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Apparent survival of North Atlantic right whales after entanglement in fishing gear

Jooke Robbins [a,*], Amy R. Knowlton [b], Scott Landry [a]

[a] Center for Coastal Studies, 5 Holway Avenue, Provincetown, MA 02657, United States
[b] New England Aquarium, Central Wharf, Boston, MA 02110, United States

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ABSTRACT

The impacts of human activities on cryptic marine species can be difficult to assess. The North Atlantic right whale is an endangered species numbering just over 500 individuals. Entanglement in fishing gear is one documented source of injury and mortality, but population-level effects have been difficult to quantify. We used documented entanglements, long-term population studies and mark-recapture statistical techniques to evaluate the effect of these events on North Atlantic right whale survival. Estimates were based on 50 individuals observed carrying entangling gear between 1995 and 2008, and compared to 459 others that were never observed with gear during the same period. Entangled adults had low initial apparent survival (0.749, 95% CI: 0.601–0.855), but those that survived the first year achieved a survival rate (0.952, 95% CI: 0.907–0.977) that was more comparable to unaffected adult females (0.961, 95% CI: 0.941–0.974) and males (0.986, 95% CI: 0.975–0.993). Juveniles had a post-entanglement survival rate that was comparable to the initial survival of entangled adults (0.733, 95% CI: 0.532–0.869) and lower than un-impacted juveniles (0.978, 95% CI: 0.969–0.985). Of three entanglement characteristics examined, health impacts were most predictive of subsequent survival, but the entanglement configuration and the resulting injuries also appeared to affect outcome. When the entanglement configuration was assessed as high risk, human intervention (disentanglement) improved the survival outcome. This is the first mark–recapture estimate of entanglement survival for any whale species. The results indicate the need for continued mitigation efforts for this species, as well as for a better understanding of entanglement impacts in other baleen whale populations.

1. Introduction

Entanglement has been identified as a conservation concern for baleen whale populations worldwide (International Whaling Commission, 2010). The North Atlantic right whale (*Eubalaena glacialis*, NARW) is an endangered species thought to number just over 500 individuals (Pettis, 2013). The primary known range of this species is along the east coast of North America, mainly south of the Gulf of St. Lawrence. There have been 122 known and presumed deaths since 1970, of which at least 57% were the result of human activities (van der Hoop et al., 2013). Observed entanglement deaths and serious injuries continue to exceed what is considered to be sustainable for the population (Cole and Henry, 2013; Pace et al., 2014) and some lethal events are likely missed (Kraus et al., 2005; Williams et al., 2011).

NARW are known to interact with fishing gear frequently (Knowlton et al., 2012), yet the impacts to individuals and populations are not well understood. Many factors may affect the outcome of an entanglement event, including: the configuration of the entanglement, its duration and injuries produced, the age of the individual and/or its condition at the time of the event and disentanglement success. Furthermore, there can be uncertainty about entanglement outcome because survivors are not necessarily re-sighted and deaths are not necessarily witnessed.

A formal entanglement reporting network exists to detect and respond to entangled NARW along the east coast of the United States and in the Canadian Bay of Fundy. There has also been annual photo-identification research on the free-ranging NARW population since the 1970s. Provided that an entangled individual is properly documented, there is a possibility of re-sighting if it survives. In such cases, mark–recapture statistical analyses provide a framework for assessing impacts. Here, we use single and multi-state mark recapture models to estimate the survival rate of NARW after reported entanglements. We also examine factors that might affect entanglement outcome, including the entanglement configuration, resulting injuries, health impacts and disentanglement efforts.

2. Materials and methods

2.1. Encounter history data

NARW can be individually identified from their natural markings using photo-identification techniques (Kraus et al., 1986). Data were

* Corresponding author.
E-mail address: jrobbins@coastalstudies.org (J. Robbins).

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obtained from the North Atlantic Right Whale Consortium (NARWC), which maintains a catalog of the population and a database of sightings across its known geographic range (NARWC, 2009a,b). An annual encounter history was constructed for each individual by pooling range-wide sightings from 1 December (the start of the calving season) through 30 November of the following year. The few whales observed dead (n = 8) were assumed to have been alive in that last year.

Sexes of NARW were known from genetic analysis of a tissue sample (Brown et al., 1994), a photograph of the genital slit or a calving history (in the case of females). Animals first cataloged as calves and less than 9 years old in the year of interest were considered juveniles, whereas those known to be at least 9 years old were considered adults (Hamilton et al., 1998; Kraus et al., 2001). For individuals without a known year of birth, a minimum age was assigned by assuming that the whale was at least 1 year old the first year it was sighted. Age class could not be confidently assigned until the sighting history spanned nine years. However, those with shorter sighting histories were considered likely juveniles in this study.

2.2. Entanglement characterization

Entanglement events were documented by members of the Atlantic Large Whale Disentanglement Network (ALWDN), coordinated by the Center for Coastal Studies (CCS, Massachusetts, USA) through 2009 under the authority of the U.S. National Marine Fisheries Service (NMFS). Disentanglements have been performed in this region since 1984, but since 1997 the ALWDN has provided a formal reporting structure, disentanglement response programs and awareness outreach along the eastern seaboard of North America. This study focused on events that were adequately documented such that entangled individuals could be re-identified with or without entangling gear.

We rated three aspects of entanglement that had the potential to affect survival and could often be assessed visually from documentation at the time of the first report: the risk likely posed by the entanglement configuration, the apparent severity of injuries and resulting health impacts. The entanglement configuration was considered high risk when there were constricting wraps, multiple gear attachment points, trailing gear or evidence of heavy weight. Cases assessed as having none of those characteristics were rated as low risk. Injury severity was considered low when it consisted only of skin abrasions that did not appear to extend into the blubber or cartilage. Medium severity injuries included broad areas of skin abrasion, and/or injuries that extended into blubber but did not penetrate muscle. High severity injuries were known to extend into muscle or bone and/or resulted in significant deformity. Health was visually assessed at the first entanglement sighting, as well as at the most recent sighting prior to entanglement. Whales were rated as health impacted if they exhibited pale skin, unusual cyamid levels and/or emaciation (Pettis et al., 2004). We also examined the survival implications when entanglement duration was shortened through human intervention (disentanglement).

2.3. Statistical modeling

When individuals are not encountered in all sampling periods, their apparent survival reflects a combination of true survival and probability of detection. Open mark–recapture population models such as the Cormack–Jolly–Seber (CJS, Cormack, 1964; Jolly, 1965; Seber, 1965) estimate survival in light of these confounding factors. The standard CJS model assumes that survival within groups varies only over time, but model structure can be adjusted to accommodate other biological hypotheses (Lebreton et al., 1992). Multi-state mark–recapture models also estimate transitions between states, after accounting for apparent survival and detection probabilities (Arnason, 1972, 1973; Brownie et al., 1993; Hestbeck et al., 1991; Lebreton and Pradel, 2002; Schwarz et al., 1993). States can be any measurable individual trait that has the potential to change from one sampling period to the next, such as entanglement status.

We used program MARK (version 5.1, Cooch and White, 2006) to evaluate entanglement impacts on NARW survival. Single-state or multi-state models were used, depending on the analysis. In single state models, entangled individuals were considered marked in the year of entanglement detection. We then estimated the annual probability of survival and re-sighting across subsequent years. When multi-state models were employed, all individuals were considered marked in the first year that they were encountered during the period of interest. Individuals were then either seen or not seen in each subsequent year, and their state when seen was also coded into the encounter history. Analysis was based on the Arnason–Schwartz (AS) multi-state model which assumes that the probability of making a transition between states depends only on the present one (i.e., no memory effect), provided that the individual survives (Arnason, 1972, 1973; Schwarz et al., 1993). Program MARK also facilitates the study of explanatory factors by allowing covariate data to be modeled infra-structurally in a linear modeling framework. We identified parameters of biological interest, evaluated the goodness of fit (GOF) of the most general model to the data and then examined support for reduced models and explanatory factors, as described below. Model averaging was performed to obtain parameter estimates when multiple models shared support from the data. Models that incorporated binary covariates were excluded from model averaging.

2.3.1. Goodness of fit testing

Mark–recapture models produce valid estimates only when the data meet model assumptions. Individuals within groups or states are expected to have an equal but independent probability of detection, as well as an equal probability of survival to the next sampling period. Emigration is permitted, but it must be random and temporary. The sampling period should be brief relative to the life span of the target species, and individuals must be successfully recognized and assigned to the correct state if re-encountered. We developed models that we anticipated to meet these criteria and used Program U-CARE (version 2.2.5, Choquet et al., 2005) to detect and diagnose unexpected heterogeneity in survival and re-sighting probabilities. When possible, significant heterogeneity was addressed by making changes to the starting model structure. However, residual over-dispersion may persist and cause estimates to be artificially precise (Burnham et al., 1987). The fit of the global model was therefore also evaluated using the "median c-hat" technique in program MARK (Cooch and White, 2006) to estimate a variance inflation factor (c-hat) that was included in the model selection process. The median c-hat procedure does not accommodate models with individual covariates. When these were required, the procedure was performed on an equivalent model without individual covariates, given that the latter serve to improve the fit of the model to the data.

2.3.2. Models and model selection

We first estimated the survival of entangled juveniles and adults separately, each relative to members of the same demographic class that were not reported entangled. This approach was taken to minimize heterogeneity, given prior evidence that juveniles have a higher rate of entanglement (Knowlton et al., 2012) as well as a higher frequency of serious injury than adults (Knowlton and Kraus, 2001). Additionally, adult females have previously been shown to have a lower survival rate than adult males (Caswell et al., 1999), and most adults were of known sex whereas the sexes of many juveniles were not yet known. By modeling age classes separately we were able to reduce the complexity of each suite of models.

For juveniles, a multi-state model was used to estimate survival among three states: 1) seen without entanglement, 2) seen entangled and 3) seen as an adult. The latter was an absorbing state that allowed juvenile survival to be informed by re-sightings later in life. For whales that were not entangled, we differentiated between known juveniles and those of unknown age but short sighting histories (likely juveniles),