North Atlantic Right Whales vs. Fishermen

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***Abstract*— The North Atlantic right whale, *Eubalaena glacialis*, population has declined over the past 10 years. The exact population is difficult to measure, but it is believed to currently be in the low to mid 400's. Although this is an improvement over the population from the late 90's, which sat below 300, the recent decline has scientists concerned that the species may be heading for extinction. There have been claims that the recent downward trend in the population can be attributed to human factors such as fishing gear entanglements and vessel strikes. This paper will investigate the effect of human factors on the North Atlantic right whale population to determine whether imposing fishing laws, such as requiring weak link ropes and restricted fishing areas, will enable population recovery.**

I. INTRODUCTION

Right whales have been battling to escape their endangered status for decades as a result of centuries of whaling. Until recently, the North Atlantic right whale (NARW), one of three right whale species, has seen a steady growth in population since the late 1900s. However, recent dip in the population has scientists concerned.

Although there have been documented North Atlantic Right Whale mortalities as a result of entanglements and vessel strikes, it is unclear whether these incidents are the primary cause of the recent population decline. Other factors such as climate change and available food sources may be contributing to the decrease in the whale population over the past 10 years. However, in New England the finger is pointed at lobstermen and fishermen, and the consequence is new regulations that could hurt their livelihood. The question that should be asked before imposing restrictions on these fishermen is, will reducing the number of entanglements and vessel strikes prevent extinction, or is the North Atlantic Right Whale bound for this fate as a result of rising sea temperatures and diminishing food sources?

My method for approaching this question is to investigate the relationship between the whale population, the number of calves born, the number of whale entanglements and vessel strikes, and the density of the North Atlantic Right Whale's primary food source, Calanus *finmarchicus* (a species of zooplankton). To get an initial understanding of the relationship between these variables, I collected historical data from various data sources. The data on the right whale population, calve births, and mortalities was gathered from the North Atlantic right whale Consortium (NARWC) Report Cards dating from 2006 through 2018 [1]. I sorted the mortalities by natural and human caused using the notes in the report card. Any unknown cause of death for which entanglement or blunt force trauma was noted or suspected was categorized as a human caused death, but if these factors were not mentioned the death was assumed to be of natural causes.

Unfortunately there were not many years of data for all of these parameters, and tracking data on the whales is very difficult because they can go unseen for months or even years. Due to the large margin for error in recording this data, I decided that strong conclusions could not be extracted from the data alone. To approach the problem in a different way, I began to build predictive population models. Using estimated parameters based on the recorded data, I set up multiple models for the rate of change of the whale population to investigate the long term effects of a diminishing food source and the presence of human factors.

II. PROBLEM DESCRIPTION

Table of Model Parameters:

Parameter	Description
W	Whale Population
Z	Zooplankton Density
W_o	Initial Whale Population
Z_o	Initial Zooplankton Density
b	Natural Per Capita Whale Birth Rate
d	Natural Per Capita Whale Death Rate
k	Z Density that leads to 50% b
h	Per Capita Human Caused Death Rate
f	Human Effect on Whale Birth Rate

To begin modeling, I considered the whale and zooplankton populations while ignoring the human factors. According to a paper on the effects of climate change on the Calanus *finmarchicus* population, the zooplankton density can be estimated as a function of ocean depth, sea surface salinity, bottom water temperature, and bottom water salinity. Using multiple climate models, the authors, Grieve, Hare and Saba, projected the temperatures and salinities, and in turn predicted the zooplankton density over time [2]. Although this study looked at two different climate models, I chose to use the zooplankton model that assumed a "business as usual" climate model. In this model greenhouse gas emissions, human population and land use follow their current trends. By examining a graphical result of this zooplankton model, I deduced that the zooplankton density was roughly linear in time. By recording densities from the model at every 20 years, starting in 2020, I fit a line to the data using least squares regression. The resulting equation for zooplankton density over time is:

$$Z(t) = -0.011t + 1.78 \tag{1}$$

One can assume that for a high enough zooplankton density, all whales are sufficiently fed and able to reproduce at their maximal rate. Thus the rate of change of the whale population is simply proportional to the current whale population:

$$\frac{dW}{dt} = bW - dW = (b-d)W \tag{2}$$

where b is the natural per capita birth rate, and d is the natural per capita death rate for the North Atlantic Right Whale.

For a low zooplankton density, however, the whale birth rate would be dampened by a factor proportional to the zooplankton density and therefore the equation would look like:

$$\frac{dW}{dt} = \frac{b}{l}Z(t)W - dW \tag{3}$$

Note that in this equation, when $Z = 0$, the whale population experiences exponential decay. This is to be expected because I am assuming that the Calanus *finmarchicus* is the right whale's only food source, and without it the whales would be unable to reproduce.

These two scenarios for $Z(t)$ require the use of a hill function as a coefficient for the birth rate of the whale population:

$$\frac{dW}{dt} = \left(\frac{Z(t)}{k+Z(t)}b - d\right)W \tag{4}$$

Note that when $Z(t) = k$ the term $\frac{Z(t)}{k+Z(t)}$ is equal to $\frac{1}{2}$, therefore k represents the zooplankton density that leads to a 50% reduction in whale births.

Now I want to introduce new parameters into equation 4 to represent the effects of human factors on the rate of change of the whale population. The first human parameter will be h, and it will represent the per capita deaths due to human related incidents (vessel strikes and entanglements). Incorporating this term into the whale population rate of change model yields the equation:

$$\frac{dW}{dt} = \left(\frac{Z(t)}{k+Z(t)}b - d - h\right)W \tag{5}$$

The second parameter, f will take into account that nonfatal vessel strikes and entanglements have an effect on the whale birth rate b. Building on equation 5, the new equation for the rate of change of the whale population is:

$$\frac{dW}{dt} = \left(\frac{Z(t)}{k+Z(t)}fb - d - h\right)W \tag{6}$$

Using differential equations 4, 5, and 6, I will investigate the behavior of the solutions and determine the values of h and f that will lead to extinction of the North Atlantic right whale.

III. SOLUTION & RESULTS

Using the data collected from the NARW Annual Report Cards, I estimated values for the per capita birth rate b, the per capita natural death rate d, and the per capita rate of human caused deaths h. The average birth rate from 2004-2011 was significantly higher than the average birth rate from 2012-2018. For b, I used the average from 2004-2011, assuming that the decrease in births was a result of a diminishing food source or an effect of entanglements, which are both captured in the model separately.

Parameter	Value
W_o	465
Z_o	1.78
b	0.041
d	0.004
h	0.005

The other value needed in order to solve equations 4, 5, and 6 is k. To fix k, we need to determine at what zooplankton density will the whale birth rate will be cut in half? One way to answer this question would be to determine how many zooplankton a right whale eats in a day, then assume that if the whale eats less than half of that, the birth rate will be cut in half. To determine the density of zooplankton that equates to a normal day's worth of food, we would need to know how much water the right whale can filter through in a day. However, if the density of zooplankton is assumed to be uniform across the North Atlantic Ocean, right whales would have no trouble meeting their daily food requirement in a matter of hours even for a very low zooplankton density [3]. The issue is that this density of zooplankton is not uniform, and the whales must swim great distances to find the denser areas. For this reason, I assumed that at an average zooplankton density of $0.5\text{x}10^5$, the right whale birth rate would be decreased by 50%. This was based on comparing the birth rate data with the zooplankton density data. However, to overcome an imprecise choice of k, I evaluated the effects of varying k in the following analysis.

A. *No Human Factors*

Starting with equation 4 and plugging in equation 1 for $Z(t)$ we can solve the differential equation using separation of variables. The solution takes the form:

$$W(t) = Ae^{(b-d)t}(-0.011t + 1.78 + k)^{90.9bk} \tag{7}$$

where

$$A = \frac{W_o}{(1.78+k)^{90.9bk}} \tag{8}$$

From equation 7, it is clear that when $b > d$, the first term is exponential growth. Because human factors have not yet been introduced, this is a reasonable behavior for the whale population. The second term is more complicated due to the multiple parameters. Note that for $t > 162$, the function Z(t) will return a negative value, which is outside of the model domain for a population density. For this reason we will only consider $0 < t < 150$ and therefore the value $-0.011t +$

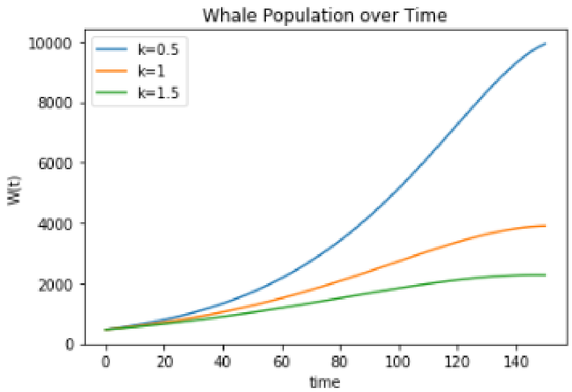

Fig. 1. Whale population over time for three different values of k. However, no human factors have been incorporated yet.

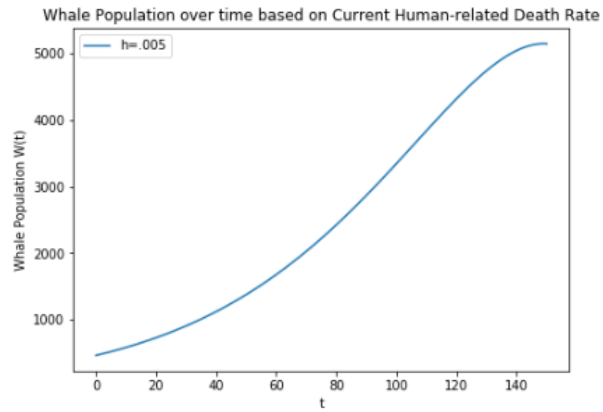

Fig. 2. Whale population over time using the actual average per capita human caused death rate of 0.005

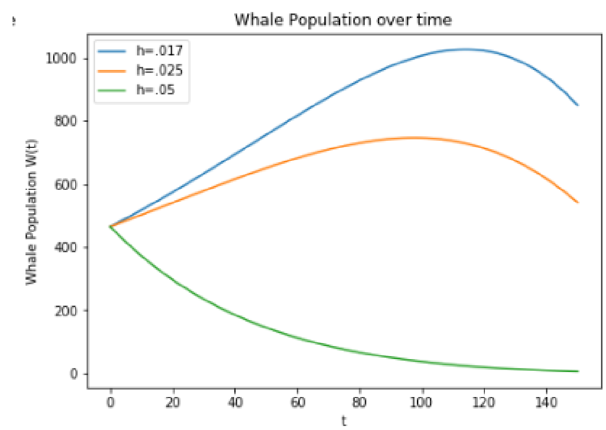

Fig. 3. The whale population experiences different behavior for different values of h.

$1.78+k$ is positive. However, since this is a negatively sloped linear function, the entire second term $(-0.011t + 1.78 + k)^{90.9bk}$ is decreasing in time. Figure 1 shows the behavior of equation 7 for multiple values of k.

B. *Constant Rate of Human Caused Fatalities*

Now that I have examined the solution of equation 4, I want to look at the solution set for equation 5, to determine how the human caused deaths are affecting the whale population. The solution for this differential equation looks very similar to equation 7, however now the total number of whales dying in a year is $(d + h)W$. Thus the solution becomes:

$$W(t) = Ae^{(b-d-h)t}(-0.011t + 1.78 + k)^{90.9bk} \quad (9)$$

Similarly to scenario A, the first part of this equation is exponential growth so long as $b > d + h$. For the values of b and d from the NARW Report Cards, only for $h \geq 0.037$ would the first part of the equation yield exponential decay. Using the value of h collected from the report cards, the first term would be exponential growth, and the second term is identical to scenario A. The solution can be seen in Figure 2.

Thus we can determine that at the current rate of deaths caused by vessel strikes and entanglements, the whale population will not collapse. However, in 2017 there was a record high of 8 deaths resulting from either entanglements or vessel strikes. Out of a population of 465, that yields a value of $h = 0.017$. If 2017 is an indication of a rise in human caused deaths, would the right whale population still be safe? To answer this question I graphed equation 9 for multiple values of h, including 0.017.

Looking at figure 3, it is clear that for some values of h, the whale population experiences growth up to a certain point, then decays from there. For $h = 0.05$, however, the population experiences decay from the start. By looking at equation 5, we can determine the threshold value for h. The rate of change of the whale population is zero if either the whale population W is zero, or if $\frac{Z(t)}{k+Z(t)}b - d - h$ is zero. The first case is not of interest, so instead we evaluate when the second case is true. Solving for h we find that $\frac{dW}{dt}$ is zero when

$$h = \frac{Z(t)}{k + Z(t)}b - d \quad (10)$$

To get a better understanding of what this means, see figure 4. However, h is a constant, and therefore it will either be greater than the curve for all time, less than the curve for all time $(0, 150)$, or cross the curve at some time, t^*. For $h = 0.05$, $\frac{dW}{dt} < 0$ for all time. For the other two values of h in figure 3, the population increases up to some time, t^*, at which point they cross the nullcline, and the population begins to decrease. Therefore, even if we take $h = 0.017$ based on data from 2017, the whale population will still grow for the next 100 years. However, if the data in 2017 indicates a growing rate of human caused deaths, the whale population could be in trouble.

When considering these results, it is important to remember the assumptions that were made in the model. Both the value of k and the function $Z(t)$ are assumptions. To understand how the equation for $Z(t)$ affects the results, let us look at a model that does not account for the effect of

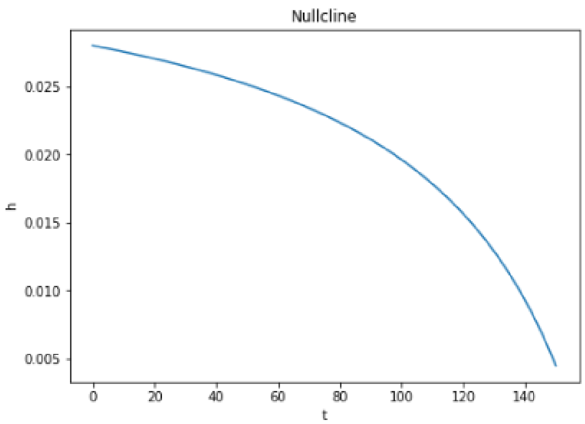

Fig. 4. Below the curve, $\frac{dW}{dt} > 0$ and above the curve, $\frac{dW}{dt} < 0$

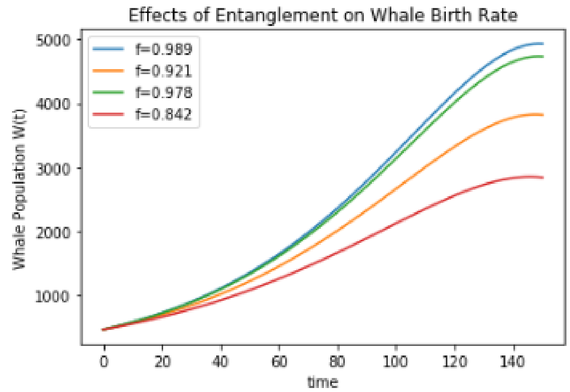

Fig. 5. Whale population model, equation 6, varying value of f, with fixed $k = 0.5$ and $h = 0.005$.

zooplankton on the whale birth rate. The equation for the rate of change of the whale population would look like:

$$\frac{dW}{dt} = (b - d - h)W \tag{11}$$

with the solution

$$W(t) = W_o e^{(b-d-h)t} \tag{12}$$

From equation 12, the rate of change of the whale population will be zero when $h = b - d = 0.037$. Thus for any $h < 0.037$, the whales population is growing exponentially, and for any $h > 0.037$, the whale population is decaying exponentially. In summary, if the effects of the zooplankton density are removed, humans could kill up to 3.7% of the whale population each year and the population would still grow. In the previous model, equation 5, this value of h would lead to population decay immediately. Therefore regardless of whether the function $Z(t)$ is accurate, it is imperative that lawmakers take into account other factors that affect the whale population, or the regulations they impose may not be enough to save the species from extinction.

C. *Human Caused Dampening of Birth Rate*

While it is valuable to know how many annual deaths caused by entanglement or vessel strikes would cause the North Atlantic right whales to go extinct, there is another consequence of these incidents that is being overlooked in section B. Not all entanglements or vessel strikes are fatal. Whales that become entangled in fishing lines or nets may drag along the gear for months or even years. This limits the animal's ability to swim, feed, and to calve. In 2018, there were no recorded right whale calves born [2]. Scientists attribute this to reduced health resulting from entanglements as well as to the reduction in available food resources [4].

In the model, I am already accounting for the effects of food availability, but a new parameter, f, needs to be introduced to account for the effects of nonfatal entanglements. Looking at equation 6, f is a coefficient for b representing the effect of nonfatal entanglements and vessel strikes on the birth rate. We can expect that this factor is proportional to the number of nonfatal incidents in a year. Using data from the 2007-2018 NARW Report Cards, the average annual per capita rate of nonfatal incidents (entanglements and vessel strikes) is 0.011. Using data on the number of females available to calve, we can come up with an estimated value for f. The average percent of females available to calve out of the total population is 13.9%. If we assume that every nonfatal incident affects a female available to calve, and prevents them from being able to reproduce for a year, we could expect a 7.9% reduction in the birth rate. However, it is possible that these incidents affect the whales for more than year. If we assume that each incident affects the whale for two years, then the average annual per capita rate of whales affected by entanglements and vessel strikes would be 0.022. Using the assumption that each of these incidents affects a female available to calve, there would be a 15.8% reduction in the birth rate. However, it is not very reasonable to assume that every entanglement and vessel strike would happen to a female available to calve. Instead, we could assume that the number of incidents involving these females is proportional to the ratio of females available to calve to the entire whale population in that year. In this case, incidents with a year long effect would reduce the birth rate by 1.1%, and incidents with effects lasting two years would reduce the birth rate by 2.2%

For these different scenarios, the parameter f is simply $100\% - X\%$, where $X\%$ is the reduction in the birth rate. In figure 5, these four different scenarios are graphed to see the effect on the population growth. Although it appears that these nonfatal incidents do not put the whale population at risk for extinction, we have to remember that this model depends on the parameters k and h as well as the function $Z(t)$.

What if instead, we look at $k = 1$, in other words the whale birth rate is reduced by 50% when the zooplankton density is $1\text{x}10^5$ zooplankton per m^3, and $h = 0.017$ based on the data from 2017. See figure 6 for the population model based on these parameters. Suddenly the future of the whale population is grim. Just as we did previously with h, we can

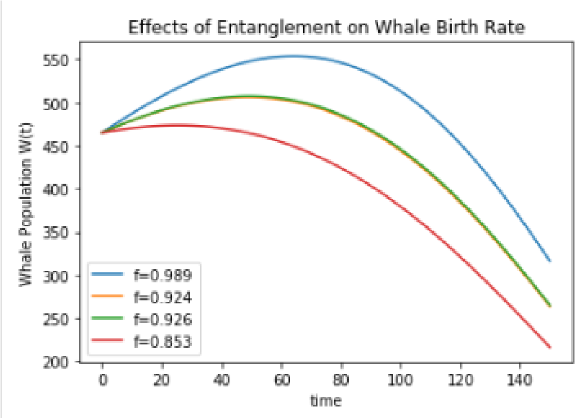

Fig. 6. Whale population model, equation 6, varying value of f, with fixed $k = 1.0$ and $h = 0.017$.

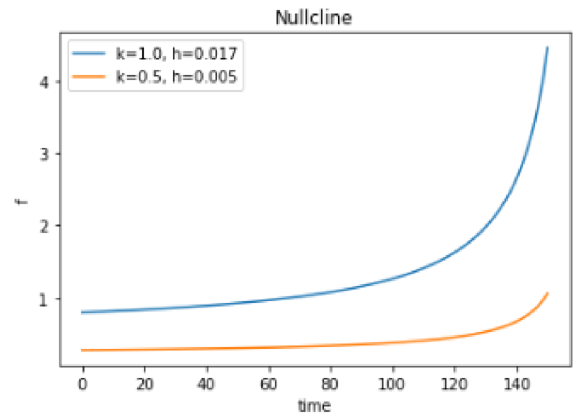

Fig. 7. Values of f above the curve result in population growth, values of f below the curve result in population decay.

look at f as a function of the other variables to determine the behavior of $\frac{dW}{dt}$. Setting equation 6 equal to 0 and solving for f, we find the rate of change of the whale population is zero when

$$f = \left(\frac{Z(t) + k}{Z(t)}\right)\left(\frac{h + d}{b}\right) \tag{13}$$

Values of f greater than the above expression will result in a positive $\frac{dW}{dt}$, and values less than that expression will result in a negative $\frac{dW}{dt}$. Thus if you increase the value of k and h, the threshold value for f is higher. Looking at figure 7, any value of f that falls under the curve will cause population decay. Note that the highest value of f is 1, equating to no effect of entanglements and vessel strikes on the birth rate. For the nullcline corresponding to $k = 1.0, h = 0.017$, any value of $f < 0.8$ will result in a decaying population for all time. For $0.8 < f < 1.0$, the population will grow for some amount of time, but after no more than 80 years the population will begin to decay. However, for the nullcline corresponding to $k = 0.5, h = 0.005$, for most reasonable values of f, the population will experience growth for at least the next 100 years. There would need to be a drastic increase in the number of nonfatal entanglements and vessel strikes to see population decay.

Returning to the value $k = 0.5$ while leaving $h = 0.017$, let's compare the models for equation 5 and equation 6. This will show us how much of an effect the parameter f has on the whale population. Figure 8 shows the difference between the two models when $f = 0.924$, which falls in the middle of the range that was expected based on the data. Although the behavior of the two population models is similar, the model that factors in the effect of entanglements on the birth rate has a much slower rate of growth, and begins to decay slightly before the other model.

IV. CONCLUSIONS

Lawmakers find themselves caught between two competing populations. However, they aren't competing for resources, and they are not predator and prey. Instead you have two populations whose coexistence poses a threat to

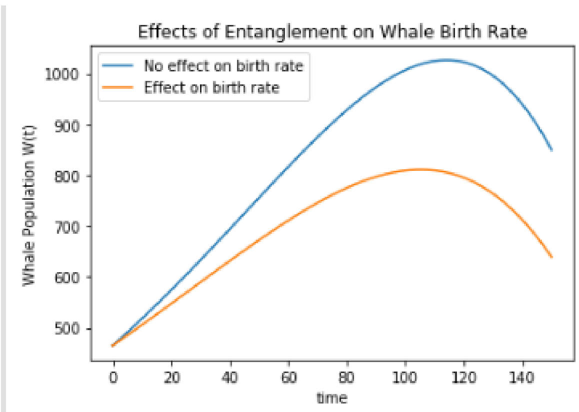

Fig. 8. $k = 0.5$, $h = 0.017$, $f = 0.924$.

one's life and the other's livelihood. On one side you have the North Atlantic right whale population, fighting to escape from its endangered species status resulting from centuries of damage done by whaling. On the other side you have New England lobstermen and fishermen whose livelihood depends on their ability to set fishing line and nets, and travel by boat throughout the North Atlantic ocean.

Will the right whale population go extinct if regulations are not put in place to reduce the number of entanglements and vessel strikes? Based on the results of the models in this paper, the answer is no. Using parameters estimated from the NARW report card data, the whale population will not grow anywhere near it's full potential, but it will maintain steady growth despite a diminishing food source and harmful effects of the fishing industry. However, a smaller population size is more susceptible to population collapse as a result of disease outbreak, pollution, or other factors not predicted by the models in this paper. For this reason, it is important that lawmakers make an attempt to reduce the number entanglements and vessel strikes. It is also worth noting that if the zooplankton density decreases at a faster rate than is assumed in this model, or the density becomes less uniformly spread across the U.S. Northeast Continental Shelf, the effects of entanglements and vessel strikes may become more consequential. As discussed in the results for each model, the thresholds for h and f depend on the zooplankton density and the value of k. However, these factors are not easily controlled. The decreasing zooplankton density is a result of climate change that will not be solved anytime soon. While the fishermen may complain that they are not the cause of the population decline, limiting their effect on the whale population may be enough to counterbalance the effects of the diminishing food source.

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