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Striking the *right* balance in right whale conservation

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Abstract: Despite many years of study and protection, the North Atlantic right whale (*Eubalaena glacialis*) remains on the brink of extinction. There is a crucial gap in our understanding of their habitat use in the migratory corridor along the eastern seaboard of the United States. Here, we characterize habitat suitability in migrating right whales in relation to depth, distance to shore, and the recently enacted ship speed regulations near major ports. We find that the range of suitable habitat exceeds previous estimates and that, as compared with the enacted 20 nautical mile buffer, the originally proposed 30 nautical mile buffer would protect more habitat for this critically endangered species.

Résumé : Malgré de nombreuses années d'étude et de protection, la baleine franche du nord (*Eubalaena glacialis*) de l'Atlantique Nord demeure au bord de l'extinction. Il y a une faille essentielle dans notre compréhension de leur utilisation de l'habitat dans le corridor de migration le long de la côte est des États-Unis. Nous caractérisons ici la convenance des habitats pour les baleines franches en migration en relation avec la profondeur, la distance de la rive et la réglementation récemment en vigueur sur la vitesse des navires près des ports principaux. Nous trouvons que la gamme d'habitats adéquats dépasse les estimations précédentes et que, par comparaison à la zone tampon de 20 milles marins présentement en vigueur, la zone tampon de 30 milles marins proposée à l'origine protégerait plus d'habitats pour cette espèce sérieusement menacée de disparition.

[Traduit par la Rédaction]

Introduction

Despite many years of study and protection, the North Atlantic right whale (*Eubalaena glacialis*) remains on the brink of extinction (Fujiwara and Caswell 2001; Kraus et al. 2005). Although a more complete understanding of right whale movement, feeding, and distribution patterns on their northern foraging and southern calving grounds has emerged (Kraus and Rolland 2007), the space used by right whales along their migratory corridor remains almost entirely unknown. This lack of knowledge impedes management of the segment of this critically endangered species, namely pregnant females and nursing mothers, whose death most impacts population survival (Fujiwara and Caswell 2001). As right whales migrate, they pass several of the largest ports on the eastern seaboard (Knowlton et al. 2002) (Fig. 1). Ship strikes are one of the primary factors limiting recovery of this species; more than a quarter of known ship strike mortalities for right whales occur in this region (Knowlton

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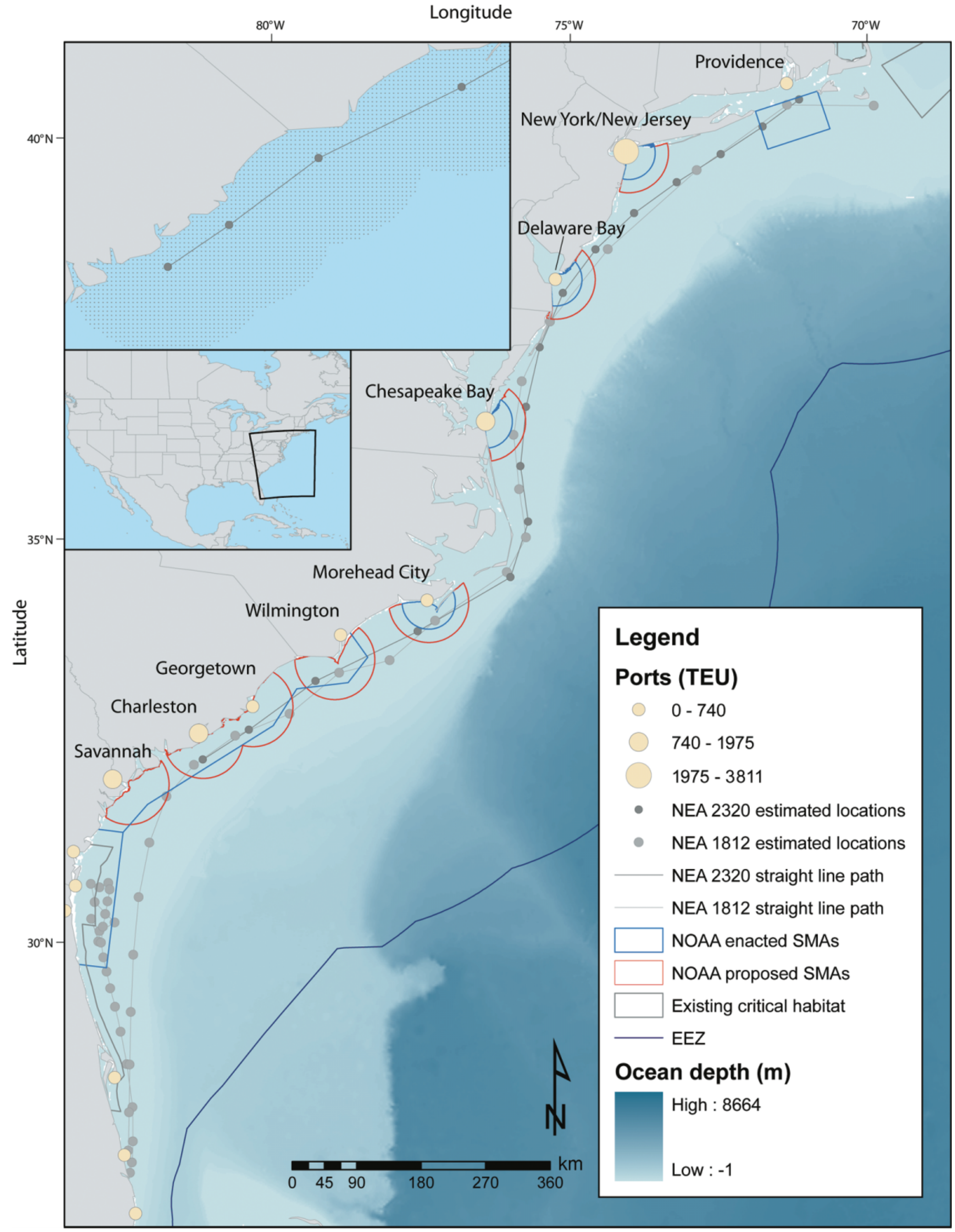
Fig. 1. The portions of two movement paths that cross the migratory corridor are depicted in relation to the proposed (red) and enacted (blue) seasonal management areas (SMA). Light grey and dark grey circles are estimated locations of NEA 1812 and NEA 2320. Major ports are in beige. The upper inset map shows the last four locations of NEA 2320's track in grey with the buffered track shown in light grey. The lower inset map highlights the study area. TEU, twenty foot equivalent units; EEZ, exclusive economic zone.



et al. 2002). Knowledge of how right whales perceive and move through this area will help inform the risk of ship strikes near these ports. Accordingly, we fit a new movement model to the migratory paths of two female right whales to estimate habitat suitability along the Mid-Atlantic corridor. In fitting this model, we emphasize (*i*) the general suitability of this important migratory corridor and (*ii*) the spatial relationship between habitat suitability and recently enacted vessel speed restrictions near shipping ports along the east coast (NOAA 2008).

Data

The data used here come from portions of movement paths from two female right whales: NEA 1812, tagged in 1996 (C.K. Slay and S.D. Kraus, unpublished data), and NEA 2320, tagged in 2000 (Baumgartner and Mate 2005). Both animals were tagged with ARGOS satellite-monitored radio tags. NEA 1812 is a reproductively active female at least 20 years old. She was first identified in Roseway Basin on the Nova Scotian Shelf in September 1988 and was last seen in August 2008 in the Bay of Fundy. NEA 1812 was accompanied by a newborn calf at the time of tagging. NEA 2320 is a reproductively active female first identified in January 1993 off Florida and last seen in March 2008 in Cape Cod Bay. Information about age, sighting history, and reproductive status comes from The North Atlantic Right Whale Catalog (http://rwcatalog.neaq.org/Default.aspx, last accessed 12 December 2008). The track of NEA 1812 originated off Fernandina Beach, Florida, on 21 February 1996 and ended in the Gulf of Maine on 2 June 1996 (Fig. 1). (Note that the ports are symbol coded according to TEU (twenty foot equivalent units), where 1 TEU approximately represents the capacity of a standard shipping container, or 1360 ft^3, information taken from the United States Army Corps of Engineers, Navigation Data Center (http://www.iwr.usace.army.mil/ndc/wcsc/by_portname06.htm, last accessed 19 February 2009).) The track of NEA 2320 originated in the Bay of Fundy on 11 August 2000 and ended just north of the calving grounds in Florida and Georgia on 15 December 2000 (Fig. 1). In both cases, we ignored the Gulf of Maine portion of the tracks because this comprised a demonstrably different behavioral state and locations were no longer in the migratory corridor. For NEA 1812, 24 locations spanned the calving ground and migratory corridor; for NEA 2320, 16 locations spanned the migratory corridor. NEA 1812 transmitted for 103 days and covered 2676 km (average of 26.0 $km \cdot day^{-1}$). NEA 2320 transmitted for 127 days and covered 5612 km (average of 44.2 $km \cdot day^{-1}$).

Methods

Because the model from Schick et al. (2008) assumes equal time intervals between locations, we fit the model from Jonsen et al. (2005) to the data as a first-stage filter to obtain an estimate of the true path. The model from Jonsen et al. (2005) is a state-space model that uses a directed correlated random walk as the process model and that returns daily estimates of the animal's true position and, where appropriate, estimates of a behavioral state. We then buffered positions along this estimated path to compare actual location visited at time t versus a range of possible locations. We chose a 100 km spatial buffer around each location at time t because this distance slightly exceeded the maximum daily distance covered by the individual whales (97 km). Using GIS, we sampled two environmental covariates, water depth (metres) and distance to shore (kilometres), at each of these possible locations along the path of the individual as well as at the centroid of each 4 km grid cell within the buffered track (Fig. 1, inset). Because there is no literature describing the response of migrating right whales to dynamic covariates such as sea surface temperate, we did not include them in our model. In certain cases where shorter movements by the animal resulted in overlap of the spatial buffers, a separate time index was derived for each of the points. In other words, at time $t = 3$, the possible locations were, for example, 100. At $t = 4$, the locations were also 100, but since the animal only moved 5 km, 90 of these 100 possible locations were the same as the previous time step. In this case, we calculated and kept the space and time index of each patch in relation to when it could have been visited by the moving animal (Fig. 1, inset). We built upon these two covariates by separately calculating quadratic terms for both water depth and distance to shore. We used quadratic terms to see if there was an optimal range for each of these covariates and because without them, the assumption would be that right whales prefer the smallest possible values for each covariate, i.e., the closer right whales are to shore, the higher the suitability. In addition, we calculated the distance from the animal's position at time $t - 1$ to the current location of possible patches at time t. This allowed us to make inference on how distance from the animal affects suitability.

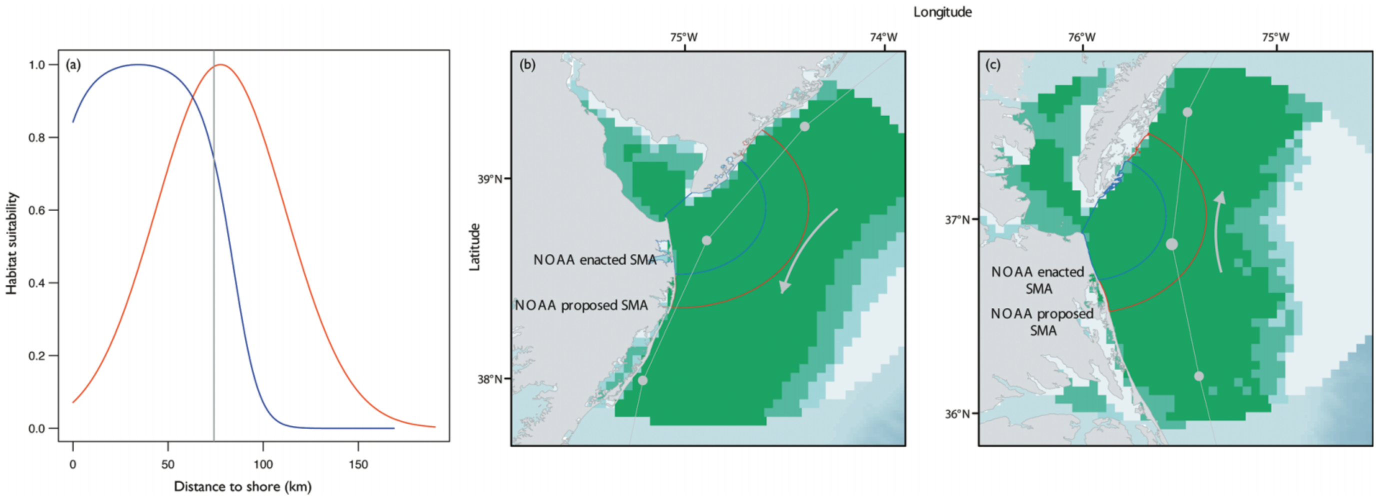
To these data, we applied the Bayesian movement model from Schick et al. (2008) that embeds a resource selection function (Manly and McDonald 2002) inside a movement model in an effort to infer the parameters governing relative habitat suitability h, where h is a function of environmental covariates. That is, how does the suitability of the patch chosen differ from those the animal could have chosen to visit? We modeled suitability as a function of the two environmental covariates, including both linear and quadratic terms for both. The model from Schick et al. (2008) exploits observed movement relative to the options available as the basis for inference on habitat preference.

We used these covariates and regression parameters to model the suitability h of areas along the track. At each point along the movement track, the animal chooses one location of many possible locations. We used a multinomial for the likelihood based on the assumption that the animal chooses the location with probability θ. Probability θ was mechanistically derived from the relative suitability h of the visited patch. Suitability h was normalized by dividing by the sum of h for all other patches. Suitability h had a functional form $\mathbf{X}\beta$. We constructed $\mathbf{X}$, and in a Gibbs sampling framework, we drew βs from a truncated multivariate normal distribution with mean values based on the current values of $\beta^{(g)}$, where the g superscript represents the current step in the Gibbs loop. The density a of the proposed value is determined in relation to the current value, and if $a > 1$, the proposed values were accepted. We derived and used an empirical covariance matrix $\mathbf{V}$ for this multivariate distribution. A default covariance matrix was used at the start of the Gibbs sampler, and we then twice calculated and employed the empirical covariance matrix after 1000 and 100 000 steps through the Gibbs sampler. We used uninformative flat priors centered on 0 with large variance. We ran the Gibbs sampler for 250 000 steps, saving the last thinned 150 000 values. Summary statistics were calculated for each of the posterior estimates of the parameters. To display habitat suitability, we used median estimates of the regression parameters and plotted estimates of suitability around each point. For the global suitability, we fixed distance and depth at their mean values while calculating suitability as a function of distance to shore.

Results

Results from the two migratory tracks analyzed here (whales NEA 1812 and NEA 2320) indicate that the estimate of habitat suitability should be revised farther offshore (Fig. 2*a*). Peak suitability values for distance to shore are slightly farther offshore for NEA 1812 than for NEA 2320 (Fig. 2*a*). In particular, NEA 1812, a migrating female with a newborn calf, occurred relatively far offshore during some

Fig. 2. (*a*) Posterior estimates of habitat suitability as a function of distance to shore across the entire migration for NEA 2320 (blue line) and NEA 1812 (red line). The vertical grey line corresponds to 75 km (40 nautical miles) offshore. Posterior estimates of habitat suitability are shown for (*b*) NEA 2320 near the mouth of Delaware Bay, and (*c*) NEA 1812 near the mouth of Chesapeake Bay. Suitable habitat is colored from high (dark green colors) to low (light blue colors). Shown are the southbound (Fig. 2*b*) and northbound (Fig. 2*c*) paths of the animal (grey dots and lines) as well as the 37 km (20 nautical miles) and the originally proposed 55.6 km (30 nautical miles) buffer around these two ports (blue line and red line, respectively). SMA, seasonal management area.



points in her migration (Figs. 1 and 2*a*). Because the analysis was Bayesian, uncertainty the parameters indicate a range of peak suitability as a function of distance to shore from 32 to 200 km for NEA 1812 and from 14 to 75 km for NEA 2320. Results thus indicate that the migratory corridor may be broader than originally thought (Fig. 2) (Knowlton et al. 2002).

Discussion

We estimated habitat suitability around all seasonal management areas (NOAA 2008) in relation to the new 37 km (20 nautical miles) speed restriction buffers and earlier proposed 55.6 km (30 nautical miles) buffers (NOAA 2006). Our analysis indicates that the enacted seasonal management area boundary covers only a small portion of suitable habitat. Enacting the original proposed zones over the Mid-Atlantic would protect an additional 15 453 km^2 of suitable habitat as follows: (*i*) 3849 km^2 around the southeastern United States, a 22% increase, (*ii*) 3042 km^2 around Morehead City, a 135% increase, (*iii*) 2052 km^2 around Chesapeake Bay, a 123% increase, (*iv*) 2188 km^2 around Delaware Bay, a 119% increase, and (*v*) a 1761 km^2 around New York/New Jersey, a 107% increase (see detailed views for Chesapeake Bay and Delaware Bay presented herein). We prefer the contiguous border for the seasonal management areas from Savannah to Wilmington but feel it would be improved by extending the boundary the full 30 nautical miles from shore, as it is clear that peak suitability for both whales ranges farther than 20 nautical miles.

While we do not undertake a full model selection analysis herein, the fact that there is a Pearson r correlation value of 0.45 between the covariates bears some discussion. To determine the effect this has on the analysis, we reran the model using one environmental covariate at a time, e.g., distance to future patch and depth, distance to future patch and distance to shore. For example, the estimate for the β governing depth for NEA 1812 is 0.12 (Bayesian credible interval 0.02, 0.27) with just depth in the model and 0.069 (Bayesian credible interval 0.005, 0.21) with depth and distance to shore. Results are similar for distance to shore: 0.47 (Bayesian credible interval 0.05, 1.14) with just distance to shore and 0.68 (Bayesian credible interval 0.1, 1.56) with both covariates. In both cases, the credible intervals for the single-covariate model contain the parameters estimated in the two-covariate model, thereby giving us confidence in the model formulation.

By taking a new approach to inference, we find that habitat suitability for migrating right whales extends farther offshore than previously thought (Knowlton et al. 2002). In addition, we show that the original proposed boundary of 30 nautical miles would protect more suitable habitat near ports. Future management and conservation activities should take these two findings into account. While we cannot draw too much inference from analysis of two tracks, we note the following. First, the entire population is extremely small, comprised of approximately 300–400 individuals, so two tagged reproductively active females represent a significant portion (2%) of the most valuable segment of the population (current estimate is 97 breeding females, Philip Hamilton, Edgerton Research Laboratory, New England Aquarium, Central Wharf, Boston, Massachusetts, personal communication). Previous estimates of population viability have stressed that if two females per year can be saved, the population growth will become positive (Fujiwara and Caswell 2001). Second, the migratory section of the species' range is the least understood but critical for pregnant females migrating southward from the Gulf of Maine to calving grounds and for mothers with newborn calves migrating northward to feeding grounds. Because these north- and southbound migration routes pass close to several of the largest shipping ports on the eastern seaboard, and because a substantial number of ship strike mortalities occur in this area (Knowlton et al. 2002), we argue that the speed restriction boundaries be revisited. While we are not estimating risk of ship strike, previous work has documented the successful reduction in risk of ship strike to right whales with a combination of traffic separation schemes and speed restrictions (Fonnesbeck et al. 2008; Vanderlaan et al. 2008). Incorporating the results presented here in conservation and management schemes would protect a larger portion of right whale habitat in this critical yet understudied area of their range.

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