Aquatic Mammals 2024, *50*(6), 569-579, DOI https://doi.org/10.1578/AM.50.6.2024.569

An Agent-Based Model of Human–Whale Interactions in the North Atlantic

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Abstract

We created an agent-based model (ABM; a computational model) for human–whale interactions in the North Atlantic area. We specifically looked at boats, lobster lines, and rogue fishnet interactions with the North Atlantic right whales (*Eubalaena glacialis*), and we assessed the conditions under which such interactions are more likely to result in injuries and fatalities for this critically endangered whale, such as the density of ships in the water. ABMs are a methodology particularly useful in data poor problems (where machine learning cannot be used), and are based on rules of interactions between various agents (human and nonhuman) and/or a specific physical environment; they can showcase and assess potential future scenarios. We informed our model with current data from the North Atlantic Right Whale Consortium and the National Oceanic and Atmospheric Administration and present our preliminary findings here.

Key Words: agent-based model, anthropogenic factors, policy, NOAA, North Atlantic right whale, *Eubalaena glacialis*

Introduction

The conservation of the North Atlantic right whale (*Eubalaena glacialis*; NARW) has been a decades-long endeavor with mixed results (Myers & Moore, 2020; Koubrak et al., 2021; Moore et al., 2021). As there are more and more species, marine or not, facing extinction in the near future (Cowie et al., 2022), efforts to preserve the endangered and critically endangered species also need to be accelerated, including the adoption of more innovative methods that can help policymakers and conservation biologists and organizations in more specific, targeted ways.

In the case of the NARW, most of the habitat of this species lies within the territorial waters of the United States and Canada (Meyer-Gutbrod et al., 2023), where most of the injuries and deaths also occur (Pace et al., 2021). Particularly in the U.S., over decades, the National Oceanic and Atmospheric Administration (NOAA) (2008) has implemented various policies to mitigate the impact of anthropogenic factors contributing to the decline of this species. Additionally, this species is closely monitored and documented through images, sightings, and behaviors in the hope that observations and data will lead to new technologies and new analyses that will help with the conservation efforts such as AI and computational methods. Another particularity of the NARW is that their habitat lies within one of the most populated coastal areas in the world, and thus they are even more directly impacted by anthropogenic factors than other species (Williams et al., 2022).

In this article, we use a computational methodology from complex systems research to understand and predict the behavior of the NARW as a coevolutionary process with anthropogenic and climate factors—agent-based modeling. Agent-based models (ABMs) are a specific class of computer simulations that have been used effectively for modeling complex systems and policy recommendations in many areas, from economics to biology and chemistry, as they incorporate heterogeneous actors and interactions, and coevolving processes and dynamics for biological, social, and physical systems (Gilbert, 2019). Additionally, unlike machine learning methods, ABMs do not require lots of data, and they can be effective even in the absence of data as they can be informed by robust theories or qualitative data and case studies as well (we give a brief explanation of the methodology below).

While ABMs have been used before to simulate the behavior and evolution of marine mammals (e.g., humpback whales [*Megaptera novaeangliae*], killer whales [*Orcinus orca*], etc.), we are not aware of an ABM that represents the interaction of any marine mammals with anthropogenic factors such as boats or fishing gear (Mock & Testa, 2007; Chudzinska et al., 2021; Mortensen et al., 2021). Herein, we model the full complex system of the North Atlantic area: the NARW, the diversity of ships, the variations in food supply for the whales, and the fishing nets and gears (active and ghost/rogue) as well as lobster lines. In this way, we hope to better simulate scenarios of interactions between the whales and anthropogenic factors, thus giving us a more detailed and effective picture of the full system.

Methods

Agent-Based Models

This methodology has been successfully applied in a very wide range of fields and problems—from social sciences to biology and physics (Railsback & Grimm, 2019). ABMs are microscale models that simulate the actions and interactions of artificial autonomous agents, which are representations of people, groups, organizations, animals, objects or places, and environments. They are widely used in ecology, biology, and social sciences (Wilensky & Rand, 2015). They can re-create and predict complex phenomena and simulate simultaneously a multitude of interactions and behaviors. The strength of ABMs lies in their explanatory power of complex, non-direct causal and emergent phenomena, and in their ability to predict various scenarios that have not been observed in reality before (e.g., future of teams in an organization, economic policy implications if implemented, etc.).

NetLogo *Software*

For our ABM of human–whale interactions, we used the *NetLogo* software, which is an integrated development environment specifically designed for ABMs. Developed at Northwestern University (Evanston, IL, USA) by Uri Wilensky, it is a friendly programming language for non-computer scientists, with an easy-to-use user interface (Wilensky & Rand, 2015).

An ABM for the NARW

Location/GIS—The geographic location is a critical component of our model, specifically focusing on the North Atlantic Ocean near the Eastern United States and Canadian coasts. This region is a known habitat for the NARW (Fujiwara & Caswell, 2001; Meyer-Gutbrod et al., 2023) and a busy area for maritime activities (Borch et al., 2016), making it essential for studying human–whale interactions.

To accurately represent this area, we used Google Earth to create a detailed map, which was then imported into our model. The Google Earth map was used for ease in importing the shape files into the *NetLogo* software. We used distinct colors to identify water and land patches, ensuring that our agents (whales and ships) moved exclusively in the water. The entire modeled area was divided into 400 × 400 patches, each representing approximately 11.5 km^2. This level of detail allowed us to simulate interactions and movements with a high degree of spatial accuracy (Figure 1).

Agents and Their Attributes—In our ABM for human–whale interactions in the North Atlantic, we represented two main types of agents: (1) whales and (2) ships. Each agent was characterized by specific attributes that influence their behavior and interactions within the model:

NARW Agents

- *Age or 365 ticks (the equivalent of a year—a tick = a day)* – NARWs have a life expectancy of 45 to 65 y (National Oceanic and Atmospheric Administration [NOAA], 2024b); therefore, in our model, we used a random number in a normal distribution with a mean of 35 and a standard deviation of 20 to assign the initial ages randomly. Whales with ages more than the set life expectancy could die of age.

- *Health* – This is a measure of the whale's overall health, which can be impacted by environmental factors and interactions with ships. This is a normalized metric, and this constant is only for the initialization of the model, after which it is updated based on interactions.

- *Heal* – A NARW's ability to recover from injuries, reflecting its resilience. This is how the model knows if a certain injured whale should recover or deteriorate and eventually die.

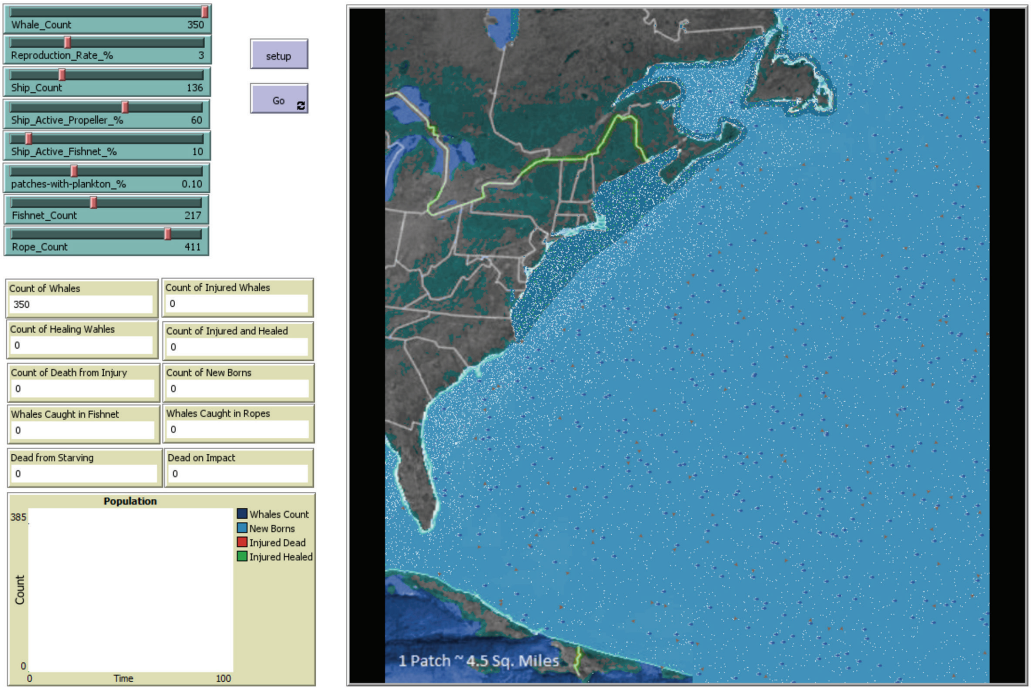
- *Energy* – The current energy level of the whale, affected by movement and plankton (food) consumption. Initial values were by randomly assigning a normalized percentage value.

- *Speed* – The velocity at which the NARW travels on average.

Ship Agents

- *Active fishnet* – Indicated whether the ship was currently using fishing nets, which can pose entanglement risks to whales.

- *Active propeller* – Indicated whether the ship's propeller was active, influencing the risk of propeller strikes.



Whale_Count 350
Reproduction_Rate_% 3
Ship_Count 136
Ship_Active_Propeller_% 60
Ship_Active_Fishnet_% 10
patches-with-plankton_% 0.10
Fishnet_Count 217
Rope_Count 411

Count of Whales 350
Count of Injured Whales 0
Count of Healing Wahles 0
Count of Injured and Healed 0
Count of Death from Injury 0
Count of New Borns 0
Whales Caught in Fishnet 0
Whales Caught in Ropes 0
Dead from Starving 0
Dead on Impact 0

Figure 1. An instantiation of our agent-based model (ABM) in *NetLogo*, with the GIS (geographical information system) layer of the North Atlantic region of interest. The green sliders are the parameters that can be set by the user, and the yellow monitors are the outputs from the model in absolute numbers at each simulation step (tick) and timeseries tracking.

- *Speed* – The velocity of the ship, which remains constant to the set value at the initialization of the model.

Interactions—The interactions between whale and ship agents are critical to understanding the dynamics of human–whale interactions. These interactions included the following:

- *Collision events* – When a NARW encounters a ship, there is a risk of collision. "Encounter" in our model means being on the same patch at the same time. In a likely collision, different outcomes are probable. The NARW may die on impact or it may get injured mildly or severely, which were determined by random numbers in our model.

- *Entanglement events* – When a ship with an active fishnet comes into contact with a whale, there is a risk of entanglement, which can reduce the whale's speed and energy. A whale may also get entangled in a derelict fishnet in the ocean as well as in lobster lines.

- *Feeding* – Whales consume plankton found in some patches. The quantity of plankton consumed affects the whale's energy levels. When a whale consumes the plankton in a patch, the quantity of plankton in that patch reduces; and if whales were not present in a patch for some time, the plankton starts to reproduce, and the amount of plankton increases.

- *Reproduction* – NARWs in specific age groups and locations can reproduce, contributing to population growth. Reproduction depends on several factors, but pregnant females give birth exclusively in the southern part of the study area (Foley et al., 2011). We used geolocation data to restrict whale births to that region. The reproduction rate is a parameter in the model that can be adjusted to analyze its effect on the population dynamics.

- *Aging and health* – Whales age over time, and their health can deteriorate due to injuries or lack of energy, leading to death. Fifty percent of whales over life expectancy (currently set at 70 y) die and are removed from the model, while an internal check-health parameter increases with eating and healing from injuries, and decreases with injuries from ship strikes and entanglements.

Parameters and Value Ranges—The parameters of our model were chosen based on a combination of real data, literature, personal discussions with marine biologists, and model calibration. Below is a table summarizing these parameters, their value ranges, and the justifications for these choices (Table 1).

Monitors and Output—To accurately track and analyze the dynamics of the NARW population and their interactions with human activities, our model included several key monitoring parameters such as injured, healed, or deceased whales. These monitors provided crucial insights into the health, behavior, and outcomes of the whale agents within the simulation environment (Table 2).

Model Calibration/Bayesian Optimization with Gaussian Processes—Ecological systems are complex, and nonlinear systems with multiple parameters affect the emergent behavior of the system. This makes traditional optimization methods insufficient. We optimized the model using manual methods, and the results were not close to the observed data. As a result, we employed Bayesian optimization with the Gaussian Process (GP) using the 'skopt' library in *Python*. The GP is an appropriate method to use with complex and noisy systems and, therefore, suitable for our ABM.

Data—The data used for the optimization step was a combination of data generated by the model

Table 1. The model parameters and their ranges

Parameter	Range	Justification
Whale_Count	0-350	Based on estimated number of right whales in the region
Reproduction_Rate	0-100	Percentage of whales with reproduction ability
Ship_Patch_Count	0-500	Average number of patches with passing ships in the region (each patch is 11.5 sq. km)
Ship_Active_Propeller_%	0-100	Percentage of ships with active propellers
Ship_Active_Fishnet_%	0-100	Percentage of ships with active fishnets
Patches-with-Plankton_%	0-60	Percentage of patches with plankton (of all patches including land, around 30% of model area is land)
Fishnet_Count	10,000-25,000	Number of derelict fishnets in the region (Hadley, 2020)
Rope_Count	200,000-300,000	Number of lobster lines/ropes in the region (Bisack & Magnusson, 2021)
Whale health	0-100	A normalized measure representing overall health status
Whale heal rate	0 or 1	Indicates whether a whale is currently healing or not
Whale energy	0-100	A normalized measure of energy levels
Active fishnet	Yes/No	Indicates whether a ship is using fishnets
Active propeller	Yes/No	Indicates whether a ship's propeller is active
Plankton amount	0-10	Amount of plankton available in patches for whales to feed on
Propeller injury %	3	Represents the risk of injury from active propellers
Fishnet injury %	5	Represents the risk of injury or death from active fishnets
Damage range	0 - 50	Range of potential damage to whale health from collisions
Live die rate	10	Probability threshold for whales dying upon collision
Injury rate	14	Probability of whales getting injured upon collision
Energy from plankton	0.6	Energy gained by whales from consuming plankton
Movement energy consumption	0.005	Energy cost percentage for whale movement by each tick
Fishnet energy take	1	Energy loss percentage for whales entangled in fishnets

Table 2. The output of the model that we are monitoring at each iteration

Monitor	Description
Count of whales	Total number of alive whales currently in the region
Count of healing whales	Count of whales that are injured but healing
Count of injured and healed	Whales that are injured and totally recovered
Count of injured whales	Whales that are currently injured
Dead on impact	Whales that died at a collision scene
Count of death from injury	Whales that died eventually as a result of an injury
Dead from starvation	Whales that are starved to death (due to entanglement, etc.)
Count of newborns	Number of newborn calves
Count of whales caught in fishnet	Number of whales entangled in fishnets

and some real-world observational data provided by the NOAA Marine Life Web Portal (NOAA IOOS [Integrated Ocean Observing System], 2024) and NOAA Fisheries (NOAA, 2024a). These data included key measures such as birth rates, injury rates, and death rates from various causes from 2017 to 2024. The averages of these values were used as target values for model calibration.

*Objective Function—*An objective function, in the context of the Gaussian Process mentioned above, is a function that is used for quantifying the performance or error of a model based on the input parameters. It measures the difference between the model's output and the observed data. There are multiple approaches for defining an objective function. The one we adopted used the sum of the squared differences between observed data points (NOAA IOOS, 2024) and the model outputs. This is a typical approach in optimization to minimize the error between the desired outcome and the actual outcome. Squaring the differences has the effect of giving more weight to larger errors.

Specifically, we aimed to minimize the differences in "Count of injured whales," "Count of deaths from injury," "Count of deaths on impact," "Count of newborn calves," and "Count of deaths from starvation" (Table 2). Therefore, we defined the objective function as follows:

$$\text{Objective} = (\text{injured} - \text{avg injured rate})^2 + (\text{injured \& died} - \text{avg death rate})^2 + (\text{dead on impact} - \text{avg dead on impact})^2 + (\text{newborns} - \text{avg newborns})^2 + (\text{dead starving} - \text{avg dead starving})^2$$

Pseudocode for the Gaussian Process Used to Calibrate Our Model

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(1) The algorithm starts with an initial set of parameter points randomly chosen.
(2) Then, the model runs with these parameters for 365 ticks (equivalent to a year as our observed data is daily and yearly).
(3) The objective function is then evaluated at these points, using the model measures and the observed data.
(4) The algorithm builds a probabilistic model, a GP, which estimates the function behavior.
(5) The algorithm uses an acquisition function to decide the next point to evaluate.
(6) After each evaluation, the GP model is updated with the new data point and its corresponding objective value.
(7) Steps 2 to 6 are repeated for a specified number of iterations or until a stopping criterion, such as convergence or a maximum number of evaluations, is met.
(8) Finally, the process provides the set of parameters that resulted in the minimum value of the objective function observed during the optimization.
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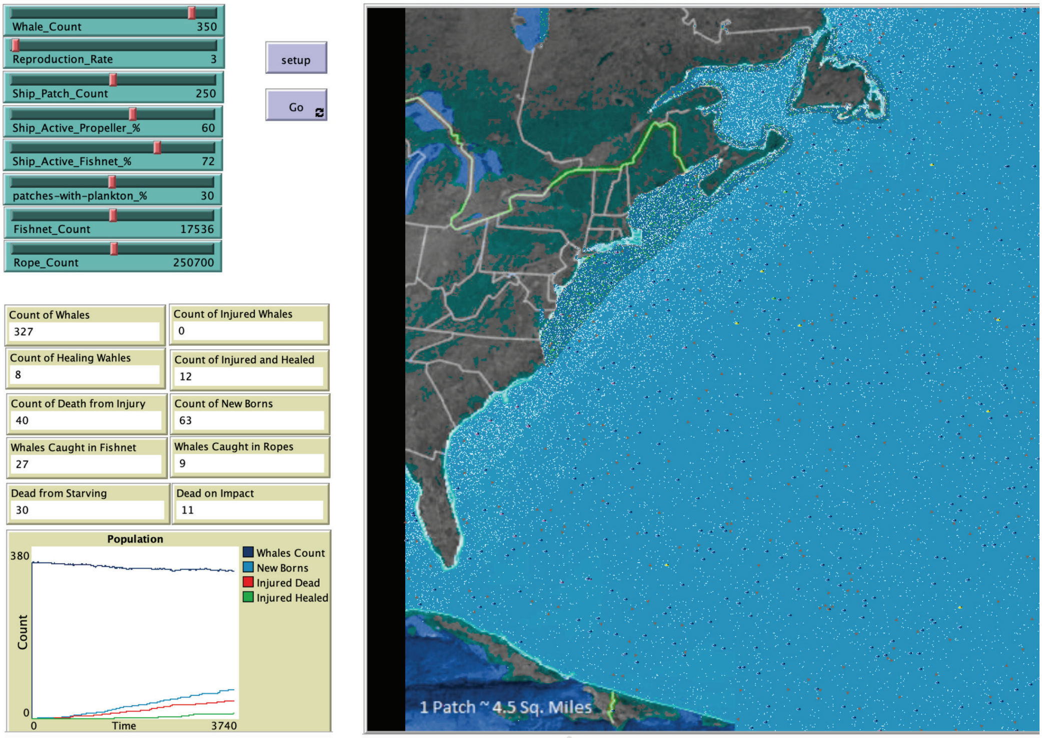
Results

Our first version of the model shows monitors in time of the NARW population in terms of total, newborn, injured, dead, entangled, and recovered individuals, based on a set of initial parametric values for the amount of available plankton, density of ships per area, rogue fishnets, and number of lobster lines. The following table shows the results of the model after manual optimization, which was far from the observed data, and after GP optimization, much closer to the observed data from 2017 to 2024 (Table 3).

As ABMs are highly dynamic, close to real-time observation models, a typical run of the model is better shown through a video demonstration than screenshots (the supplemental video for this article is available on the *Aquatic Mammals* website). In addition to our video demo, we also included a screenshot of a typical model run with initial

Table 3. Typical results from the optimized model

Per year	Observed data	Manual optimization results	Gaussian Process optimization results
Injured	10.75	46	12
Died from injury	5.00	31	2
Dead on impact	1.80	22	4
Newborns	15.75	19	16
Dead of starvation	1.50	0	0


Whale_Count 350
Reproduction_Rate 3
Ship_Patch_Count 250
Ship_Active_Propeller_% 60
Ship_Active_Fishnet_% 72
patches-with-plankton_% 30
Fishnet_Count 17536
Rope_Count 250700

Count of Whales 327
Count of Injured Whales 0
Count of Healing Wahles 8
Count of Injured and Healed 12
Count of Death from Injury 40
Count of New Borns 63
Whales Caught in Fishnet 27
Whales Caught in Ropes 9
Dead from Starving 30
Dead on Impact 11

Figure 2. A typical run of the model that shows the decline of the North Atlantic right whale (*Eubalaena glacialis*; NARW) population within 10 y (one simulation year = 365 ticks). In this case, the model starts with a population of 350 individuals; a low reproduction rate (3 calves/y); medium values for ship density in the water, active propellers, rogue fishnets, and actively fishing ships; and a medium number of lobster rope lines.

parameter values set at medium values (Figure 2). With our ABM, any researcher, even without being familiar with this methodology, can set up the desired parameters, design scenarios, and observe outcomes.

Scenarios

For example, if we wanted to know under which boat speed regimes the NARW population is more likely to rebound and pass a critical point, we can set and vary the speed parameter in the model at any point in the simulation and observe in the monitor graph how the population will change. Another scenario can be with respect to the distribution of fishnets as percentage of area or of boat density, and, similarly, we can track the tipping point for when the NARW population will grow for a sustained period of time. Or, the model can run any combination of existing plankton density, ship density, speed variation, rogue fishnets, or lobster lines that will result in scenarios that can be further explored by marine biologists.

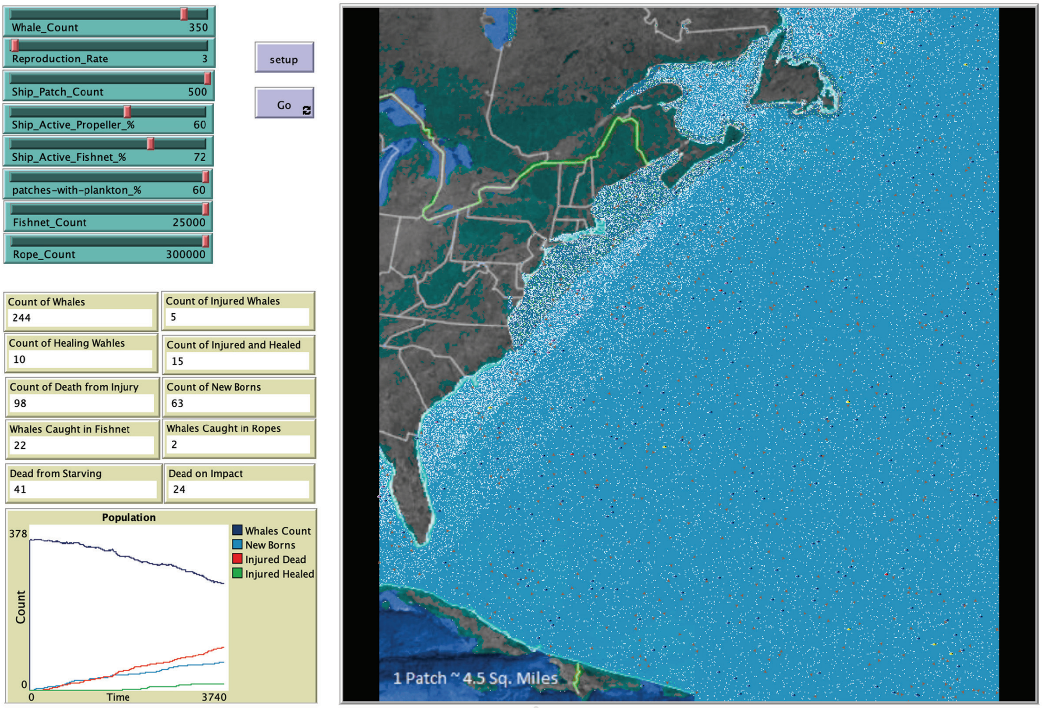
One scenario we devised was for the maximum and minimum values of parametric ranges for ship density, rogue fishnets, lobster ropes, quantity of plankton, and ship speeds (Figures 3 & 4). In the maximum case, the population sharply declined; while at the minimum case, the population was sustained at around 350 individuals.

We also tested for scenarios in which we minimized either the number of lobster lines, rogue fishnets, or ship density in the water while keeping other parameters at maximum values (Figures 5, 6, & 7). Of all these scenarios, it was the scenario with the least number of ships in the water that led to a stable population of whales in the next decade.

Naturally, we looked for the combination of parameters that led to the population of whales not only to be stable but to increase (Figure 8). We found such a scenario when we minimized the number of lobster lines and rogue fishnets but maximized the abundance of plankton, with a threshold of having nine ships or less per square kilometer, even if all these ships had active propellers and were actively fishing.

Discussion

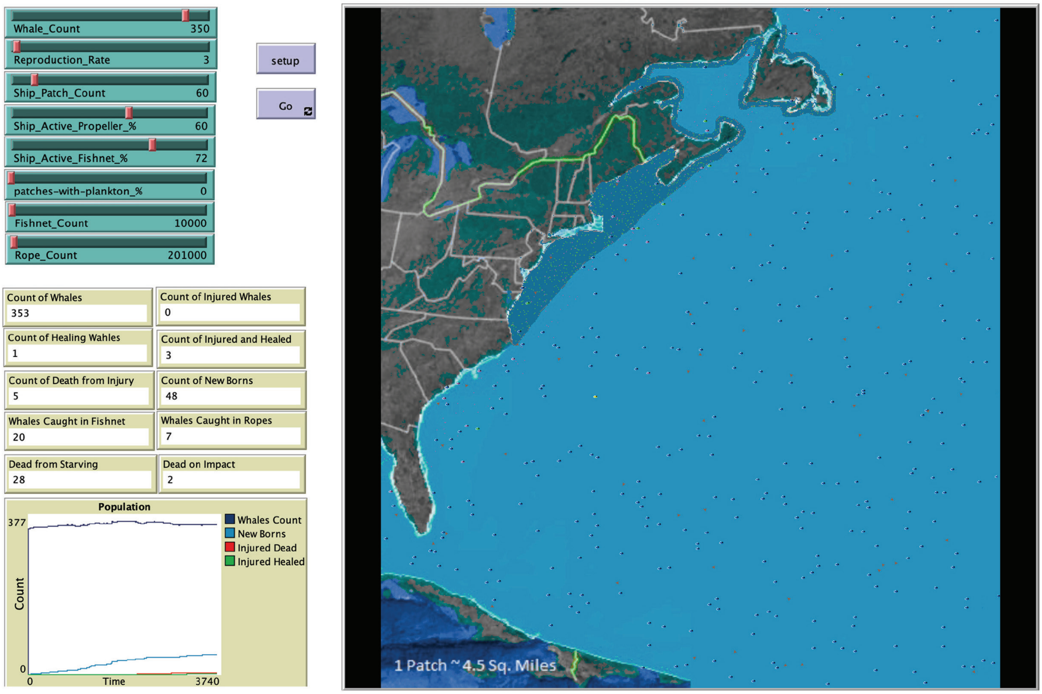
We are currently in the process of identifying all scenarios and possible combinations of parameters that lead to a sustainable or an increase in the NARW population by performing a full parametric sweep and analyzing all simulation data. We believe that our model provides a much-needed computational



Whale_Count 350
Reproduction_Rate 3
Ship_Patch_Count 500
Ship_Active_Propeller_% 60
Ship_Active_Fishnet_% 72
patches-with-plankton_% 60
Fishnet_Count 25000
Rope_Count 300000

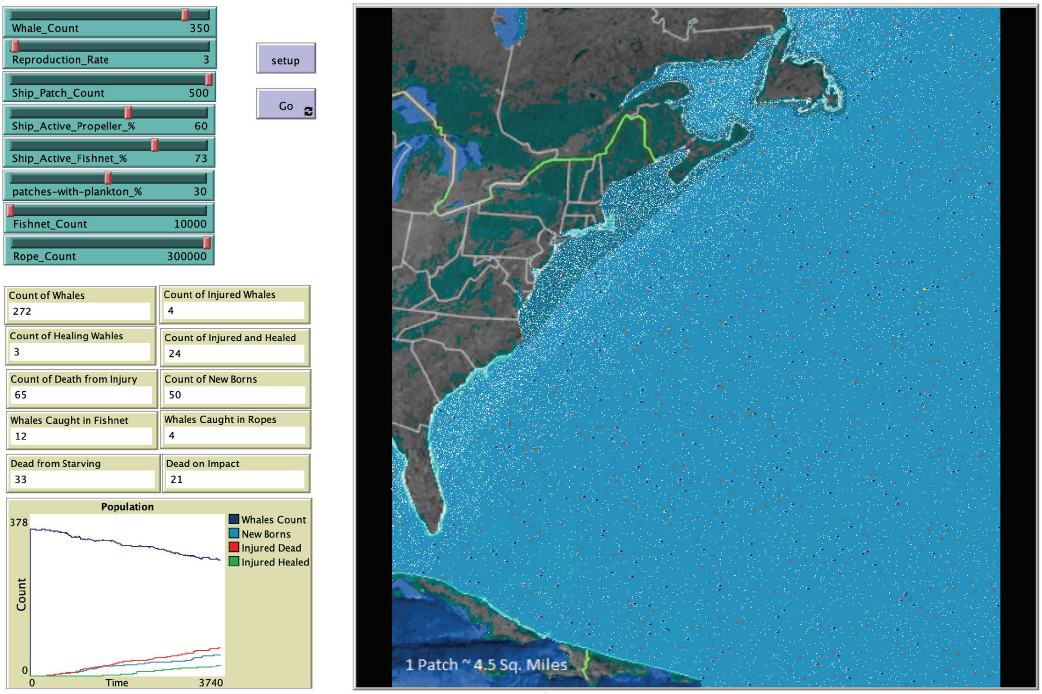
Count of Whales 244	Count of Injured Whales 5
Count of Healing Wahles 10	Count of Injured and Healed 15
Count of Death from Injury 98	Count of New Borns 63
Whales Caught in Fishnet 22	Whales Caught in Ropes 2
Dead from Starving 41	Dead on Impact 24

Figure 3. At maximum values of ship density in the water, rogue fishnets, and lobster ropes, even with an abundance of plankton, the whale population sharply declines in the next 10 y.


Whale_Count 350
Reproduction_Rate 3
Ship_Patch_Count 60
Ship_Active_Propeller_% 60
Ship_Active_Fishnet_% 72
patches-with-plankton_% 0
Fishnet_Count 10000
Rope_Count 201000

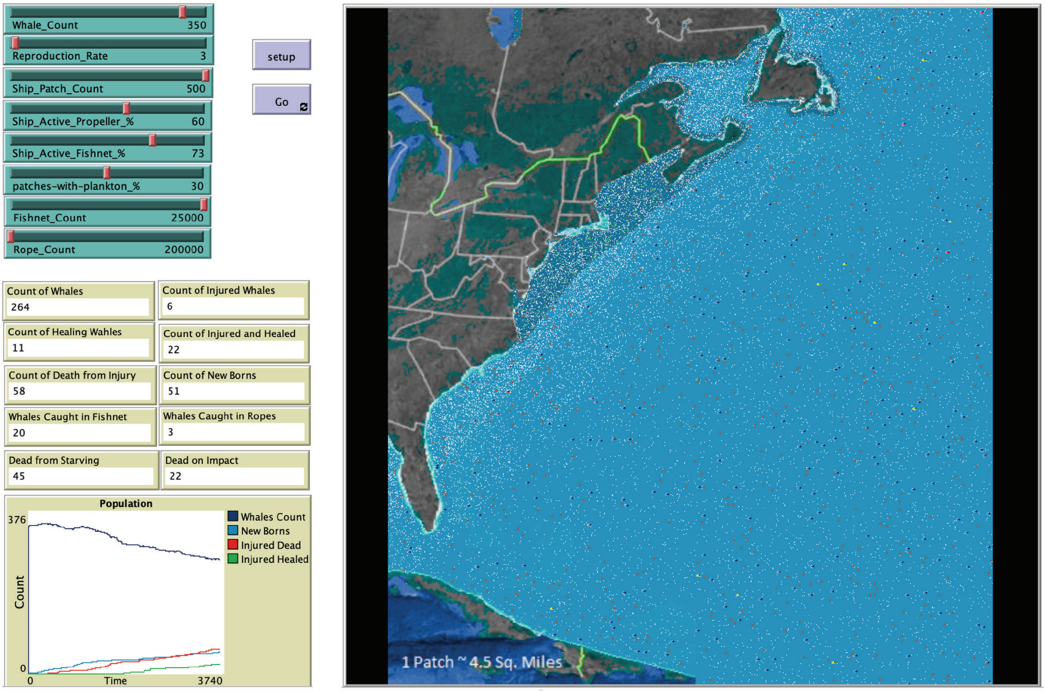
Count of Whales 353
Count of Injured Whales 0
Count of Healing Wahles 1
Count of Injured and Healed 3
Count of Death from Injury 5
Count of New Borns 48
Whales Caught in Fishnet 20
Whales Caught in Ropes 7
Dead from Starving 28
Dead on Impact 2

Figure 4. At very low values of ship density in the water, rogue fishnets, and lobster ropes, even with a scarcity of plankton, the whale population remains stable in the next 10 y.


Whale_Count 350
Reproduction_Rate 3
Ship_Patch_Count 500
Ship_Active_Propeller_% 60
Ship_Active_Fishnet_% 73
patches-with-plankton_% 30
Fishnet_Count 10000
Rope_Count 300000

Count of Whales 272
Count of Injured Whales 4
Count of Healing Wahles 3
Count of Injured and Healed 24
Count of Death from Injury 65
Count of New Borns 50
Whales Caught in Fishnet 12
Whales Caught in Ropes 4
Dead from Starving 33
Dead on Impact 21

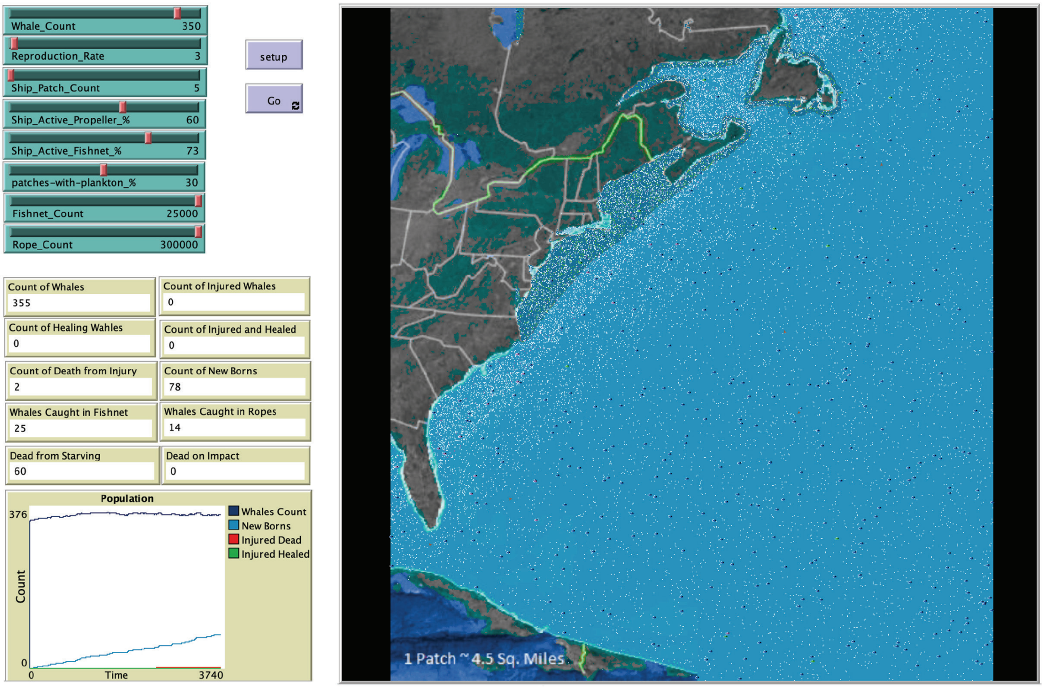
Figure 5. At very low values of rogue fishnets, but high values of lobster ropes and ships in the water, the whale population declines in the next 10 y.



Whale_Count 350
Reproduction_Rate 3
Ship_Patch_Count 500
Ship_Active_Propeller_% 60
Ship_Active_Fishnet_% 73
patches-with-plankton_% 30
Fishnet_Count 25000
Rope_Count 200000

Count of Whales 264
Count of Injured Whales 6
Count of Healing Wahles 11
Count of Injured and Healed 22
Count of Death from Injury 58
Count of New Borns 51
Whales Caught in Fishnet 20
Whales Caught in Ropes 3
Dead from Starving 45
Dead on Impact 22

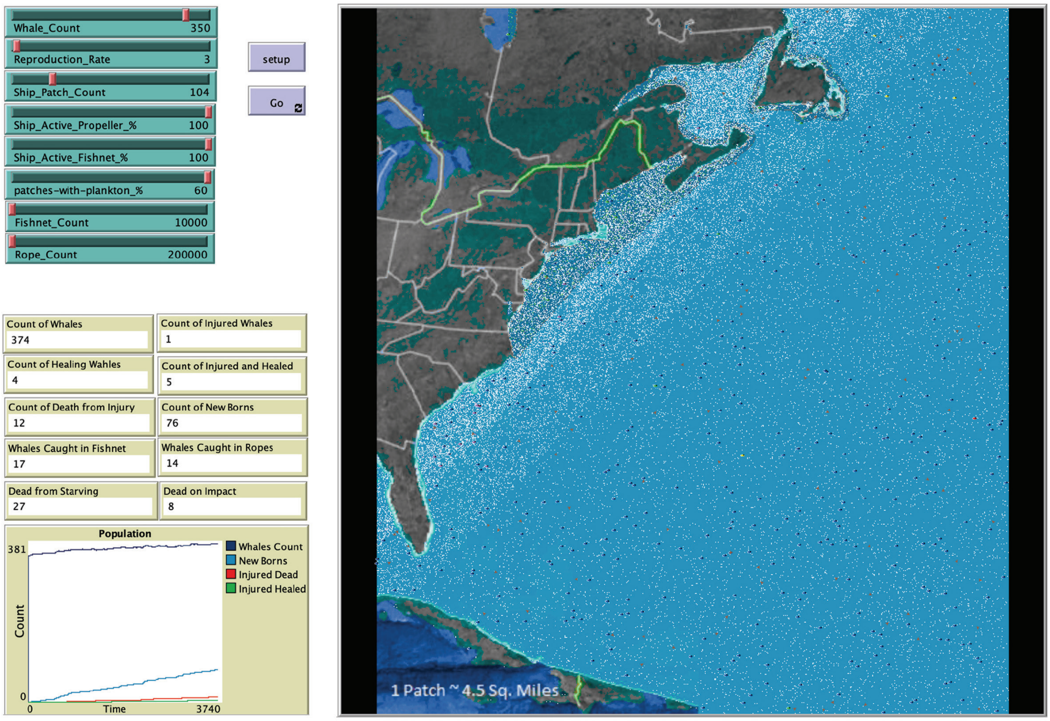
Figure 6. At very low values of lobster ropes, but high values of rogue fishnets and ships in the water, the whale population still declines in the next 10 y.



Whale_Count 350
Reproduction_Rate 3
Ship_Patch_Count 5
Ship_Active_Propeller_% 60
Ship_Active_Fishnet_% 73
patches-with-plankton_% 30
Fishnet_Count 25000
Rope_Count 300000

Count of Whales 355
Count of Injured Whales 0
Count of Healing Wahles 0
Count of Injured and Healed 0
Count of Death from Injury 2
Count of New Borns 78
Whales Caught in Fishnet 25
Whales Caught in Ropes 14
Dead from Starving 60
Dead on Impact 0

Figure 7. At very low values of ships in the water, but high values of rogue fishnets and lobster ropes, the whale population remains stable in the next 10 y.


Whale_Count 350
Reproduction_Rate 3
Ship_Patch_Count 104
Ship_Active_Propeller_% 100
Ship_Active_Fishnet_% 100
patches-with-plankton_% 60
Fishnet_Count 10000
Rope_Count 200000

Count of Whales: 374
Count of Injured Whales: 1
Count of Healing Wahles: 4
Count of Injured and Healed: 5
Count of Death from Injury: 12
Count of New Borns: 76
Whales Caught in Fishnet: 17
Whales Caught in Ropes: 14
Dead from Starving: 27
Dead on Impact: 8

Figure 8. At values of nine ships or less per sq. km in the water, minimum values of rogue fishnets and lobster ropes, and maximum abundance of plankton, the whale population increases in the next 10 y.

framework for scientists to understand which combinations of factors are going to push the NARWs beyond the tipping point toward extinction or toward sustainable rebound. Computationally, we can explore a wide range of future scenarios for both the short term (days) and long term (decades). Our model currently shows that we need a combination of very low values for rogue fishnets, lobster ropes, and ships in the water for the population of NARWs to thrive in the next decade. We also show that just minimizing the impact from the lobster ropes is not sufficient for the population to bounce back.

To be accurate in our predictions, though, and to provide useful recommendations to policymakers, we still need to adjust the model (calibrate and validate) more granularly than using GP optimization. We hope that by actively being in touch with the whale researcher community, we can keep on adjusting and recalibrating our model to the point where it can be a very reliable tool for researchers and policymakers who are relentlessly working to save this critically endangered species.

We hope our model also may be an example of what we can expect in the future from our interaction with other species as human–wildlife interactions and human expansion into natural habitats are only expected to increase in the future (Bhatia et al., 2020). Our hope, though, is that successful efforts for conservation of this species—the North Atlantic right whale—can in the future be expanded to other species and habitats and that our model may be used widely by marine biologists and conservationists to better understand under which scenarios the population of any critically endangered species is more likely to rebound or completely become extinct.

Note: The supplemental video for this article is available in the "Supplemental Material" section of the *Aquatic Mammals* website: https://www.aquaticmammalsjournal.org/supplemental-material.

Acknowledgments

The authors would like to thank the following individuals for very useful comments, conversations, and help with resources: Dr. Michael Moore (WHOI), Dr. Mike Asaro (NOAA), Dr. Mauricio Cantor (Oregon State University), Mr. Trevor Spradlin (NOAA Federal), Dr. Jennifer Lewis (George Mason University), and Dr. Daniel Palacios (Marine Mammal Institute). The authors would also like to thank the NARW Consortium and Dr. Robert Kenney for data access.

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