulated datasets, then this means the effect is unlikely to be due to confounding factors.

Secondly, we compared the tagged cases with the matched controls in terms of time between tagging event and last sighting (which is a proxy for survival), time to next calving event after tagging and number of calves born between the tagging event and the last sighting. If these metrics are on average worse for tagged animals than controls, then this supports that any detected effect is not due to confounding.

Results and Discussion

There were 75 tags deployed on 70 individual NARWs between 1988 and 2001, 33 of type A and 42 of type C. Of the 70 individuals, 41 were females and 28 were males, while the sex was unknown for 1. Of the 75 total deployments, 38 tags were deployed on adults, 23 on juveniles, 2 on calves, and 12 on individuals of unknown class (but treated as juveniles when selecting matching controls; note that, in some cases, an individual's age class changed between different tag deployments). All parameter estimates reported below are posterior medians followed by 95% equal-tailed credible intervals (CI) in square brackets. Where 95% CIs of the estimated effect of tagging on health include 0, we interpret this as lack of evidence for an effect, given the data and model used.

The estimated effect of tag deployment on health (irrespective of tag type; model v1) was centred on a negative value and the 95% CI showed a small overlap with 0 (-0.071 [-0.146, 0.004]); however, the analysis by tag type (model v2) highlighted that only tags of type A had an estimated effect with a 95% CI that did not overlap with 0 (-0.138 [-0.257, -0.023] for tag A, vs. -0.028 [-0.127, 0.069] for tag C). The estimated decrease in health in the time step of tag A deployments corresponded to a median hazard ratio of 0.87. In practice, for an individual in good health (e.g., with 3-month survival probability of 0.995), being tagged with a tag of type A corresponded to a decrease in 3-month survival probability to 0.990 [0.983, 0.994]; whereas for an individual in poor health (e.g., with 3-month survival probability of 0.900), being tagged with a tag of type A corresponded to a decrease in 3-month survival probability to 0.865 [0.831, 0.895]. In terms of annual survival probability, this corresponded to a decrease from 0.980 to 0.961 [0.935, 0.978], and from 0.656 to 0.561 [0.478, 0.640], respectively.

For comparison, the effect of the deployment of a tag of type A on health was estimated to be about 0.6 times the effect of a vessel strike resulting in a shallow wound (which was -0.217 [-0.405, -0.033]), and about 0.3 times the effect of a severe entanglement (which was -0.486 [-0.550, -0.423]).

The 95% CI of the estimated effect of tag deployment on the asymptote of calving probability (irrespective of tag type) overlapped with 0, both when considering tag deployment at any point prior to a calving opportunity (model v3; -0.193 [-0.593, 0.228]) and when considering tag deployment at the year prior to a calving opportunity (model v4; 0.130 [-1.262, 1.506]). The 95% CI of the estimated effects also overlapped with 0 when conditioning by tag type (model v5: tag A -0.478 [-0.996, 0.038], and tag C 0.136 [-0.371, 0.679]; model v6: tag A 0.384 [-1.197, 2.040], and tag C -0.212 [-1.827, 1.353]). However, we note that the effect of being tagged with a tag of type A in model v5 has a probability of 0.97 of being negative. The median effect would correspond to a decrease in maximum calving probability for the average female in a year when she is available to reproduce from 0.3 to 0.21.

Rerunning models v1 and v2 using the first and third simulated sets of controls (i.e., alternative individuals of the same sex and age class, assumed to have been tagged in the same period as the true tagged individuals) resulted in an estimated effect of tagging that was centred on a positive value and/or largely overlapped with 0, both when ignoring tag type and when modelling a separate effect for tags of type A and C (Table 1). Using the second simulated set of controls, the effect of any tag deployment on health was negative, with a 95% CI that did not overlap with 0, while the effects by type were both centred on a negative value and showed some small overlap with 0 (Table 1). We investigated this set of controls and found that 4 of the randomly selected matched controls for tag A (vs. 3 in the real data) and 5 of the matched controls for tag C (vs. 3 in the real data) were last seen in the time step of simulated deployment, which likely contributed to the estimated effect of these pseudo-deployments. There is not a sufficient number of potential control individuals to support further replication of the case-control exercise and quantify the false positive rate, but this result highlights the issues associated with a small sample size. Overall, we interpret these results as an indication that the estimated effect of tagging was unlikely to be the result of some other factor affecting health and survival during the tagging period, but there is a chance that animal deaths have occurred in conjunction with, but not due to, the tag deployments, contributing to the estimated effect as in the second test dataset.

***Table 1**. Results of the test models run on the simulated datasets, where tag deployments were assigned to a set of control animals.*

Test dataset	Model version	Estimated effect(s) on health
1	v1	0.053 [-0.047, 0.149]
1	v2	tag A: -0.049 [-0.207, 0.107] tag C: 0.116 [-0.01, 0.243]
2	v1	-0.116 [-0.218, -0.017]
2	v2	tag A: -0.115 [-0.271, 0.044] tag C: -0.114 [-0.249, 0.021]

Test dataset	Model version	Estimated effect(s) on health
3	v1	0.044 [-0.052, 0.139]
3	v2	tag A: 0.021 [-0.163, 0.209] tag C: 0.053 [-0.058, 0.165]

It is possible that not all individuals were affected by tag deployment to the same extent. The trajectories of the estimated health of different tagged individuals illustrate this variability: in some cases, tagging was indeed associated with a change in the visual health assessment variables that are used to inform the underlying health metric (e.g. Fig. 1a); in others, the drop in health was imposed by the model on the trajectory, despite the lack of evidence for an effect in the data (e.g. Fig. 1b); finally, in some cases tag deployment coincided with exposure to other extrinsic or intrinsic stressors that may have confounded its effect (e.g., a calving event; Fig. 1c). The estimated effect of tagging on health is averaged across all tagging events and over this variation. Factors that could have contributed to a differential impact include attachment duration (e.g., days vs. weeks), the tag breaking after deployment, variable implantation angle and depth, or simply a different physiological reaction by different animals. Some of this deployment-specific information is available in the NARW Consortium database, and could be used in further qualitative analyses of each tagging event.

Figure 1: *Time series of data streams (top panel) and estimated health (black line and grey ribbon in bottom panel, reporting the posterior mean and standard deviation) for three NARW individuals. Health is the complementary log-log transformation of survival probability at the three-month scale (for reference: health values of 2.5 and 0 correspond to survival probability > 0.999 and 0.63, respectively). The estimated time of death (i.e., posterior median survival = 0) is represented as a red dot along the health time series, where available. Entanglement events are represented by a dot followed by a segment indicating the estimate of most likely duration over which the gear remained attached to an animal (coloured by severity). Vessel strikes are indicated by a star in the same interval in which the injury was detected (coloured by injury type). Calving events are represented as segments covering the lactation period. Scores for the four visual health assessment variables (body condition, skin condition, rake marks and cyamid presence) were averaged and rounded over a three-month interval for plotting. Each plot also reports the individual number from the North Atlantic Right Whale Catalog (http://rwcatalog.neaq.org) and the sex. Tagging events with a tag of type A are reported as a green dot along the health trajectory.*

Comparisons between tagged individuals and matched controls are reported as medians, followed by the range in square brackets. Please note that, given that only tags of type A had an estimated effect with a 95% CI that did not overlap with 0 in the analysis described above, comparisons were limited to individuals instrumented with tags of this type and their matched controls.

The comparison of the time between tag deployment and last sighting (as a proxy for survival) indicated that, on average, control individuals tended to be seen for longer after the tagging time step, but with large variation among individuals (18 [0, 30.2] years for tagged individuals vs. 21.8 [0, 30.2] years for controls; Fig. 2). In particular, 73% of tagged individuals were known to be alive 5 years after the tagging date, as opposed to 85% of control individuals, which corresponded approximately to an additional 4 possible deaths. Moreover, of the tagged individuals, 3 were not sighted after the three-month interval in which they were tagged (corresponding to 9% of individuals, vs. 8% of individuals not seen after the three-month interval in which tag deployment was simulated in the matched controls).

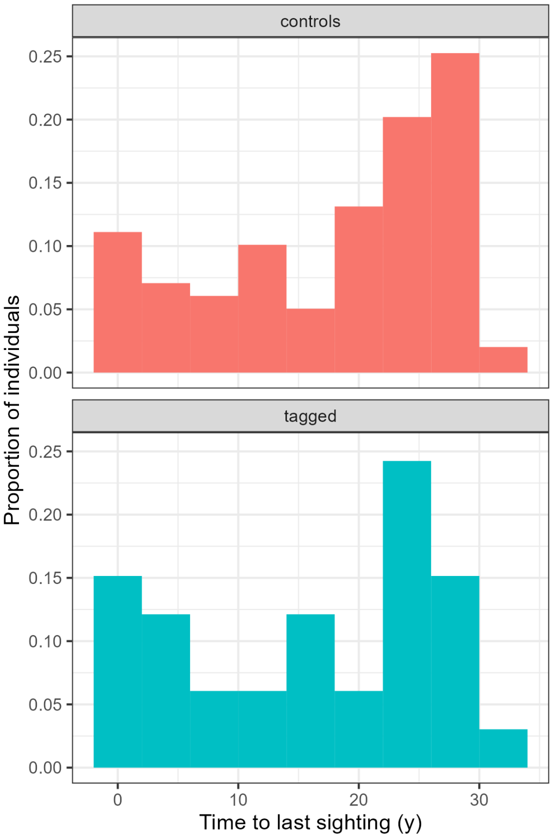

Figure 2: *Distribution of time between tag deployment (either real or simulated) and the last sighting of an individual, for control and tagged individuals.*

The time to the next calving event was also longer on average in tagged females, but again the variability was large (5 [0, 11.2] years for tagged individuals vs. 3 [0.2, 20] years for controls; Fig. 3). As a result of the differences in apparent survival and, to a lesser extent, reproduction, the number of calves observed between the tagging event and the last sighting of a female was also higher in control individuals (Fig. 4). Note that, because the number of calves is a discrete quantity, the median is the same (3 [1, 7] for tagged individuals vs. 3 [1, 19] for controls) but the mean is higher (3.2 for tagged individuals vs. 4.4 for controls).

In summary, we found no evidence in this exploratory data analysis that confounding factors may have affected our findings.

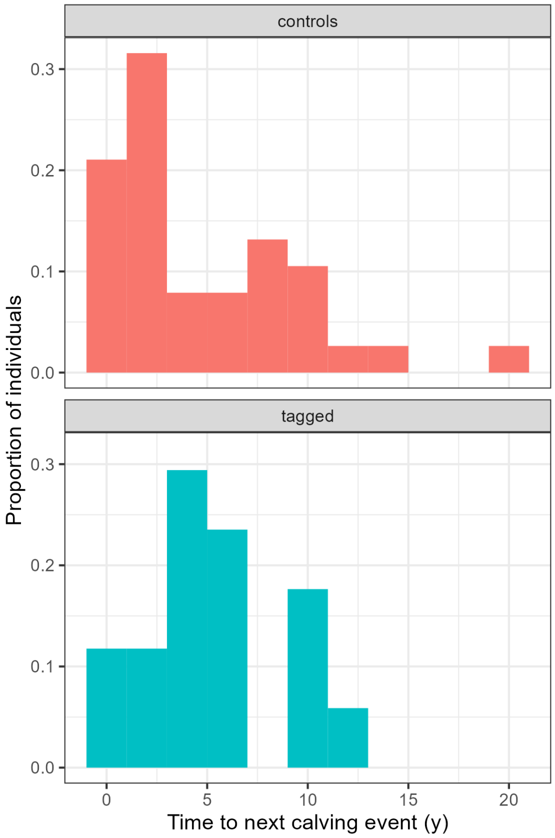

Figure 3: *Distribution of time between tag deployment (either real or simulated) and the first subsequent calving event, for control and tagged individuals.*

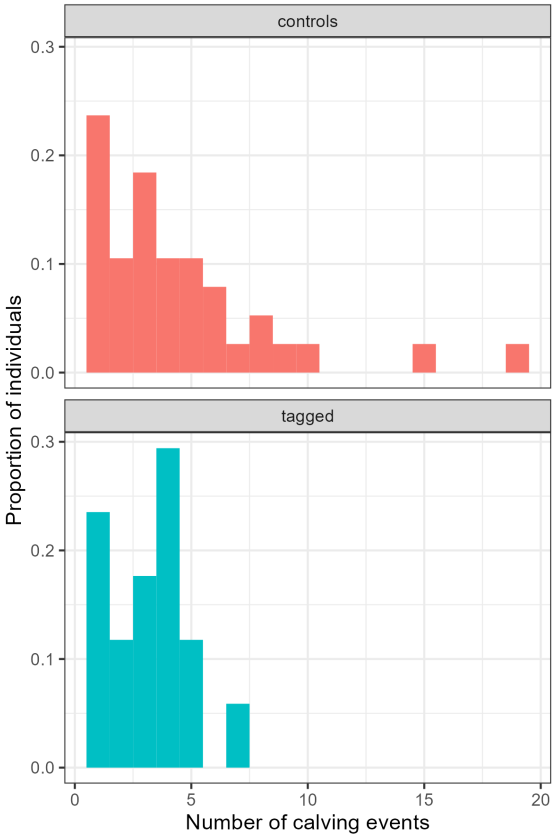

Figure 4: *Number of calving events after tag deployment (either real or simulated), for control and tagged individuals.*

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Appendix

Details of tag deployments on North Atlantic right whales in 1988-2001. When the exact age was unknown, an individual was marked as either an adult (A) or an individual of unknown class (U). Data compiled by Dr Amy Knowlton at the New England Aquarium.

Whale ID	Deployment date	Sex	Age	Tag type	Tag design
1705	28/05/1988	F	1	C	JG-RAD
1202	29/05/1988	U	U	C	JG-RAD
1405	29/05/1988	F	4	C	JG-RAD
1624	29/05/1989	M	U	A	JG-RAD
1705	01/06/1989	F	2	A	JG-RAD
1163	03/06/1989	F	8	A	JG-RAD
1903	09/09/1989	M	0	A	JG-RAD
1422	13/09/1989	M	A	A	1989 ST-3?
1611	13/09/1989	F	3	A	1989 ST-3?
1138	21/09/1989	M	8	A	1989 ST-3, BM-SAT-B
1602	21/09/1989	F	3	A	1989 ST-3, BM-SAT-B
1027	12/10/1989	F	A	A	1989 ST-3, BM-SAT-A
1703	12/10/1989	F	2	A	1989 ST-3, BM-SAT-A
1121	15/10/1989	M	A	A	JG-RAD
1146	15/10/1989	M	A	A	1989 ST-3, BM-SAT-A
1428	15/10/1989	M	A	A	1989 ST-3, BM-SAT-B
1135	24/08/1990	F	A	A	1990 ST-6, BM-SAT-C
1140	24/08/1990	F	A	A	1990 ST-6, BM-SAT-C
1152	24/08/1990	M	A	A	1990 ST-6, BM-SAT-C
1248	24/08/1990	F	A	A	1990 ST-6, BM-SAT-C
1127	25/08/1990	F	A	A	1990 ST-6, BM-SAT-C
1981	25/08/1990	M	1	A	1990 ST-6, BM-SAT-C
1629	26/08/1990	F	U	A	1990 ST-6, BM-SAT-C
1941	26/08/1990	F	1	A	1990 ST-6, BM-SAT-C
1702	31/08/1990	M	3	A	JG-RAD
1421	12/09/1990	M	A	A	1990 ST-6, BM-SAT-C
1245	22/09/1990	F	8	A	JG-SAT
1243	27/09/1991	F	9	A	1990 ST-6, BM-SAT-C
1608	28/09/1991	F	5	A	1990 ST-6, BM-SAT-C
1406	05/10/1991	F	7	A	1990 ST-6, BM-SAT-C

Whale ID	Deployment date	Sex	Age	Tag type	Tag design
2440	09/12/1994	M	0	A	NEA-RAD
1268	01/02/1995	F	A	C	NEA-RAD
1254	27/02/1995	F	A	C	NEA-RAD
1609	10/09/1995	M	9	A	JG-SAT
1802	11/09/1995	F	7	A	JG-SAT
1281	16/09/1995	F	A	A	JG-SAT
1503	16/09/1995	F	10	A	JG-SAT
2220	03/10/1995	M	U	A	JG-SAT
1026	08/10/1995	M	15	C	NEA-SAT-A
1813	08/10/1995	M	U	C	NEA-SAT-A
2250	08/10/1995	M	U	C	NEA-SAT-A
1334	07/02/1996	F	A	C	NEA-SAT-B
1705	08/02/1996	F	9	C	NEA-SAT-B
1812	21/02/1996	F	A	C	NEA-SAT-B
1308	06/09/1996	F	13	C	NEA-SAT-B
1408	16/09/1996	F	12	C	NEA-SAT-B
2610	01/10/1996	F	U	C	NEA-SAT-B
1509	20/01/1997	F	A	C	NEA-SAT-C
1243	22/01/1997	F	15	C	NEA-SAT-C
1405	28/01/1997	F	13	C	NEA-SAT-C
2135	23/04/1997	M	6	C	NEA-SAT-C
1153	18/08/1997	F	17	C	NEA-SAT-D
1125	25/08/1997	F	A	C	NEA-SAT-D
1136	27/08/1997	M	A	C	NEA-SAT-D
1327	29/08/1997	M	A	C	NEA-SAT-D
1122	11/09/1997	M	A	C	NEA-SAT-D
1048	26/09/1997	M	A	C	NEA-SAT-D
1303	04/10/1997	F	A	C	NEA-SAT-D
2223	25/03/1998	F	6	C	CCS RADTG
2710	01/09/1999	F	2	C	NEA-RADTG
2430	09/07/2000	F	U	C	1998 ST-15 D
2645	13/07/2000	F	4	C	1998 ST-15 D
1613	11/08/2000	M	14	C	1998 ST-15 D
2320	11/08/2000	F	U	C	1998 ST-15 D

Whale ID	Deployment date	Sex	Age	Tag type	Tag design
2743	11/08/2000	M	3	C	1998 ST-15 D
2795	11/08/2000	M	U	C	1998 ST-15 D
1027	12/08/2000	F	A	C	1998 ST-15 D
1114	12/08/2000	F	A	C	1998 ST-15 D
2240	12/08/2000	F	A	C	1998 ST-15 D
2310	12/08/2000	M	U	C	1998 ST-15 D
2601	12/08/2000	F	4	C	1998 ST-15 D
2617	12/08/2000	F	4	C	1998 ST-15 D
3030	12/08/2000	M	U	C	1998 ST-15 D
2614	01/08/2001	F	5	C	1998 ST-15 D
2110	14/08/2001	M	10	C	1998 ST-15 D