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Estimating North Atlantic right whale (*Eubalaena glacialis*) location uncertainty following visual or acoustic detection to inform dynamic management

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Abstract

The United States and Canada employ dynamic management strategies to improve conservation outcomes for the endangered North Atlantic right whale (*Eubalaena glacialis*). These strategies rely on near real-time knowledge of whale distribution generated from visual surveys and opportunistic sightings. Near real-time passive acoustic monitoring (PAM) systems have been operational for many years but acoustic detections of right whales have yet to be incorporated in dynamic management because of concerns over uncertainty in the location of acoustically detected whales. This rationale does not consider whale movement or its contribution to location uncertainty following either visual or acoustic detection. The goal of this study was to estimate uncertainties in right whale location following acoustic and visual detection and identify the timescale at which the uncertainties become similar owing to post-detection whale movement. We simulated whale movement using an autocorrelated random walk model parameterized to approximate three common right whale behavioral states (traveling, feeding, and socializing). We then used a Monte Carlo approach to estimate whale location over a 96-hr period given the initial uncertainty from the acoustic and visual detection methods and the evolving uncertainties arising from whale movement. The results demonstrated that for both detection methods the uncertainty in whale location increases rapidly following the initial detection and can vary by an order of magnitude after 96 hr depending on the behavioral state of the whale. The uncertainties in whale location became equivalent between visual and acoustic detections within 24–48 hr depending on whale behavior and acoustic detection range parameterization. These results imply that using both visual and acoustic detections provides enhanced information for the dynamic management of this visually and acoustically cryptic and highly mobile species.

KEYWORDS

dynamic management, movement behavior, near real-time passive acoustic monitoring, right whale, visual survey

1 | INTRODUCTION

The United States and Canadian government agencies have implemented a variety of management measures in an effort to improve conservation outcomes for the endangered North Atlantic right whale (*Eubalaena glacialis*; hereafter right whale). One such strategy is dynamic management, which broadly refers to risk-mitigation actions within defined areas in response to near real-time whale detections in those areas. Such actions are designed to reduce risk from the two primary sources of right whale mortality: vessel strike and fishing-gear entanglement (e.g., Knowlton & Kraus, 2001).

In U.S. waters, the National Oceanic and Atmospheric Administration (NOAA) can establish dynamic management areas (DMAs) on a case-by-case basis around persistent aggregations of right whales. The DMAs set a voluntary speed limit of 10 km for vessels ≥20 m length that remains active for 15 days or until the risk of vessel strike is deemed reduced (NOAA, 2019). There are currently no mechanisms in place for dynamic fishery management to reduce right whale entanglement risk in U.S. waters.

DMAs are monitored as frequently as possible, but because they are voluntary, NOAA has no mandate to conduct regular surveillance or enforce compliance. The aerial survey team at the Northeast Fisheries Science Center typically patrols DMAs at least weekly and DMAs are kept active as long as an aggregation persists within. NOAA has also established the Right Whale Sightings Advisory System to collect, validate, and communicate opportunistic visual detection reports by others that may also be used to establish a DMA (RWSAS, 2019).

Canadian governmental agencies instituted dynamic management for the first time in 2018, motivated by the 2017 unusual mortality event wherein 12 right whales were found dead in the Gulf of St Lawrence (Daoust, Couture, Wimmer, & Bourque, 2017; Davies & Brillant, 2019). Large areas of the Gulf of St Lawrence were subject to dynamic management in 2019 (TC, 2019). These included several zones associated with traffic separation schemes in the Honguedo Strait and Jacques-Cartier Passage wherein the visual detection of a single right whale triggered a mandatory 15 days, 10 km speed limit for vessels ≥20 m length. There were also several large areas subject to dynamic and mandatory closures of fixed-gear fisheries (primarily snow crab, *Chionoecetes opilio*, and lobster, *Homarus americanus*). A single right whale visually detected in such areas triggered a 15-day closure of a number of $10' \times 10'$ grid cells in the vicinity of the detection. Affected fishers were given a predetermined period (nominally 48 hr) to recover gear from these closed areas. Right whales visually detected outside these management areas also triggered fisheries closures on a case-by-case basis (DFO, 2019).

Transport Canada (TC) and Fisheries and Oceans Canada (DFO) are responsible for mitigating vessel-strike and gear-entanglement risk, respectively, to right whales in Canadian waters. In 2019, TC conducted weekly aerial surveys of those sections of the shipping corridors subject to dynamic management. Failure to survey within a week (e.g., due to weather, maintenance) triggered a precautionary area closure until a visual monitoring survey was completed. DFO could not guarantee any regular visual monitoring of areas subject to dynamic fisheries closures. Preliminary reports from 2018 and 2019 indicated that DFO achieved a total of 1–3 dedicated visual surveys of such areas during the 6-week snow crab fishing season (Johnson, 2018). Both DFO and TC incorporate, and act upon, validated (i.e., verified by an expert) visual detections provided by various governmental and non-governmental agencies. The collation and dissemination of all available near real-time right whale monitoring and detection data in Atlantic Canada (visual and acoustic) occurs via WhaleMap (Johnson, 2018).

Maintaining visual monitoring effort within and beyond known right whale habitats is a consistent challenge for dynamic risk-mitigation management and right whale conservation in general. Over the last several decades archival passive acoustic monitoring (PAM) has emerged as a powerful tool for efficient, safe, and persistent monitoring of right whales over time and space scales that are much greater than those achieved using conventional (aircraft and vessel) visual detection methods (e.g., Davis et al., 2017). While most PAM applications are archival (meaning that all data are archived on the monitoring platform), technologies that transmit detection information in near real-time have been in use for at least a decade (e.g., Spaulding et al., 2009). For example, the Woods Hole Oceanographic Institution has developed a near real-time PAM system that has been operational in a variety of ocean regions using two autonomous platforms: Slocum electric gliders (Baumgartner et al., 2013, 2020; hereafter ocean gliders) and moored buoys (Baumgartner et al., 2019). The performance of this system has been well characterized, and it has a false positive rate near or equal to zero for several baleen whale species, including North Atlantic right whales (e.g., near real-time right whale sounds are never erroneously reported as present when such sounds are not present in the acoustic record; Baumgartner et al., 2019, 2020). Since 2014, ocean gliders and buoys equipped with this system in the northwest Atlantic have logged ~4,700 days at sea with ~1,500 definitive right whale acoustic detections (Johnson, 2018). Although such detections have been used on numerous occasions to inform research efforts, visual surveys and military operations, they have never been used directly to trigger dynamic management in either U.S. or Canadian waters.

These near real-time passive acoustic detection systems are currently not capable of acoustically localizing a detected call. They report the position of the acoustic platform when a call is detected, not the position of the whale. Because many low-frequency baleen whale calls can propagate long distances underwater (km to 10s of km) there can be large uncertainty in the reported position of a near real-time acoustic detection. This uncertainty has often been cited as the primary rationale for not using near real-time acoustic detections to inform management decisions.

This rationale omits an important consideration: whale movement. There is always some delay—typically 24 hr or more—between a whale detection and associated management action. The reported position of a visually detected whale is initially precise but becomes more and more uncertain as time passes and the whale moves. Thus, the whale location when first visually detected is an inaccurate estimate of where the whale will be located when the management action goes into effect. The reported location of an acoustically detected whale has low specificity (typically estimated as the location of the passive acoustic instrument ± the acoustic detection range), yielding a similarly inaccurate estimate of where the whale will be located when the management action goes into effect. While both methods of detection have location uncertainties over management time scales, visual detections to date have been assumed, without documented foundation, to have lower uncertainty than acoustic detections for management purposes. Here we assess this assumption by first simulating right whale movements after visual and acoustic detection and then comparing the temporal evolution of location uncertainties between the two methods.

2 | METHODS

We simulated individual whale movements using a modified version of the autocorrelated random walk model of van der Hoop, Vanderlaan, and Taggart (2012). In brief, the model relied on placing a simulated whale at a given location, selecting an initial movement direction, and then simulating the movement trajectory by iteratively applying a swimming speed and turning angle at each model time step over a specified period. Initial movement direction was randomly selected from a uniform distribution between 0° and 360°. Swimming speed was randomly selected at each time step from a uniform distribution between 0 and 1.23 m s^{-1}, following Baumgartner and Mate (2005). The autocorrelated random walk was achieved by expressing the turning angle as the rate of change in direction (turning rate), where turning angles were constrained to a given angle per decametre (dam) travel. We used three different parameterizations of turning rate based on observations from Mayo and Marx (1989) to approximate movement patterns associated with three behavioral states; traveling (5.3° dam^{-1}), feeding (19.3° dam^{-1}), and socializing (52.5° dam^{-1}). A model time step of 2.5 s was chosen to simulate high resolution movements. A duration of 96 hr for each model simulation was chosen to encompass the range of dynamic-management response times observed in Canadian waters. Figure 1 illustrates trajectories of a single simulation for a whale for each of the three behavioral states over a 24 hr period.

We used a Monte Carlo approach to estimate the uncertainty in whale location over a 96 hr period following visual and acoustic detection based on 100,000 realizations of each simulated whale behavior. Location uncertainty was calculated as the distance between the reported location and the true (simulated) whale location over time. The reported location, which was equivalent to the reported location of a visual detection or the location of a passive acoustic detector, was placed at the origin of a Cartesian grid. For visual detections, we assumed that the initial uncertainty in the reported position was small because most dedicated right whale visual survey protocols require the survey platform to approach the detected whale to confirm species, number, behavior, and position, as well as other information. As such, the true initial location of a visually detected whale was calculated relative to the reported location with a range chosen randomly from a uniform distribution of 0–100 m and a bearing chosen randomly from a uniform distribution of 0–360°, resulting in an initial uncertainty of 0–100 m.

The uncertainty in the location of an acoustic detection is typically much greater than that associated with visual detections and is not well described. We used a logistic curve to model three different detection functions with a 50% probability of detection at 5, 10, and 15 km to represent short-, medium-, and long-range detection scenarios, respectively (Figure 2). The short- and medium-range estimates followed observations from coastal sites near Cape Cod (Clark, Brown, & Corkeron, 2010) as well as model-based estimates from Tennessen and Parks (2016), while the long-range detection scenario was based on observations in the central Bay of Fundy (Laurinolli, Hay, Desharnais, & Taggart, 2003). The true initial location of an acoustically detected whale was calculated relative to the reported location with a range

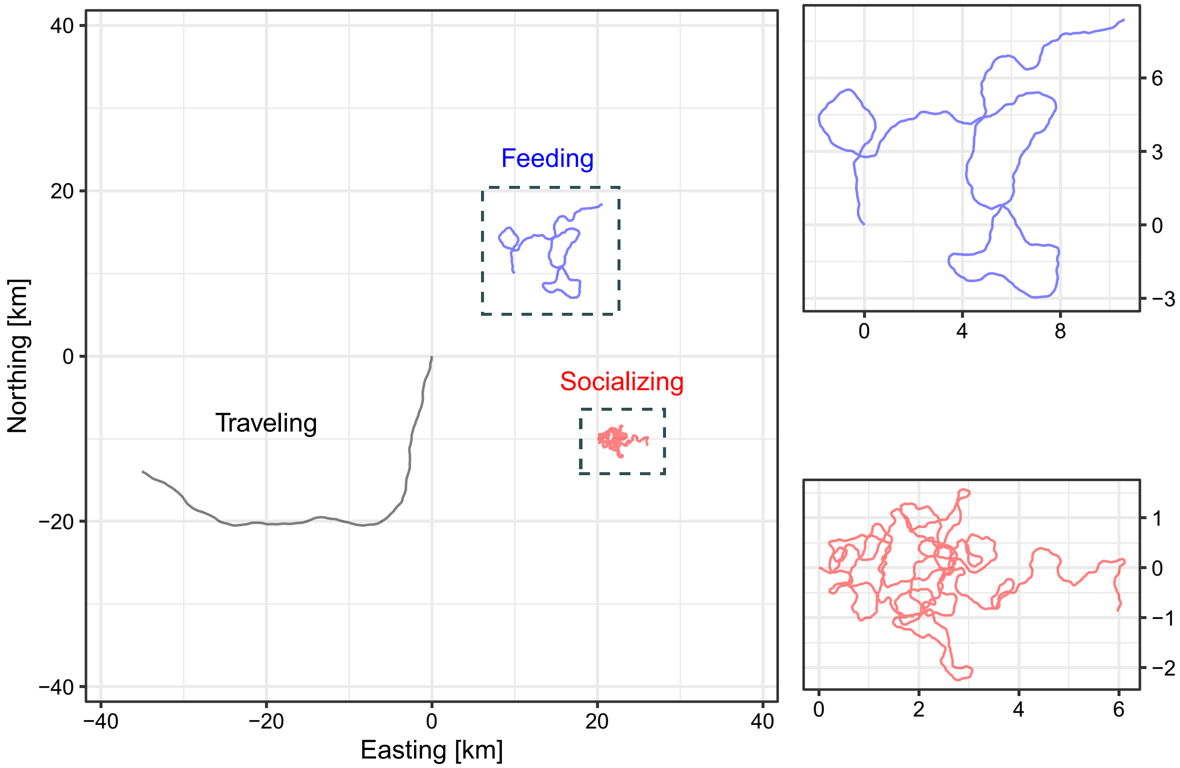

FIGURE 1 Example tracks (trajectories) of simulated right whales exhibiting traveling, feeding, and socializing behaviors over a 24 hr period

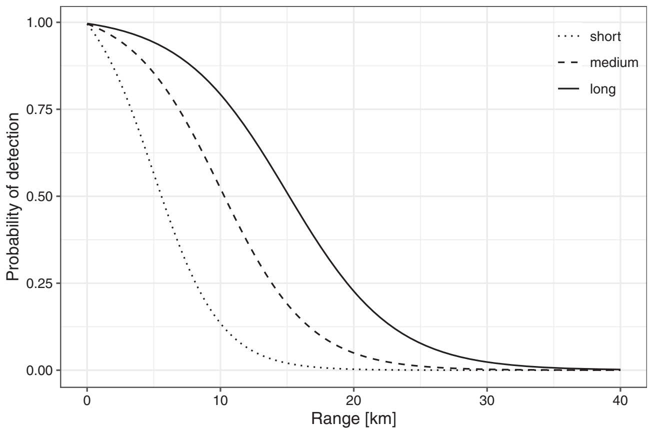

FIGURE 2 Acoustic detection functions used in the simulations to represent short (dotted line), medium (dashed line), and long (solid line) range detection scenarios

chosen randomly from the detection range logistic curve and a bearing chosen randomly from a uniform distribution of 0–360°.

Simulation results were based on 12 model runs, each with 100,000 realizations of a simulated whale that encompassed the combinations of the behavioral (traveling, feeding, socializing) and acoustic detection range (short, medium, and long) parameterizations. Simulated whale positions were used to calculate location uncertainties as the straight-line distance (range) from the estimated initial location at the center of the Cartesian grid at hourly intervals.

The difference in location uncertainty between visual and acoustic detections was evaluated using pairwise comparisons. We first simulated a trajectory and then defined the starting point based on either visual or acoustic detection uncertainty as described above. The difference in location uncertainty, r, at time t was calculated as follows:

$$r(t) = r_v(t) - r_a(t)$$

where r_v and r_a were the ranges from the origin to the visual and acoustic whale locations, respectively, at time t. This was applied for all trajectories and time steps. We then calculated the proportion of positive r values at each time step to estimate the probability of a visual detection providing a location estimate with an uncertainty greater than that of an acoustic detection. An illustration of the method is available online (Figure S1). All analysis was conducted using the R programming language (R Core Team, 2017). Visualizations were produced using the ggplot2 package (Wickham, 2016). The R code used for this analysis is available from GitHub: https://github.com/hansenjohnson/rw_sim.

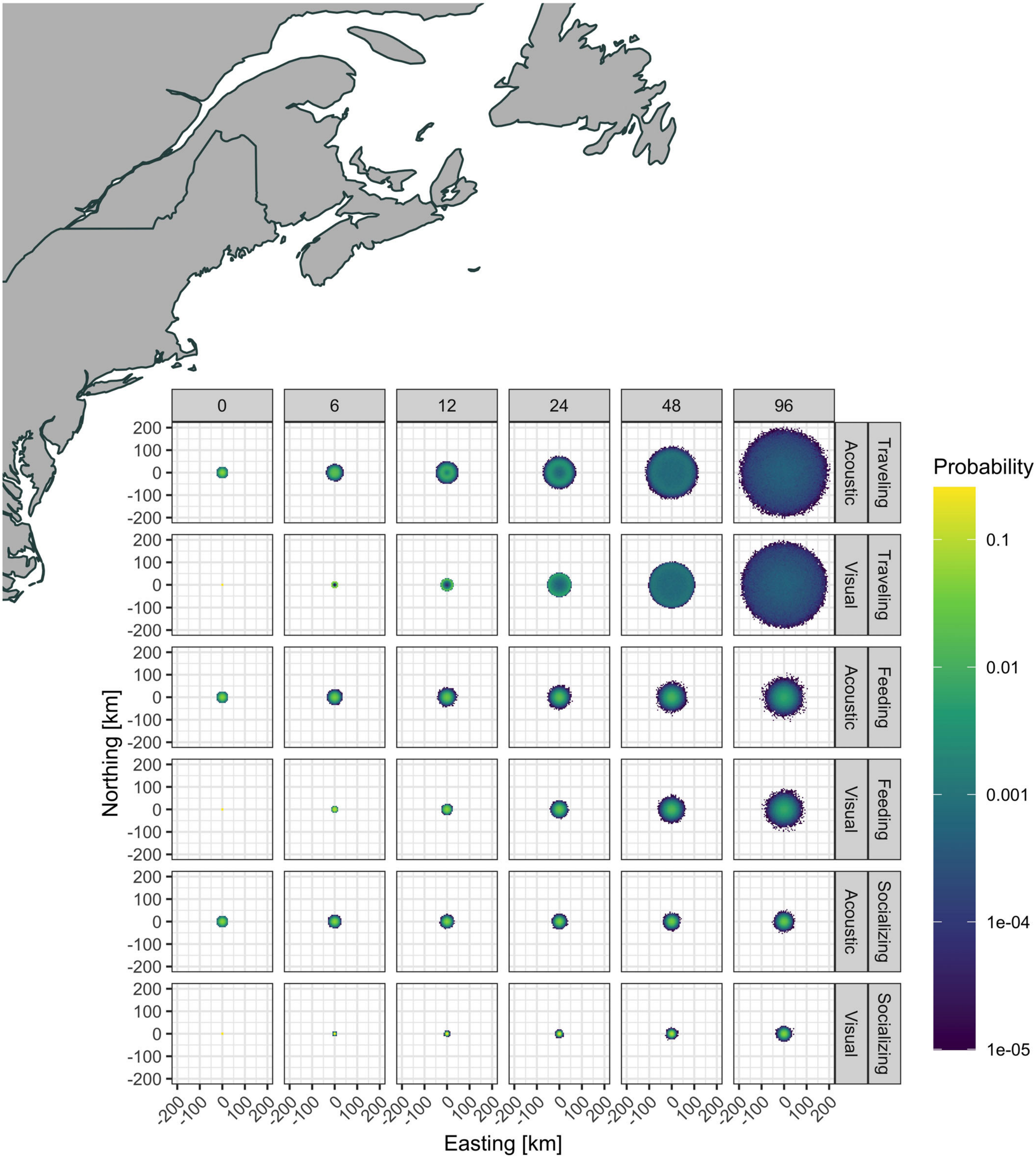

FIGURE 3 Evolution of location uncertainty after visual or acoustic detection of right whales in traveling, feeding, or socializing behavioral modes over the 96 hr model period. Color indicates the location probabilities per 5 × 5 km grid cell. Columns show the time (in hours) since detection. Rows indicate the detection method (visual or acoustic) and simulated whale behavior (traveling, feeding, or socializing). The center of the domain (0,0) indicates the reported position of the detection. The acoustic data were generated using the medium detection range parameterization. Data for the other detection range parameterizations are not shown. The map provides an indication of the approximate spatial scale of the location uncertainty estimates. (See Figure S3 for an animation of the simulation)

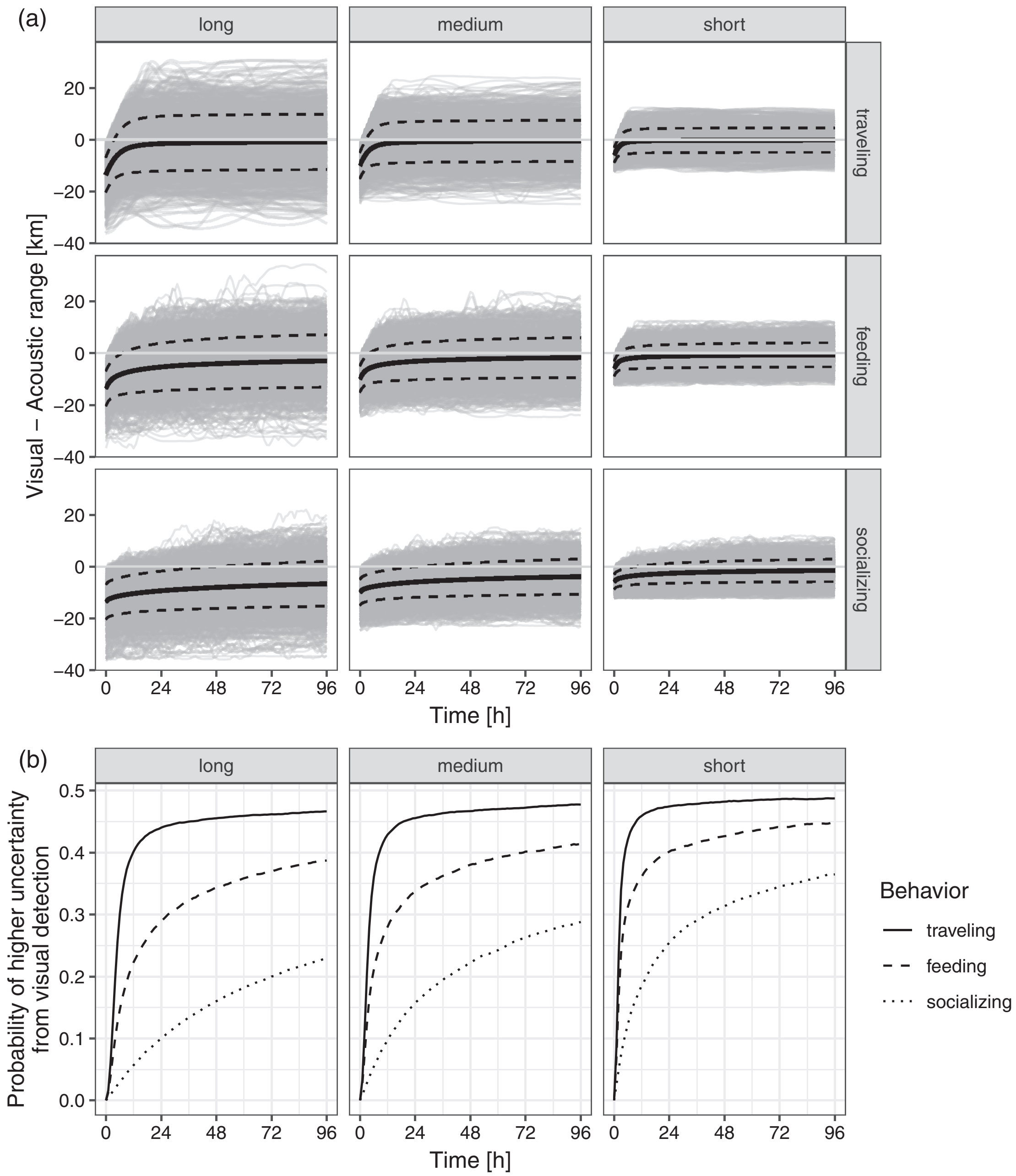

FIGURE 4 Differences in whale location uncertainties between visual and acoustic detection methods over the 96 hr model period. The columns indicate acoustic detection range parameterizations (long-, medium-, and short- range). In panel (a), rows show the modeled movement behaviors (traveling, feeding, and socializing) and each dark gray solid line represents the range difference time series for a single simulated track (n = 100,000). The solid and dashed black lines show the average and standard deviation of the range differences, respectively. The zero-difference line is emphasized in light gray. Panel (b) shows the probability of obtaining greater whale location uncertainty from a visual detection versus an acoustic detection

3 | RESULTS

Model results demonstrated that whale movement contributed to a rapid increase in whale location uncertainty following detection and the magnitude of this uncertainty was dependent on the movement behavior of the whale. Median uncertainty in visually detected whale location after 96 hr, which was almost entirely driven by movement, was 103 km (interquartile range, IQR: 69 km) for traveling whales, 28 km (IQR: 21 km) for feeding whales, and 10 km (IQR: 8 km) for socializing whales (Figure 3). Location estimates derived from visual and acoustic detections for each behavior were qualitatively similar over time scales of days (Figure 3). Timeseries plots are available online (Figure S2).

Location uncertainties for the visual and acoustic detection methods converged over time, and convergence was generally faster with higher displacement behaviors (traveling) and shorter acoustic detection range parameterizations. The differences between visual and acoustic location uncertainties never exceeded the maximum acoustic detection range, and the average difference approached zero over time (Figure 4a). Within 24 hr there was a 10–47% chance that the acoustic detection provided a more accurate location estimate than a visual detection, with the larger values again associated with shorter acoustic detection ranges and higher displacement behaviors (Figure 4b).

Computing the probability that a simulated whale would remain within a given radius of its initial reported position provided a means of evaluating the efficacy of potential dynamic management strategies implemented on different time/space scales in habitats dominated by particular behaviors. This probability decreased with time, higher displacement movement behaviors, and smaller radii. There was a less than 10% chance of a traveling whale remaining within a ≤25 km radius of its reported position after 24 hr, regardless of detection method. The probability of a whale remaining within 5 km of its reported position dropped below 10% in less than 24 hr for traveling and feeding whales, and in approximately 96 hr for socializing whales. In contrast, the probability of a feeding or socializing whale remaining within 25 km of the reported position after 24 hr was 71–92% or 91–100%, respectively. This decreased slightly for socializing whales but dropped to below 50% for feeding whales after 96 hr. In these cases, acoustic and visual methods produced similar estimates with better agreement in shorter detection range scenarios.

4 | DISCUSSION

Our results provide a reminder of the considerable mobility exhibited by North Atlantic right whales, and how their mobility contributes to a rapid expansion in location uncertainty following visual or acoustic detection. Our results also highlight the influence of the whale's behavioral state on mobility and thus the post-detection uncertainty in whale location. Whales in the simulated traveling mode moved a maximum of ~200 km from their initial detection location over the 96 hr study period, an order of magnitude greater than whales simulated in a socializing behavior mode. Baumgartner and Mate (2005) observed that right whales are capable of traveling ~80 km day^{-1}, nearly twice that simulated here. Conversely, there is evidence that right whales, particularly those exhibiting feeding or social behavior, may remain within a relatively small area (1–10 km radius) over several days (e.g., Baumgartner & Mate, 2005).

In most cases, our study demonstrates that whale movement obfuscates the initial differences in uncertainty between visual and acoustic detection methods such that the two provide equally uncertain estimates of whale location on dynamic management timescales. This is perhaps not surprising given that the spatial extent of daily right whale movement (~80 km day^{-1}; Baumgartner & Mate, 2005) is of the same order as the maximum acoustic detection range (~30 km radius; Laurinolli et al., 2003). The rate and extent of convergence between location uncertainties from visual and acoustic detections are governed by the acoustic detection range and the type of movement behavior. Shorter detection ranges and greater displacement-movement behaviors lead to faster convergence.

A simple concept that emerges from our analyses is that an acoustically detected whale is just as likely to move toward the reported position as it is to move away. In contrast, a visually detected whale will almost certainly move away from the reported position over time. This appears to explain the more rapid expansion of location uncertainties for visually versus acoustically detected whales over the ~24 hr period following the initial detection. From a management perspective, it also appears to demonstrate the folly of considering right whale detections as static points on a map instead of as location estimates that have rapidly expanding uncertainty over time.

Our analysis focuses on the detection information used to trigger dynamic management strategies. The specifics of these strategies are beyond the scope of this paper, but our movement simulations provide some insights into which general strategies may be most effective. Dynamic management is only successful if the whale that triggers a response remains within the managed space over a time scale that is sufficient to allow risk mitigation to be implemented. Thus, successful risk-management strategies must incorporate the rapid expansion in location uncertainties if the elected strategy is to be effective. Focusing on small areas (e.g., ≤5 km radius) is demonstrably illogical. This is perhaps best illustrated in the left-most column of Figure 5, where there is only a maximum 50% chance that a whale will remain within the 5 km radius management area for a ~24 hr period. Unless there is considerable (e.g., environmental or behavioral) reason to believe the whales will remain within, or frequently revisit, a small area such as above, or management measures are implemented near-

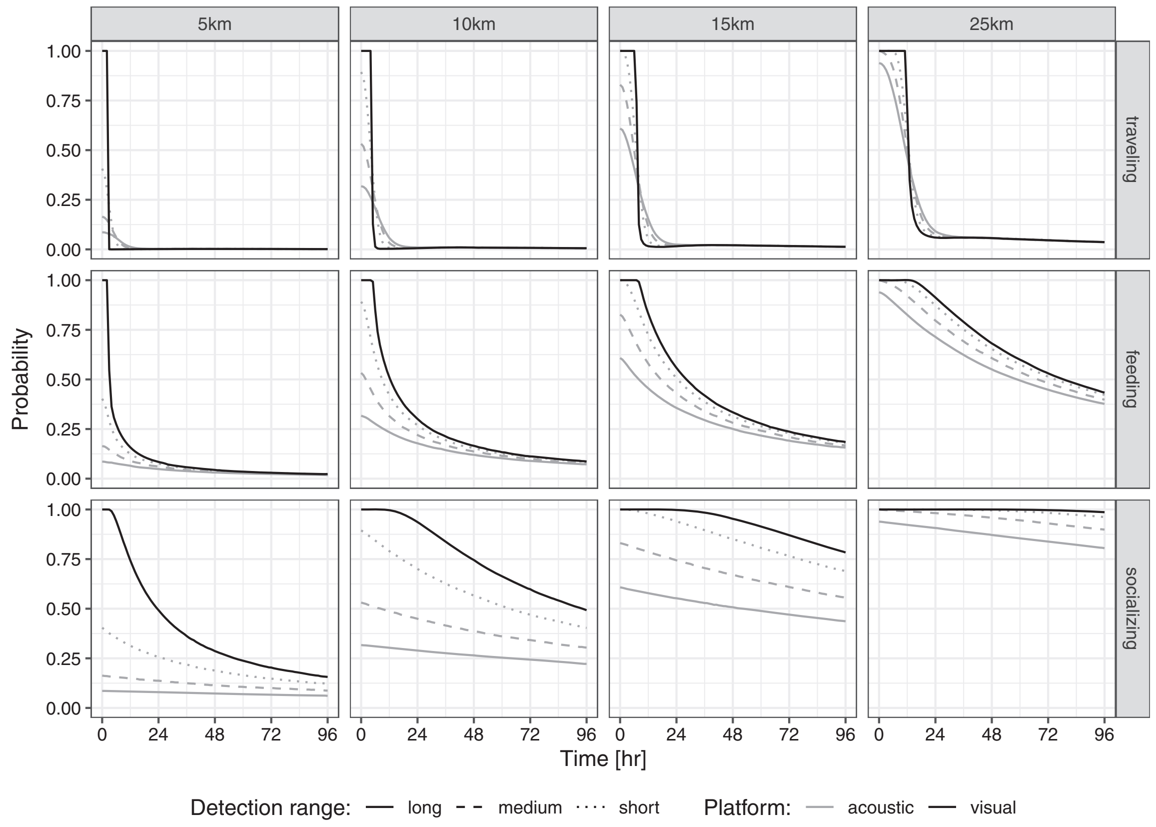

FIGURE 5 The probability a right whale detected acoustically or visually in a given behavioral state was within a given radius of the reported position over the 96 hr model period. Columns indicate radii about the reported position (5, 10, 15, and 25 km) used in the probability calculation. Rows show the modeled movement behaviors (traveling, feeding, and socializing)

instantaneously, it is unlikely that such management measures will prove effective. Similarly, spatial dynamic management in migratory corridors where whales are persistently traveling is unlikely to be successful when reliant on either visual or acoustic detection methods given the extent of location uncertainty that arises from whale movement. For example, one could implement a protective area of 25 km radius around a detection and have a ∼10% chance that a traveling whale remains within that area after ∼24 hr (Figure 5). Seasonal management of larger areas would likely be more effective in such regions.

Dynamic management is likely to be most effective when applied to large (>10 km radius) areas dominated by feeding or socializing. Acoustic and visual detections provide similar information in those conditions, though acoustic detections have higher uncertainty when detection ranges are long, such as in deep waters (>100 m) with low ambient noise levels (e.g., Laurinolli et al., 2003). Areas that have been monitored using near real-time passive acoustics, including south of Cape Cod, the Great South Channel, the Boston shipping lanes, Roseway Basin, and the southern Gulf of St Lawrence are more likely to fall into the short- to medium-range detection scenarios (e.g., Tennessen & Parks, 2016).

We emphasize that this modeling study is not an attempt to faithfully depict reality. Rather, it attempts to provoke a critical reflection on dynamic management strategies and the data used to trigger them. We rely upon several simplifying assumptions to model uncertainty in reported whale position, especially for acoustically detected whales. Whale movement is a complex behavior mediated by a wide array of poorly constrained factors. The model we used here is greatly simplified. It does not, for example, attempt to include the influence of any physical (e.g., hydrodynamic conditions, water temperature, stratification, depth), biological (e.g., conspecifics, prey) or anthropogenic (e.g., shipping) factors on whale movement. However, we intentionally chose parameterizations of movement behaviors and acoustic detection ranges that would allow us to capture realistic extremes of location uncertainty; more complicated movement behaviors or the selection of a different acoustic detection range parameterization should produce location uncertainties that fall within these extremes, and therefore the conclusions of our study would remain the same.

This work only considers a whale once it has been detected; comparing acoustic versus visual detectability is beyond the scope of this study (see Clark et al., 2010 for such a study). This work also only applies to single whales, as near real-time acoustic density estimation of ephemerally vocalizing species from a single-hydrophone platform is not currently feasible. The thresholds used to characterize the convergence between visual and acoustic location uncertainties are somewhat subjective because there is no established method for quantifying acceptable uncertainty in data used for management purposes. We have attempted to address that subjectivity by providing multiple metrics and displaying the results in a variety of different ways and invite readers to draw their own conclusions.

We encourage further studies that focus on constraining the major sources of uncertainty mentioned in this study: variability in behavioral state and acoustic detection range. Whale behavior studies are limited and insufficient to construct substantiated behavioral budgets across habitats, seasons, and demographics; these budgets are essential for effective management (Kenney, Mayo, & Winn, 2001). Efforts are underway to constrain acoustic detection range for near real-time PAM platforms, but this, as with movement behavior, is difficult to constrain as it varies widely across the time and space domains within which right whales are known to occur. We also urge the research and management communities to measure compliance with dynamic management efforts and to quantify the effective risk reduction associated with these efforts. Furthermore, it is essential that management strategies be developed in a transparent, scientifically supported manner so that they can be understood, evaluated and improved upon by affected industries, researchers, and the general public.

Our analyses demonstrate the equivalence of acoustic and visual detection information in a range of conditions and provide compelling evidence that near real-time acoustic detections are relevant and useable for dynamic risk management. We suggest that the most effective dynamic management strategies would cover large areas, be fully implemented quickly, and target habitats where right whales are typically engaged in low-displacement behaviors (e.g., toward the bottom-right of Figure 5). In such circumstances, visual and acoustic detection methods can be used interchangeably. Many such areas are covered occasionally, at best, by visual surveys and could stand to gain tremendously from the efficiency and persistence of near real-time PAM from autonomous platforms.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

AUTHOR CONTRIBUTIONS

Hansen D. Johnson, Mark F. Baumgartner, and Christopher T. Taggart conceived of and designed the study. Hansen D. Johnson conducted the analysis and drafted the initial manuscript. All authors contributed to the review and submission of the final manuscript.

DATA AVAILABILITY STATEMENT

All code required to reproduce this simulation and analysis is available at https://github.com/hansenjohnson/rw_sim

ETHICS STATEMENT

Not applicable.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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