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North Atlantic Right Whales- Evaluating Their Recovery Challenges in 2018

US DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Northeast Fisheries Science Center
Woods Hole, Massachusetts
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North Atlantic Right Whales - Evaluating Their Recovery Challenges in 2018

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ABSTRACT

The North Atlantic right whale (*Eubalaena glacialis*) population has been in decline for 8 years due to increased mortality and sublethal effects from multiple factors. Together these have contributed to a decrease in calving. Shifting ecosystem conditions have also changed North Atlantic right whale behavior and fishing patterns. For example:

- North Atlantic right whales have expanded their distribution farther into northern waters, and are visiting different foraging areas.
- Calanoid copepod distributions appear to be in a similar state of change and this may be affecting available forage for North Atlantic right whales
- The whales' range expansion has exposed them to vessel traffic and fisheries in Canadian waters, which did not have protections for right whales in place until late last summer (2017).
- American lobster (*Homarus americanus)* populations are also changing distribution, moving north and into deeper, cooler waters of the Gulf of Maine. The US fisheries are moving farther offshore to capitalize on this, increasing the overlap between their fishing activity and North Atlantic right whale foraging areas and migration corridors.

The net result of these events is that severe entanglements have increased among North Atlantic right whales. Animals are in poor body condition likely from a combination of repeated entanglement stress, potentially limited forage and increased migratory costs- all contributing to a decrease in female calving rate. Ship strikes are still a real threat to the population. At the current rate of decline, all recovery achieved in the population over the past three decades will be lost by 2029.

INTRODUCTION

Signs of Trouble

After several decades of recovery and years of collaboration among stakeholders, the North Atlantic right whale (*Eubalaena glacialis*), hereafter referred to as the right whale, began to decline (Pace et al. 2017). This trend was subtle at first, initially signaled by fewer sightings in traditional survey areas, but other warning signs began to emerge (Kraus et al. 2016). The number of documented mortalities increased markedly in 2016 and 2017 (Hayes et al. 2018; Hayes et al. 2017) and an improved way of modeling the population's numbers (Pace et al. 2017) revealed a clearer picture of the population size and decline in numbers. Concern further escalated throughout 2017 and 2018 when only 5 calves were born and there were 19 confirmed mortalities through August.

Taken together these signs meant that risks posed to right whales and associated management measures needed to be revisited for multiple US fisheries on the Atlantic coast. This occurs through the biological opinion process under the federal Endangered Species Act, which was reinitiated in October 2017, and through the take reduction team process under the federal Marine Mammal Protection Act.

Demographic Effects

Increased mortality rates and decreased calving have moved the population into a decline that has continued for at least the last 8 years. At present, right whale deaths attributable to human activity are mostly caused by ship strikes and entanglement in pot/trap and anchored gillnet fishing gear. An encounter with fishing gear is the most frequent cause of documented right whale serious injuries and deaths in recent years. The odds of an entanglement event are now increasing by 6.3% per year, while ship strikes events remain flat (Fig. 1). At the current rate of decline, the population will have returned to its 1990 numbers, likely with comparatively reduced genetic diversity, and could decline past a point of no return in just a few decades.

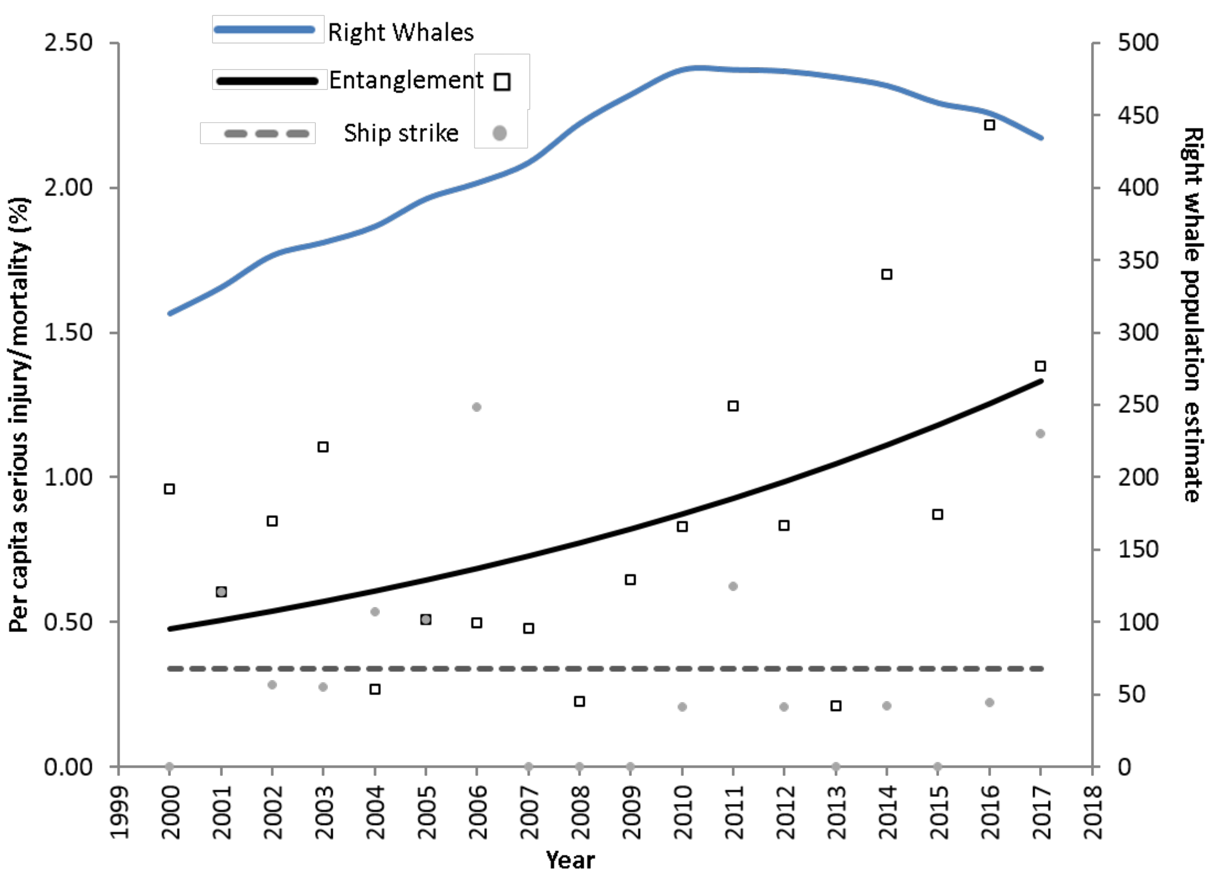

Fig. 1 **North Atlantic right whale serious injury/mortality rates from known sources 2000-2017 (Henry et al 2017; 2016 & 2017 values preliminary). Models are simple logistic regressions fit using maximum likelihood-based estimation procedures available in R. The right whale population trend is overlaid and referenced to right y-axis (Hayes et al, 2018).**

Distribution Change

Historically, right whales have returned to habitats in specific geographic locations annually, ensuring that a large portion of the population could be seen in each year. Therefore annual population estimates were conducted by simply sighting and counting as many animals as possible each year. Resulting estimates also assumed that an animal had died if it were not seen for 6 consecutive years.

Changes in this distribution pattern began around 2010 when the population peaked at 481 individuals. The whales were no longer using some of their established habitat areas in as great a number, and not staying within them for as long. This meant a new method was needed to account for animals, even those not sighted in a year. Once developed, this more advanced assessment tool, based upon mark recapture methods, enabled rapid assessment of the population with increased precision within one calendar year, much faster than the five or so years required to get good confidence on an annual estimate using the previous method. It also provided precise population estimates with greater resolution on the number of whales that likely died in any given year. Estimates made using the new method confirmed that in recent years, many deaths (around 10 to 20/yr) were going undetected annually and that by the end of 2016, the right whale population had declined to 451 individuals. A revised population estimate accounting for the many deaths and few births of 2017 is being developed and will be available later this year.

Increased Mortality

The large number of observed right whale mortalities in 2017 triggered an unusual mortality event (UME) to investigate the causes. The National Marine Fisheries Service (NMFS) is authorized to declare UMEs under the federal Marine Mammal Protection Act when an unanticipated significant die-off occurs in a marine mammal population, requiring an immediate response. Two other UMEs were declared that year due to 80 humpback whale and 40 minke whale deaths. Ongoing investigations for these two species have preliminarily identified causes of death that include entanglements, ship strikes, and disease.

In contrast to other large whale species, the problems of right whales are often more apparent because they are monitored more intensely and their coastal distribution means more opportunity for overlap with human activities, leading to it being nicknamed ‘the Urban Whale’ (Kraus et al. 2007).

While perhaps more attention is paid to the right whale given their more dire population status, it can be an indicator of more chronic problems that need addressing, not just for the sake of right whales but also for other populations of large whales. By example, although Gulf of Maine humpback whale status has improved, entanglement mortalities still remain high for this stock (Hayes et al. 2018).

There is considerable urgency to address the issues of mortalities that stem from human activities. Large whales, including right whales, are long-lived and can breed multiple times during their lives. This means these species can be resilient and able to recover after periods of poor reproduction. However, recovery for any species cannot take place if the number of deaths is more than the number of births in the population.

POTENTIAL CAUSES OF THE DECLINE

Ecosystem Dynamics

One of the constant challenges of resource management is that things change. While it is much easier to make management decisions if conditions are static, ecosystems are inherently dynamic and will change over time in response to a variety of influences. This is the case for the emerging story for right whales.

Sometime around 2010, ecosystem shifts occurred within their habitat that changed right whale movements and fishing practices in a way that has increased interaction between whales and fishing gear, and that potentially presents other environmental challenges.

Currently the Gulf of Maine is warming faster than 99.9% of all other ocean regions on the planet (Pershing et al. 2015). This is having dramatic impacts across the food web, from the middle and upper trophic level organisms such as American lobster (*Homarus americanus),* Atlantic cod (*Gadus morhua)* and right whales (Greene 2016); to the zooplankton at the base of the food web such as calanoid copepods (Grieve et al. 2017; NEFSC 2018).

Whales and Fisheries Are On the Move

American lobster are experiencing strong population fluxes and redistributions with temperature warming. The southern New England lobster fishery has been severely limited by epizootic shell disease, which lobsters become susceptible to at warmer temperatures. In the Gulf of Maine, coastal waters remain cool enough and offshore, deeper waters have warmed enough for lobsters, and lobster fishing, to expand farther offshore. As a result, Maine lobster landings have increased steadily for the past 30 years, with an increasing portion of this caught 3 or more miles offshore over the past 10 years (Fig. 2). Note that Maine lobster landings did downturn sharply in 2017, and future trends are uncertain.

Prey Availability Drives Reproductive Success

It is essential to also recognize that environmental factors and lower trophic level dynamics also contribute to right whale birth and mortality rates. Changes in prey availability influence right whale health and reproduction. In particular, abundance of the copepod *Calanus finmarchicus* in the Gulf of Maine is a strong predictor of right whale reproductive success (Greene and Pershing 2004; Meyer-Gutbrod and Greene 2014; Meyer-Gutbrod et al. 2015).

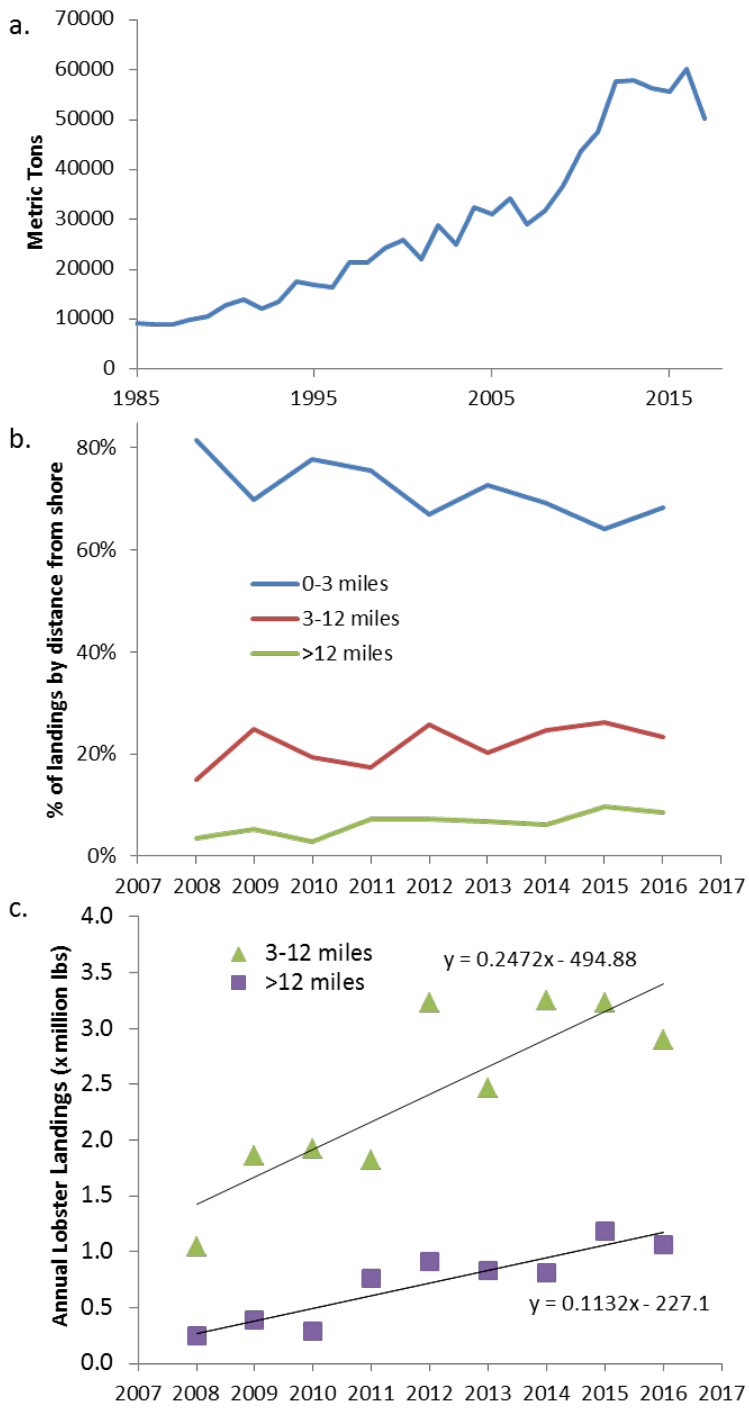

Fig 2. American lobster landings in Maine: a) total annual landings b) relative proportion of landing by distance from shore c) increase in landings from 3-12 and >12 miles offshore from Maine's 10% harvester reporting, no VTR data included. https://www.maine.gov/dmr/commercial-fishing/landings/

Meyer-Gutbrod and Greene (2018) followed individual whales over the past three decades to evaluate the relationship of calving and mortality rates to prey availability. They found that prey availability is a driver of decadal differences in the right whale population's recovery. Periods of low prey availability coincided with reduced birth rates (Meyer-Gutbrod and Greene 2018) and the interval between births has been observed to lengthen during periods when prey availability is low (Meyer-Gutbrod et al. 2015).

Similarly, years with few births contribute to years of decline or stagnation in population growth, indicating the pronounced effect of reproductive variability on species viability (Pace et al. 2017). That said, Meyer-Gutbrod and Greene (2018) modeled population growth rates under scenarios of high and low prey availability and found that the population should continue to grow even with poor prey availability and only fails to do so when whale mortalities reach 8 to 10 per year. It is worth noting natural mortality seems to be very rare in adult right whales: there has been no confirmed case of natural mortality in adult right whales in the past several decades (Corkeron et al. *Accepted with revision;* Henry et al. 2017; van der Hoop et al. 2013).

Right Whales Follow Prey in a Changing Ocean

The copepod *C. finmarchicus* has shifted in distribution and abundance in recent years due to unprecedented warming in the Gulf of Maine, and this is likely to impact the right whale population (Greene 2016; Mills et al. 2013; Reygondeau and Beaugrand 2011). It appears that in the last decade (~2005-2015), that there has been a general decline in *C. finmarchicus* in the Gulf of Maine (2009-2014, but 2015 was average abundance) and on Georges Bank (below average abundance since 2008) (NEFSC 2018) as well as the Scotian Shelf (Johnson et al. 2017).

Changes in plankton forage species abundance likely played a role in the changing movement patterns of right whales that began sometime in the past 10 years. There have been decreases in both acoustic detections and physical observations of right whales in the northern Gulf of Maine and the Bay of Fundy, and a concurrent increase in sightings of many of the same animals in the Canadian Gulf of St. Lawrence (Daoust et al. 2018; Davis et al. 2017; Meyer-Gutbrod et al. 2018; Meyer-Gutbrod and Greene 2018).

During winter, whales are spending more time offshore in the mid-Atlantic, and less time on the coastal calving grounds just off the southeastern U.S., where in 2017 and 2018 calving has been quite poor.

Reproduction Requires Robust Females

Reproduction depends on adequate adult female health and body condition. Reproductive females are particularly vulnerable to prey reductions because pregnancy and lactation increases caloric demand and they have less access to prey during migration to calving grounds (Fortune et al. 2013; Miller et al. 2012; Rolland et al. 2016).

Several of the ecosystem shifts mentioned earlier are likely to have negative consequences for reproduction in right whales. First, a reduction in prey will have energetics costs for females. Northward shifts in the right whales' feeding grounds, as a result of changes in prey availability, will increase energetic cost of the calving migrations from the southern calving grounds off the coast of Florida and Georgia, particularly if animals do not adapt to also calve farther north.

The cost of entanglement has also been shown to have direct and indirect consequences for right whales (van der Hoop et al. 2017b; van der Hoop et al. 2017c). This will be detailed next, but in the Gulf of Maine where ecosystem shifts are occurring more trap fishing is also occurring offshore, increasing the overlap with right whale foraging areas.

Whales have also expanded their range, foraging into the Gulf of St. Lawrence. This increased the whales' exposure to risk from fixed gear fisheries. Some of this risk has reduced by strong protections put in place by the Canadian government during the spring of 2018 (DFO/TC Canada 2018; DFO Canada 2018).

Anthropogenic Stressors

In a review of mortality sources for all large whales, entanglement in fishing gear was the number one cause, followed by natural causes and then vessel strikes. An exception to this is the right whale for which there is very little evidence of natural mortality in adult whales, likely due to shortened life spans associated with anthropogenic causes (Corkeron et al. *Accepted with revision*), as all confirmed causes of adult mortality and serious injury since 1970 have been due to fishing gear and vessel strike (Henry et al. 2017; van der Hoop et al. 2013).

The relative contribution from these two causes was approximately equal through the year 2000 (van der Hoop et al. 2013), but entanglement events resulting in death or serious injury have increased steadily since then, while ship strike frequency has remained lower with no specific trend (Fig. 1). For the recent 19 known right whale mortalities (17 in 2017 and 2 to date in 2018), the cause of death could be determined for 10. Ship strikes are implicated in five blunt force trauma cases and entanglement in the remaining five. In 2017, seven other entangled whales were observed: three were disentangled, three shed the gear, and one was not seen again.

Ship Strikes

Reducing Risk

Ship strikes are currently the second most frequently documented cause of mortality in right whales. The per capita mortality frequency has not varied much, hovering around 0.34% deaths or serious injury events per year (Fig. 1). Several management actions were implemented in U.S. and Canadian waters beginning in 2008 to reduce the risk of collisions between right whales and large vessels. Major actions include:

- Voluntary two-way routes for commercial vessels off the Southeast U.S. and in Cape Cod Bay
- Modification of the Boston, Massachusetts Traffic Separation Scheme
- Canada and the International Maritime Organization established the voluntary Area To Be Avoided concept in the Roseway Basin
- Seasonal Management Areas in habitats off of Massachusetts, ports along the Mid-Atlantic coast, and the southeastern U.S. where vessels are required to slow to speeds less than 10 knots during transits for vessels 65 ft in length or longer

- Intermittent implementation of voluntary speed restrictions in Dynamic Management Areas within which right whale aggregations are observed outside the boundaries of the Seasonal Management Areas

Several analyses have been conducted to evaluate the effectiveness of these management efforts (Conn and Silber 2013; Lagueux et al. 2011; Silber et al. 2014; van der Hoop et al. 2012). In general, while these analyses were based on a short time-series of available data, collectively they suggest that after ship-strike rules put in place, a reduction in right whale mortality from ship strikes followed, and in general were at the lowest on record per capita from 2010 through 2016.

Responding to Changing Risk

In 2017, right whale deaths by ship strike increased when 5 ship-strike mortalities were confirmed, 1 in U.S. and 4 in Canadian waters (Fig. 1), likely caused in part when right whales began to spend more time in new areas with high vessel traffic and no speed restrictions. Increased survey effort in these areas also made it more likely that these events would be observed and reported.

Entanglement

Reducing Risk

Management efforts to reduce entanglement risks in U.S. waters have focused on gear technology to make entanglements less likely to harm or kill whales, restricting where and when gear that poses a threat can be used when whales are likely to be present, and reducing the amount of gear in the water column (Fig 3). Measures are recommended through a take reduction team, as mandated under the federal Marine Mammal Protection Act. Each team comprises a variety of experts and stakeholders, who assist NOAA Fisheries in developing a take reduction plan when necessary.

Since 1997, a series of rules have been implemented based on the take reduction plan (Fig. 3). These include the sinking groundline (2009) and vertical line (2015) rules. While there appears to have been a subsequent reduction in entanglements caused by groundline (Morin et al. 2018), which moved 27,000 miles of line from the water column to the bottom (NMFS, 2014), absolute entanglement rates appear to be on the rise (Fig 1).

Increase in Entanglement Risk

Fewer but Stronger Lines in US Waters

There may also have been unintended consequences of the 2015 vertical line rule. The rule required ‘trawling up’ (using more traps per trawl) in some regions. While this reduced the number of lines, it also meant that lines had to be stronger to accommodate the increased load of multiple traps. This natural adaptation, and the fact that stronger rope was available, contributed to an increase in the severity of entanglements as found by Knowlton et al. (2016), who observed very little evidence of entanglement with ropes weaker than 7.56 kN (1700 lbsf).

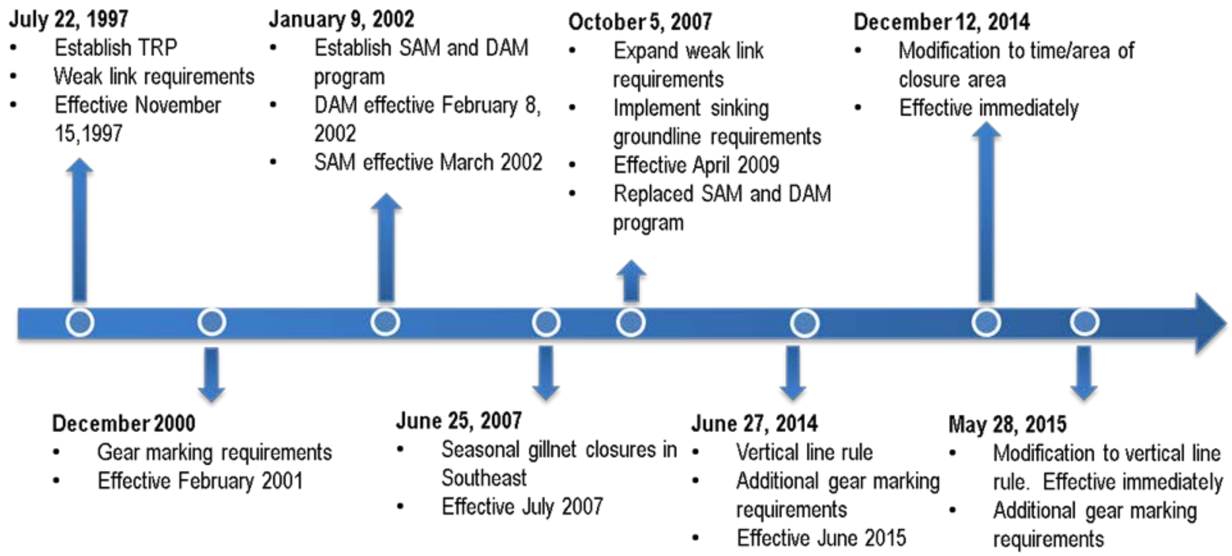

Fig 3. Timeline of significant management actions focused on reducing fishing entanglement

Entanglement Trends Upward

Knowlton et al.(2012) showed that nearly 85% of right whales have been entangled in fishing gear at least once, 59% at least twice, and 26% of the regularly seen animals are entangled annually. These findings represent a continued increase in the percentage of whales encountering and entangling in gear, which grew from to 61.5% in 1995 (Hamilton et al. 1998), to 75.6% in 2002 (Knowlton et al. 2005), confirming further the growing severity of the problem.

More Vertical Line in Right Whale Habitat

Rough estimates are that approximately 622,000 vertical lines are deployed from fishing gear in U.S. waters from Georgia to the Gulf of Maine. Notably until spring of 2018, very few protections for right whales were in place in Canadian waters. In comparison to recent decades, more right whales now spend significantly more time in more northern waters and swim through extensive pot fishery zones around Nova Scotia and into the Canadian Gulf of St. Lawrence *(Daoust et al. 2018)*.

Taken together, these fisheries exceed an estimated 1 million vertical lines (100,000 km) deployed throughout right whale migratory routes, calving, and foraging areas. Figure 4 illustrates the scale of the challenge by providing fishery statistics for the various regions (data sources provided in Appendix 1).

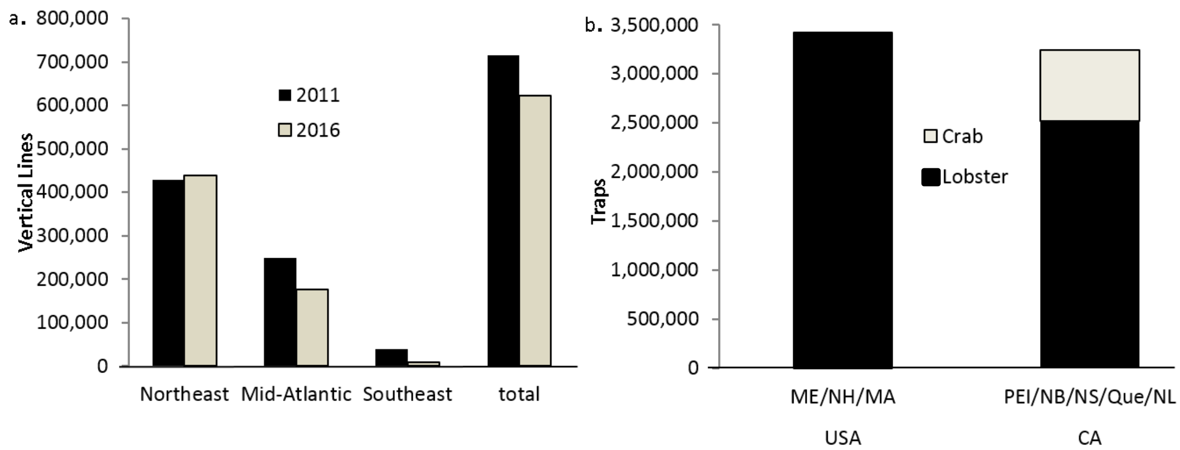

Fig 4. Index of fishing effort. a) The change in number of vertical lines in US waters from 2011 to 2016, b.) The approximate number of traps in USA Northeastern states and Canadian provinces. Data sources in Appendix 1.

Closures Are Effective, But May Not be Enough

A great deal of effort has been put into identifying entanglement 'hot-spots': relatively small areas where focused management measures can have minimal impact to fishing while providing great benefit to whales. Clear examples of this approach include the seasonal closure of Cape Cod Bay, and now the static closure within the Area 12 fishing zone of the Canadian Gulf of St. Lawrence. Both are relatively small areas where a significant portion (30 to 50+ %) of the right whale population has reliably occurred for several weeks to months over the past few years. Management actions have a population level benefit with impacts restricted to very local portions of fisheries. While still difficult choices, this has been the preferred management approach.

However, these closures, while likely very effective regionally, may not be enough. Each vertical line out there has some potential to cause an entanglement. With a 26% annual entanglement rate in a population of just over 400 animals, this translates to about 100 entanglements per year, which is significant for such a small population. But from the perspective of an individual fixed gear fisherman, they may never encounter a right whale. With more than 1 million lines out there, any single line has perhaps a 1 in 10,000 chance of entangling a whale in any one-year period. This can vary somewhat from regions with high to low densities of lines and/or whales.

However, in general, this means a fisherman and his or her descendants could go several generations without ever entangling of a right whale. Given this, it's easy to believe that *'all these entanglements are happening somewhere else'* regardless of where one fishes. Being able to directly link an entanglement with specific gear deployed at a specific place in time is rare, but by mapping known locations of gear that led to the entanglement of a right whale, one can see that there is no place within the fished area along the East Coast of North America for which entanglement risk is zero (Fig 5).

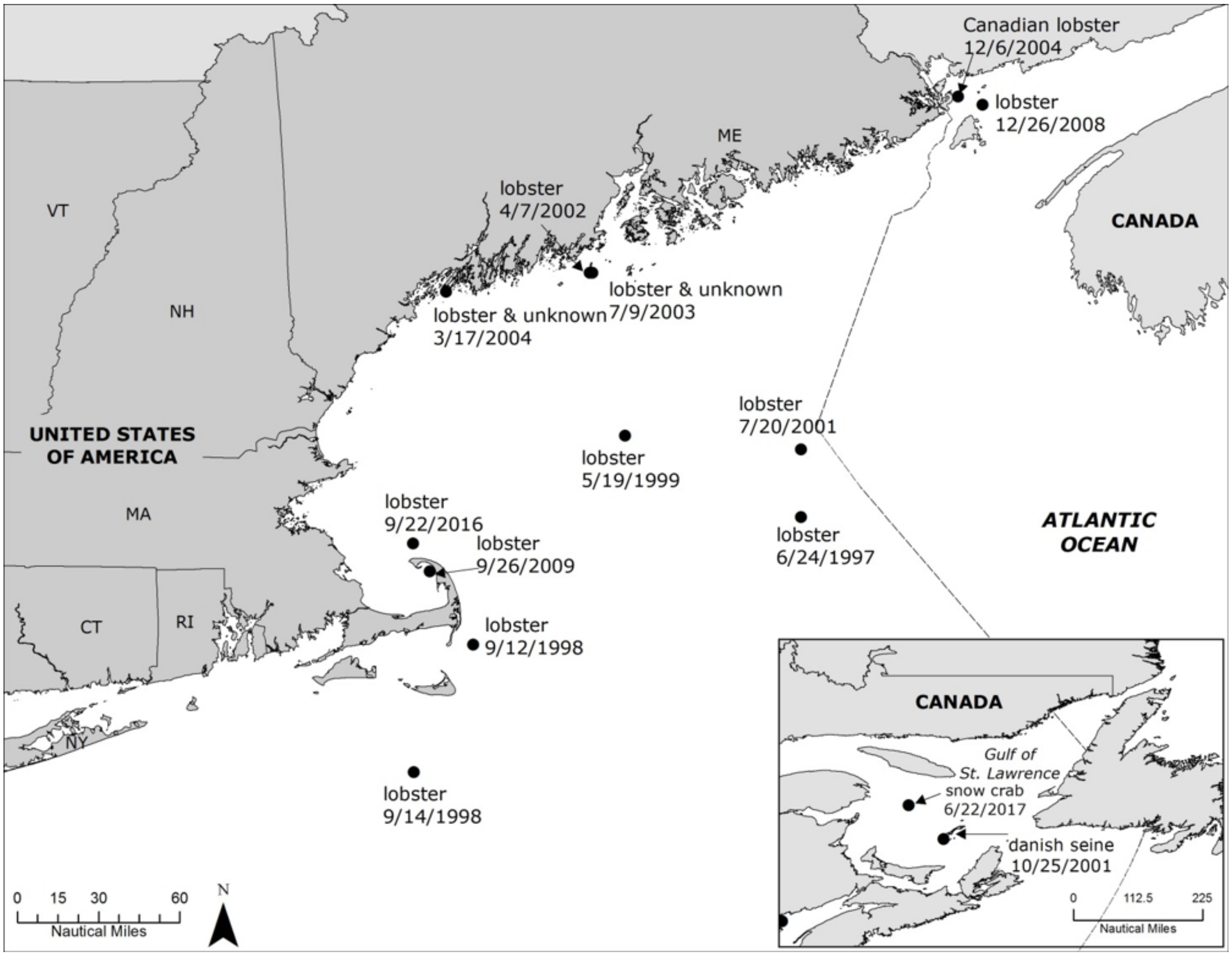

Fig 5. Right whale entanglements from 1997 through 2017 for which the set location and type of gear are known, and gear was recovered from a whale.

Sublethal Challenges- Skinny Whales and Few Calves

Fundamentally, a population increases when there are more births than deaths. Much attention has been paid to direct mortality caused by ship strikes and entanglement, but less focus has been put on the secondary effects of these and other variables where animals survive but fail to thrive because of the harm done. This is particularly evident in calving among mature females.

Biological Cost of Stressors

The abundance of photographs of known individual right whales taken over several decades have been used to develop health indicators associated with natural and human-caused stressors (Schick et al. 2013). This has been refined into a quantitative health score, including a predictive threshold below which females seem incapable of having a calf (Miller et al. 2012; Rolland et al. 2016).

We understand that right whales are exposed to numerous sublethal stressors, including fluctuating food resources (Meyer-Gutbrod and Greene 2014) and even underwater noise (Rolland et al. 2012). Several recent studies have also focused on sublethal effects of entanglement, the first of which includes increased swimming energy costs from dragging gear (van der Hoop et al. 2016). Even if disentangled, there are several injuries that can have costs lasting long after disentanglement. These include trauma wounds from rope cuts that may or may not eventually heal, and damage to baleen plates that can prevent efficient filter feeding for many years since these plates grow slowly.

Recent studies have also shown that even without accounting for injury, the drag from carrying rope and other gear for long periods of time can be energetically more expensive for a female than the migratory and developmental costs of a pregnancy (van der Hoop et al. 2017a; van der Hoop et al. 2017b; van der Hoop et al. 2017c).

Biological Demands of Right Whale Pregnancy

While serious injuries represent 1.2% of all entanglements, there are often sublethal costs to less severe entanglements. Should an entanglement occur but the female somehow disentangles and recovers, it still has the potential to reset the clock for this “capital” breeder. She now has to spend several years acquiring sufficient resources to get pregnant and carry a calf to term, the probability of a subsequent entanglement is fairly high, and this will create a negative feedback loop over time, where the interval between calving becomes longer. This is certainly a contributing factor in the longer calving interval for females, which has now grown from 4 to 10 years (Pettis et al. 2017).

Figure 6 demonstrates a simple model for estimating the probability that an animal will NOT become entangled over time. Similar to asking what are the odds of NOT getting ‘heads’ in 10 coin tosses, this model simply asks what are the odds of not getting entangled over time if there is a 74% chance of not getting entangled each year (Knowlton et al. 2012). Historically the median calving interval of a female right whale is 3 to 4 years (Pettis et al. 2017). The model estimates that animals have a about a 30 to 40% chance of not getting entangled during that period, or, conversely, a 60 to 70% chance of getting entangled.

With the calving interval now nearly twice as long as in the past, half as many calves are being born. So while entanglements often do not kill an animal, they may have a large impact by reducing or preventing births in the population. There is an additional variable, stress, which is much harder to quantify but known to have costs in mammals that are foraging in an environment with some mortality threat (Hernández and Laundré 2005).

It is difficult to tease out the relative effects of poor foraging conditions and the energetic costs of entanglement on the increased frequency of thin whales and the subsequent decrease in calving. Both are likely having some influence. While there are dozens of documented cases of ship strikes and entanglement linked to right whale mortality, to date there is no confirmed observation of a right whale starving to death from poor forage.

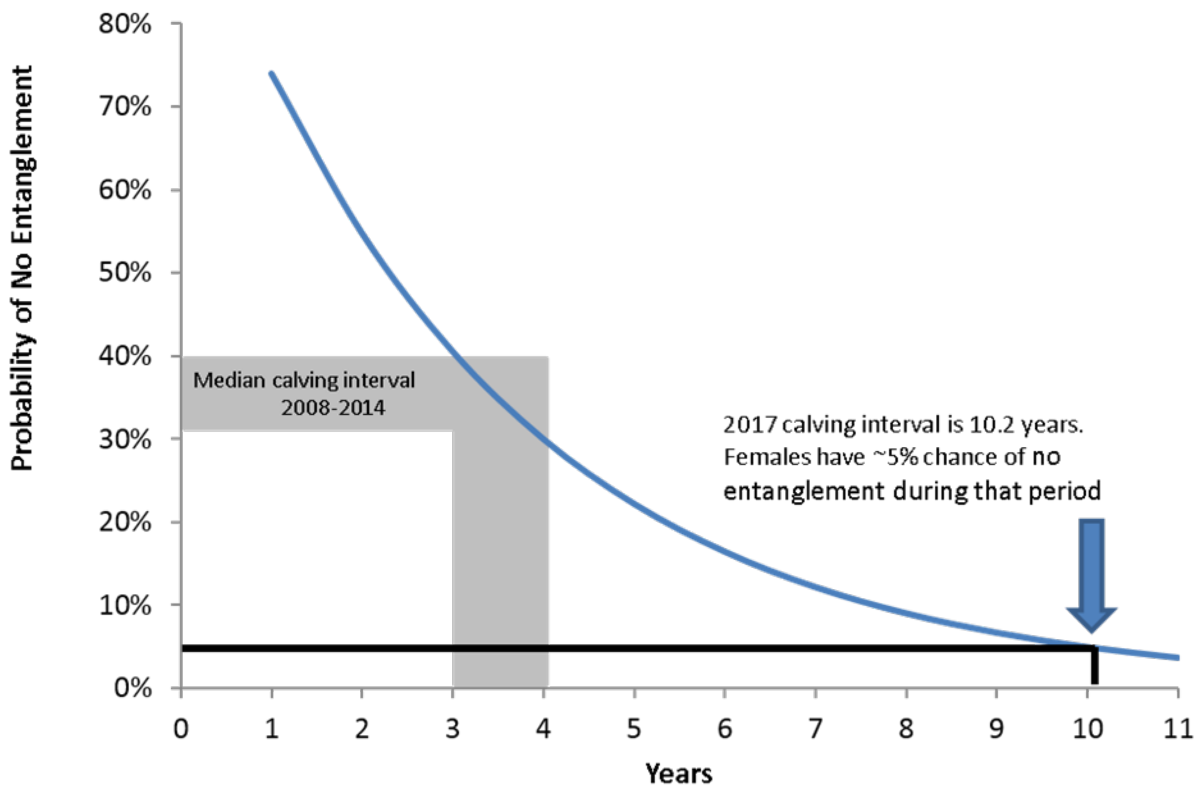

Fig 6. Cumulative annual probability of no entanglement (annual rate = 74%)

HOW LONG DO NORTH ATLANTIC RIGHT WHALES HAVE?

A Long-Lived Animal

Right whales have the potential to be a very long-lived species. In the southern hemisphere where shipping and fishing pressures are much lower, there is little evidence of human activities causing right whale mortality. There is also little evidence of natural mortality in adult animals (Corkeron et al. *Accepted with revision*). Since the ban on commercial whaling of Southern right whales in 1935 (Gambell 1993) these animals have not yet lived long enough to die of natural causes.

Meyer-Gutbrod and Greene (2018) demonstrated that even under poor foraging conditions, right whales should be able to recover if annual human-caused mortality is kept somewhere below 8-10 deaths per year. This means that in the absence of human-caused mortalities, right whales could potentially endure several decades under poor foraging conditions and still recover once environmental conditions improve. However, in the current situation in the northern hemisphere, where animals are living much shorter lives, there is great cause for concern that the risk of extinction is much higher than in the southern hemisphere, where animals are not regularly subject to human caused mortality.

An Illustration of Potential Decline, 2017-2067

A Matrix Model

In order to measure current population trends, we used a three-stage (calf, juvenile, adult) matrix population projection model (Caswell 2006) for female right whales, derived from Corkeron et al. (*Accepted with revision*), to project the future abundance of right whales. Survival values used for input into the population projection model were calculated using a Cormack-Jolly-Seber (Pace et al. 2017) variant of a mark-resight model (see Appendix 2 for details) and determined the population is declining at 2.33% per year.

We started the model estimating an abundance of 160 females alive at the end of 2017. With approximately 1.5 males per female (Pace et al. 2017), 160 females would result in an overall species abundance of about 400. It is possible that this abundance estimate may be marginally low, but since the model overestimates calving success, we assumed that these biases should cancel each other out.

Using the stage derived from the matrix model, we assumed that the 2017 starting population of 160 females was composed of 10 calves, 60 juveniles, and 90 adults. We ran 1000 stochastic projections forward 50 years (Fig. 7).We then extracted median and 95% quantile estimates of projected abundance from those projections, and estimates of the number of adult females remaining, for 5, 10, 15, 20, 25 and 50 years. Results are shown in the Table.

Results

The model projects that in 2067, 50 years from 2017, there would be 49 female North Atlantic right whales remaining, of which only 32 would be adults. In 20 to 25 years (2037-2042) there would be fewer than 50 adult females. In the near term, at the current rate of decline, all recovery in the population over the past 3 decades will be lost by 2029, with the population returning to the 1990 estimate of 123 females.

Notably, the model does not adjust for varying environmental conditions, which are known to fluctuate on a decadal time scale for North Atlantic Ecosystems (Nye et al. 2014) and are presently unfavorable. This approach may overestimate the rate of population decline but not the overall trajectory.

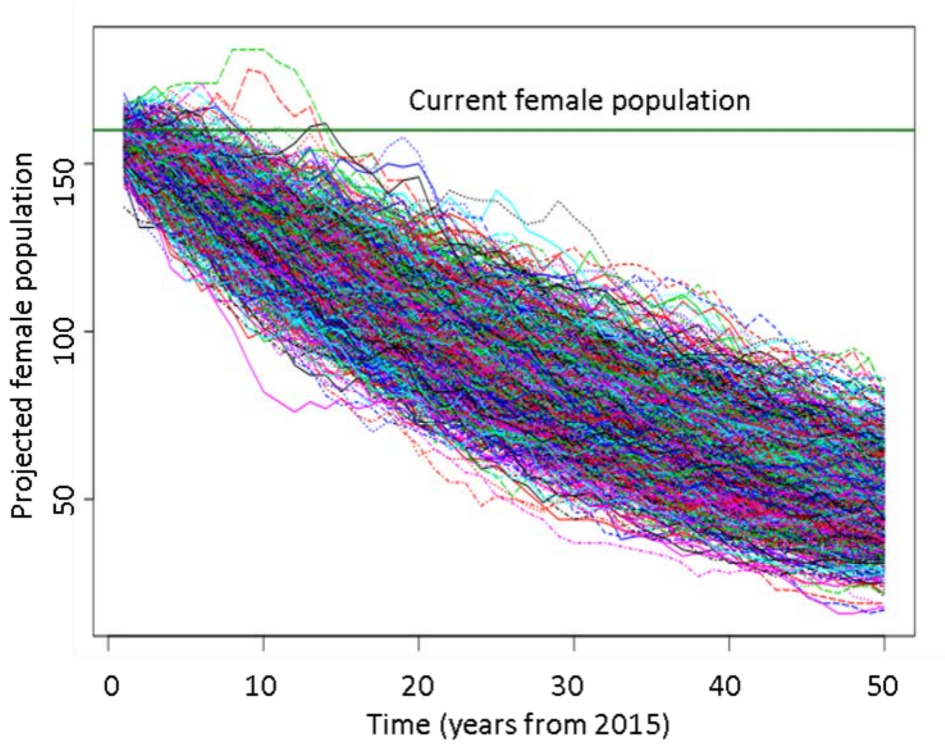

Fig. 7 Matrix population projection model output of North Atlantic right whale female population trend under current population conditions.

Table of matrix projection model output of female North Atlantic population trends for 5-year intervals, 2017-2067

Years from 2017	Number of females	Cis	Number of adult females
5	144	126 to 161	75
10	129	107 to 150	67
15	114	91 to 141	59
20	102	77 to 130	53
25	90	66 to 119	47
50	49	27 to 76	32

The threshold for functional extinction is very hard to define and likely varies by species. If the population declines to the 1990 level, there is a new threat: a repeated genetic bottleneck. Genetic bottlenecks happen when a population is so small that the genetic make-up of remaining group is not the same as that of the initial population. The effect of repeated bottlenecks is likely to mean that if the population returned to the 1990 level, that group would have less genetic diversity than the group that existed in1990. This can lead to reduced resilience and contribute to increased risk of extinction (Amos and Harwood 1998; Melbourne and Hastings 2008).

INDICATORS OF SUCCESSFUL MANAGEMENT MEASURES

Determining the management actions necessary to reverse the current population trend is beyond the scope of this document. However, the scale of the actions will need to be quite significant to be successful. Entanglement has increased dramatically and ship strikes continue to occur.

The population decline began in 2010 (Fig. 1), when entanglement was occurring at a rate of 26% among sited animals per year (Knowlton et al. 2012). Since then, the right whale range expansion has put them in the path of more shipping and more fishing gear – encountering almost twice the amount of gear owing to expansion of more fishing farther offshore in US waters and northward into Canadian waters (Fig. 4).

It is logical to conclude that to reverse the right whale decline, it may be necessary to reduce the impacts of entanglements and other harmful human interactions with right whales across their expanded range to pre-2010 levels. For recovery it may be necessary to go further, considering more modifications to fishing and shipping practices to compensate for potentially reduced forage opportunity and increased migratory costs.

Several biological indicators can be recommended for monitoring the short- and long-term effectiveness of any management actions that might be put in place to reduce the rate of both ship strikes and fishing gear entanglement.

Short-term indicators include fewer observed numbers of ship strikes and entanglements. These could be noticeable within 6 months to 1 year, but there is considerable variation around detectability of these events and the results will initially have a great deal of uncertainty. It takes approximately 1 year to conduct a population assessment and determine any changes in abundance. The assessment will alleviate some the uncertainty in detecting mortality risks that that might be mitigated by management actions. It should be noted that number of mortalities is the bluntest indicator of management success.

However, teasing the relative effects of management actions and natural variability on population size and condition will take several years of data and analysis. Metrics such as the frequency of scarring, improvements in body condition, and overall health scores could be detectable under stable environmental conditions in 2 to 3 years. Similarly, if environmental conditions are adequate for females to accumulate enough resources to calve, it will likely take at least 2 to 4 years to separate the impact of management action that reduced the frequency of, say, costly entanglements from the impact of natural variability. Ultimately, confidence in any estimate of population trajectory will emerge over 5 to 10 years.

In an ideal situation, evidence of human-caused injuries and mortality decreases, body condition improves, and the birth rate exceeds the death rate, resulting in more North Atlantic right whales.

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APPENDIX 1 Data Sources for Figure 4

Several data sources were used to construct Fig 4. All vertical line estimates in 4A were provided by Industrial Economics. Trap counts provided in 4B were acquired from a variety of sources. Raw trap counts were provided for Maine and Massachusetts. Trap counts for New Hampshire and all Canadian provinces were generated by multiplying license counts by trap limits. These were quite variable across regions, in which case the multiplier used is reported in the Table in the report.

Table 2. Data sources for trap counts and license numbers by country and regions.

Location	species	# traps	data year	Source
Maine	Lobster	2,901,000	2016	https://www.maine.gov/dmr/commercial-fishing/landings/documents/lobster.table.pdf
New Hampshire	Lobster	133,700	2010	https://www.greateratlantic.fisheries.noaa.gov/protected/whaletrp/trt/meetings/2012 meeting/Day%202/day_2_1c_new_hampshire_alwtrp_proposal.pdf
Massachussetts	Lobster	383,447	2011	http://www.lobstermen.com/wp-content/uploads/2009/10/MASS-LOBSTER-INDUSTRY-2012.pdf
Canada	**species**	**# license**	2016	http://www.dfo-mpo.gc.ca/stats/commercial/licences-permis/species-especes/se16-eng.htm?
Nova Scotia	lobster	3,249	2016	http://www.dfo-mpo.gc.ca/stats/commercial/licences-permis/species-especes/se16-eng.htm?
	crab	748	2016	http://www.dfo-mpo.gc.ca/stats/commercial/licences-permis/species-especes/se16-eng.htm?
New Brunswick	lobster	1,460	2016	http://www.dfo-mpo.gc.ca/stats/commercial/licences-permis/species-especes/se16-eng.htm?
	crab	123	2016	http://www.dfo-mpo.gc.ca/stats/commercial/licences-permis/species-especes/se16-eng.htm?
Prince Edward Island	lobster	1,245	2016	http://www.dfo-mpo.gc.ca/stats/commercial/licences-permis/species-especes/se16-eng.htm?
	crab	39	2016	http://www.dfo-mpo.gc.ca/stats/commercial/licences-permis/species-especes/se16-eng.htm?
Quebec	lobster	591	2016	http://www.dfo-mpo.gc.ca/stats/commercial/licences-permis/species-especes/se16-eng.htm?
	crab	382	2016	http://www.dfo-mpo.gc.ca/stats/commercial/licences-permis/species-especes/se16-eng.htm?
Newfoundland	lobster	2,353	2016	http://www.dfo-mpo.gc.ca/stats/commercial/licences-permis/species-especes/se16-eng.htm?
	crab	3,379	2016	http://www.dfo-mpo.gc.ca/stats/commercial/licences-permis/species-especes/se16-eng.htm?
Canada	**species**	trap limit range	trap multiplier used	**Source**
Nova Scotia- GOSL	lobster	225-300	275	http://dfo-mpo.gc.ca/fm-gp/peches-fisheries/comm/atl-arc/lobster-notice-avis-homard-
Nova Scotia- GOSL	crab	75-150	150	neiges-en.html
Nova Scotia- east	crab	30-60		http://dfo-mpo.gc.ca/fm-gp/peches-fisheries/ifmp-gmp/snow-crab-neige/snow-crab-neiges2013-eng.htm
New Brunswick	lobster	240-300	275	http://dfo-mpo.gc.ca/fm-gp/peches-fisheries/comm/atl-arc/lobster-notice-avis-homard-
	crab	75-150	150	neiges-en.html
Prince Edward Island	lobster	240-300	275	http://dfo-mpo.gc.ca/fm-gp/peches-fisheries/comm/atl-arc/lobster-notice-avis-homard-
	crab	75-150	150	neiges-en.html
Quebec	lobster	235	235	http://www.dfo-mpo.gc.ca/fm-gp/peches-fisheries/ifmp-gmp/lobster-homard/index-eng.htm
	crab		200	
Newfoundland	lobster	185	235	https://thisfish.info/fishery/atlantic-lobster-canada-lfa11/
		100-425		http://waves-vagues.dfo-mpo.gc.ca/Library/282426.pdf
	crab	200	200	http://dfo-mpo.gc.ca/decisions/fm-2018-gp/atl-07-eng.htm

APPENDIX 2 Model Inputs and Methods used for Population Projection

In order to determine current rate of population decline we used a simple, three-stage matrix population projection model (Caswell 2006) for female right whales, derived from Corkeron et al. (*Accepted with revision*), to project the future abundance of North Atlantic right whales. The model's three stages are: calf, juvenile and adult. Survival values used for input into the population projection model are derived from survival estimates calculated using a Cormack-Jolly-Seber (as opposed to the published Jolly-Seber, Pace et al 2017) variant of a mark-resight model (see Appendix 1 for details). We used the lower 95% credibility intervals of the median estimates of survival for 2011-2015 from the model. These were: calves: 0.86137, juveniles: 0.92684, and adult females: 0.92684. The matrix projections also assume: a calving interval of 4.75 years (the mean of median inter-calf intervals for calving females 2011-2017, from the 2017 North Atlantic Right Whale Report Card (Pettis et al. 2017), ; females maturing at 11; and a current maximum longevity of 50. With no calves born this year, this calving estimate is arguably optimistic, but the inter-calf interval estimate for 2018 would be undefined, and so is unusable. Survival and transition probabilities for stages were calculated as described in Corkeron et al. (*Accepted with revision*).The model was run in R 3.4.3 (R_Core_Team 2017), using the libraries *diagram* (Soetaert 2017), *popbio* (Stubben and Milligan 2007) and *popdemo* (Stott et al. 2016).

The matrix used for analyses is:

	calf	immat	adlt
calf	0.00000	0.00000	0.10526
immat	0.86137	0.86254	0.00000
adlt	0.00000	0.06430	0.92443

This gives an intrinsic rate of increase of 0.9767, or a decline of 2.33% per year.

To develop a stochastic projection from this model, we took a starting abundance estimate of 160 females alive at the end of 2017, as the unusually high observed mortality of right whales that year (Meyer-Gutbrod and Greene 2018) meant that starting earlier would not capture one important recent anthropogenic impact on this species. With approximately 1.5 males per female North Atlantic right whale now (Pace et al. 2017), 160 females would give an overall species abundance of ~400. It is possible that this abundance estimate may prove to be marginally low, but as the model overestimates calving success, we assume that these biases should cancel each other out. When an abundance estimate for 2017 is available (by October-November 2018) the model can be revised.

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