NORTH PACIFIC RESEARCH BOARD PROJECT FINAL REPORT

Spatial modeling of optimal North Pacific right whale (*Eubalaena japonica*) calving habitats

NPRB Project 718 Final Report

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Abstract:

Despite decades of protection, the North Pacific right whale (*Eubalaena japonica*) remains critically endangered and, at present, we have no information about the location of the whales' calving habitat. We sought to identify the location of calving habitat in the North Pacific based on the calving habitat preferences of right whales in the Atlantic Ocean. The evaluation focused on three environmental parameters: depth, sea surface temperature and surface roughness. Physical data was obtained from satellite derived and directly measured sources. We employed a previously developed log likelihood model based on right whale calf observations from the Atlantic and assumed that conditions preferred by whales in the Atlantic were also favored by whales in the North Pacific. Application of the model to the Pacific yielded three regions with spatially and temporally robust habitat. The model identified the Baja Peninsula/Southern California coast, the Northwestern Hawaiian Islands and the southern coast of China and northern coast of Vietnam. Limited right whale observations and historic records from these regions provide supporting evidence of right whale presence in these areas. In water surveys are needed to verify if right whales presently use these areas for calving.

Key Words:

North Pacific Right Whale, Eubalaena japonica, North Pacific Ocean, Calving Habitat, Spatial Modeling

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Study Chronology:

This project served as a follow-on to a non-NPRB funded effort to identify optimal right whale calving habitats in the Atlantic Ocean. This earlier project, which formed a portion of Dr. Good's 2008 dissertation, included the development of an optimal right whale calving habitat model. This model was then applied to the North Pacific to identify optimal habitats for North Pacific right whales as part of NPRB project #718. Results from the North Pacific project will be combined with results from other parts of the world in a manuscript detailing modeled right whale calving habitat around the globe to be submitted for peer-review publication in September 2009. We changed the title of our project to make it more succinct for the purposes of this report. This implies no change in the objectives or outcome of the project.

Introduction:

Despite decades of protection, the North Pacific right whale remains critically endangered (Rosenbaum *et al.* 2000). The whales' current status is the consequence of intensive commercial whaling, especially in the eastern Pacific, and exacerbated by illegal Soviet harvests during the 1960s (Ivashchenko *et al.* 2007). Historical records demonstrate that right whales once ranged across the entire North Pacific (Clapham et al. 2004; Josephson et al. 2008) but today little is known about the distribution of the remnant population. Visual and acoustic surveys in the Bering Sea and Gulf of Alaska have located right whales, including calves, during the summer over the past several years (Shelden *et al.* 2005). Recently, NMFS designated these areas as critical habitat for right whales given their presumed importance as foraging grounds (71 FR 38277, 6 July 2006). This is an important step in recognizing right whale foraging habitats but fails to include the other essential habitat for right whales: calving grounds.

At present, we have no information about the location of calving habitat for North Pacific right whales beyond general speculation (Brownell et al. 2001; Clapham et al. 2004). Historic sources do not disclose or even discuss the existence of a discrete calving ground (Scarff 2001). In the past 75 years, only a handful of right whales have been sighted during the winter months in Hawaii (Herman et al. 1980; Rowntree et al. 1980; Salden & Mickelsen 1999), off California (Brownell et al. 2001; Carretta et al. 1994; Scarff 1991; Woodhouse & Strickley 1982), off Washington (Rice & Fiscus 1968), off the Baja Peninsula (Gendron et al. 1999; Rice & Fiscus 1968) and off Japan (Omura 1986) but no calves were recorded in any of these sightings. Despite the lack of information on any calving habitat, there is ample reason to suppose that Pacific right whales travel to lower latitude areas distinct from their foraging habitats to calve during the winter months. Right whales in the Atlantic, Indian and Southern Pacific Oceans all travel to discrete, coastal calving grounds in winter to calve. **We hypothesize that the locations of current (or historic) calving grounds in the North Pacific may be identified, in part, though predictive spatial modeling based on the habitat preferences of calving right whales in the Atlantic Ocean.**

The failure to identify a calving habitat is a serious gap in our understanding of Pacific right whale life history that may well impact our ability to manage threats to the whales' recovery. Indeed, recovery efforts implemented solely in foraging regions may be hampered if animals are adversely affected in their calving habitats. It remains imperative that the reproductive habitats of Pacific right whales are identified, monitored and evaluated for threats.

Objectives:

The singular objective of this project was to identify regions in the sub-tropical North Pacific which offer conditions that are consistent with right whale calving habitats in other parts of the world. Our models use hydrographic and remotely sensed data to identify suitable calving areas based on the conditions preferred by calving right whales in the North Atlantic.

Methods:

Data Processing:

We acquired physical data for the North Pacific Ocean from several sources and custom processed these observations to meet the needs of our analysis. We used ArcGIS Desktop 9.3 (ESRI, Redlands, CA), Python (Python Software Foundation), and R statistical software packages to conduct data processing and analysis. Three types of environmental data were used to identify optimal calving habitat: bathymetry, sea surface temperature and sea surface roughness. We derived bathymetric data from S2004 one-arc-minute global bathymetry (unpublished data, W. Smith). The product is an unpublished but verified (Marks & Smith 2006) amalgamation of Smith and Sandwell (1997) and the General Bathymetric Charts of the Ocean from the British Oceanographic Data Center. This data set provides the highest resolution global coverage currently available. As a complement to these data, we used the Global Self-Consistent, Hierarchical, High-resolution Shoreline (GSHHS) data set which also offers global coverage (Wessel & Smith 1996).

For ocean temperature, we used Advanced Very High Resolution Radiometer (AVHRR) Version 5 sea surface temperature (SST) imagery obtained from the National Oceanic and Atmospheric Administration's National Oceanographic Data Center. This latest version of the AVHRR data has an accuracy of 0.3°C and a resolution of 4.6 km making it one of the highest resolution datasets available with a global extent. To ensure that clouds were eliminated from the data, only pixels with an image quality level > 3 were included in the data processing (Kilpatrick *et al.* 2001). We calculated monthly temperature averages for each of the 24 months examined.

We obtained sea surface roughness data from the NASA Scatterometer Climate Record Pathfinder project through Brigham Young University's Microwave Earth Remote Sensing Laboratory. We used enhanced resolution backscatter images from the QuikScat instrument for our analysis (Long & Hicks 2005). Normalized radar backscatter (sigma-0) is a measure of wind-driven surface roughness over the ocean. This is an excellent measure of surface choppiness although, because roughness is primarily a measure of the amplitude and extent of wind-induced capillary and gravity waves, in calm conditions the scatterometer may fail to detect swell propagating from a distant source. Level 1b backscatter data is commonly used to examine sea ice extent or climate variation, but its applicability as a direct measure of surface conditions also proved an excellent fit for this novel use.

Because the analysis employed a monthly timeframe, we focused on optimizing spatial and not temporal resolution. As a result, all available satellite passes were aggregated and higher resolution "slice-based" backscatter images were chosen over "egg-based" images despite increased noise in the data from any individual pass. Slice images have a pixel resolution of 2.225km and an effective resolution of approximately 5km. For each month in our analysis we calculated the average normalized backscatter value.

In most areas, backscatter imagery is contaminated at the land/sea interface due to much larger sigma-0 values over land in comparison to ocean. To resolve this problem, we removed contaminated data within this interface and used values from adjacent offshore pixels as a proxy for inshore conditions. The extent of the interface was determined by examining trends in pixel deviation perpendicular from shore. Using a moving window analysis, all pixels falling outside 1 standard deviations from the mean were substituted with values from the nearest high quality cells. An interpolation was not performed, but rather inshore conditions were presumed to be best represented by adjacent uncontaminated cells.

Data Analysis:

We used four models for our analysis; one for each month of the calving season, December – March. A monthly temporal unit was appropriate for analysis due to the lengthy stays of females at known calving areas. According to Best (2000), females with calves remain on South African calving grounds an average of 59 ± 3.9 days. We used monthly data aggregated over a 6 year period (1999-2005) to create a climatology of habitat conditions. This time period was used because it matches the period of right whale observations in the Atlantic from which the habitat models were developed.

Environmental data were entered into our previously developed right whale calving habitat models. The models rely on a Bayesian methodology to estimate non-parametric multivariate density functions for each of the 3 variables (SST, surface roughness and depth). Mode coefficients from the density functions provide the parameters for a log likelihood function to calculate a likelihood surface of calving habitat (Equation 1). We used Receiver Operator Characteristic (ROC) curves to assess model accuracy and establish optimal habitat thresholds values. For a more complete description of the model development please consult Good (2008).

Equation 1

$$\Pr(habitat) = \left[(\mu_{depth})(s_{depth}) - \log\gamma(\mu_{depth}) - (e^{s_{depth}})(x_{depth}) + (\mu_{depth} - 1)(\ln x_{depth}) \right] + \left[(\mu_{sst})(s_{sst}) - \log\gamma(\mu_{sst}) - (e^{s_{sst}})(x_{sst}) + (\mu_{sst} - 1)(\ln x_{sst}) \right] + \left[(\mu_{rough})(s_{rough}) - \log\gamma(\mu_{rough}) - (e^{s_{rough}})(x_{rough}) + (\mu_{rough} - 1)(\ln x_{rough}) \right]$$

The function was applied to all coastal areas and many offshore portions of the Pacific Ocean to ensure that the broadest possible region was evaluated. Surface roughness data were not available for the mid-ocean environment so this zone was not evaluated. However, the depth profile of these areas is so far outside that preferred by right whales for calving (<30m) that we are confident no habitat areas were missed. Additionally, surface roughness data was not available for the Hawaiian Island region at the completion of this report. For the Hawaiian Islands region the model was run using solely sea surface temperature and depth data. Previously determined optimal threshold values were used as cutoff points to distinguish habitat from non-habitat. We derived a final, single model of optimal calving habitat by combining all four monthly models. This resulted in an output delineated by the number of months (1- 4) a given area was selected as optimal calving habitat. This final combined model was applied to the North Pacific and we report here on the spatial extent and temporal continuity of the predicted calving habitat for right whales throughout this range.

Results:

Application of the habitat model to the North Pacific revealed several regions with optimal calving habitat for right whales. In the eastern North Pacific, the model identified suitable habitat in coastal regions between 23º N and 36º N. In the western North Pacific, the model identified coastal calving habitat between 15º N and 38º N. The model predicted three discrete regions with optimal right whale calving conditions including: southern California and the Baja Peninsula in Mexico, the Northwestern Hawaiian Islands and the southern coast of China and northern coast of Vietnam.

In the eastern North Pacific, the model predicted calving habitat along the U.S. and Mexico coasts as far North as San Francisco and extending south to the southern tip of the Baja Peninsula (Figure 1). The model identified the broadest and most temporally robust habitat along the Baja Peninsula from Point San Antonio (29.5°N) south to Sebastian Vizcaino Bay (28.5°N). This zone offers the most optimal calving habitat in the eastern North Pacific. To the south of Sebastian Vizcaino Bay, the modeled habitat becomes more temporally limited and was only selected during one month of the calving season. To the north of the Bay, along the southern California coast, the modeled habitat is sparse and broken up with pockets of temporally robust habitat occurring around the Channel Islands (34°N) and off Oxnard, CA.

In the mid North Pacific, the model predicted calving habitat in the Hawaiian Islands, most notably at the far northwestern end of the archipelago (Figure 2). The spatial extent of the predicted habitat in this region is much more limited than that in either the eastern or western Pacific due to a lack of shallow habitat. The model identified the most temporally robust habitat at Kure, Midway and Pearl and Hermes Islands (Figure 3). This zone appears to offer the most optimal calving habitat in the region. In the remainder of the northwest islands the model identifies spatially broad habitat, in parts, but it is temporally limited.

In the western North Pacific, the model identified calving habitat from Vietnam north along the China coast (Figure 4) with some sparse habitat seen off Korea and Japan (Figure 5). We found the most spatially and temporally robust habitat along coastal areas in the Gulf of Tonkin and off Fujian Province in China. The model identified habitat off Korea and Japan but it was spatially discontinuous and temporally limited.

We report the results of the predictive habitat model in the rawest format possible to offer full transparency in our findings. In many regions, the model predicted temporally limited habitat that is suitable during only one month of the calving season. Given that mother/calf pairs remain on calving grounds in other parts of the world for an extended period (Best 2000), temporal consistency of habitat is likely of considerable importance for calving. These areas are unlikely to represent ideal habitat. In other areas, the model identifies spatially sparse or scattered cells as habitat. It is also unlikely that these noncontiguous cells represent robust habitat. To identify the most optimal calving areas, it is necessary to consider both the spatial extent and temporal consistency of the habitat as a whole.

Discussion:

In the eastern North Pacific, our model identified the west coast of the Baja Peninsula, in particular the coastal area around Sebastian Vizcaino Bay, as optimal habitat in this region. Historic whaling along Baja was once widespread but according to historic records targeted mostly gray (*Eschrichtius robustus*) and blue whales (*Balaenoptera musculus*) during the winter months. According Charles Scammon’s 1874 account of the whale fishery in this region, however, some right whales were taken during the winter “as far south as the Bay of San Sebastian Viscaino, and about Cedros Island” (Scammon 1874).

One historical report is available from Reeves and Leatherwood (1985), of two right whales sighted on April 4 1865 east of Guadalupe Island (28.5°N) off Baja. Only a handful of winter observations have been made in the region since 1950 and none included a calf. In March 1965, two right whales were recorded off Punta Abreojos (27°N) just to the south of Sebastian Vizcaino Bay (Rice & Fiscus 1968). Another single right whale was sighted off Cabo San Lucas (23.2°N) in February 1996 (Gendron et al. 1999). Despite a dearth of sightings or historical documentation, limited evidence does support the existence of a historical or remnant calving ground off Baja.

The habitat model also identified areas of calving habitat in the Gulf of California off the east coast of the Baja Peninsula. No right whale sightings, either historic or modern day are available for this region. It is possible that this habitat is not functionally available to right whales due to the very warm waters a right whale would have to pass through around the southern tip of Baja to access this area. Sea surface temperatures off the southern tip of Baja regularly exceed 23°C during the winter months. In contrast, temperatures at the most robust habitat areas ranged from approximately 14 - 18°C.

Right whales with calves remain longer at calving grounds than other individuals (Jones & Swartz 1984; Rowntree et al. 2001) and thus must be able to tolerate habitat conditions for an extended period of time. Of 648 right whale calf sightings off the U.S. southeast coast documented between 1999-2005 only 6 occurred in areas with surface waters greater than 20°C despite the wide spread availability of warm water habitat (Good 2008). The thick blubber of parturient females may pose a thermal constraint. The extreme thickness of right whale blubber, designed to retain heat and store energy, may impede the ability of these animals to inhabit warm waters. Although, calves are unlikely to face such constraints; blubber from newborn calves in South Africa averaged 5cm in thickness (Reeb *et al.* 2007).

Since 1950, several right whale sighting have been documented along the southern California coast during the winter including observations at La Jolla (32.8°N) (Gilmore 1956), Santa Barbara (34.5°N) (Woodhouse & Strickley 1982), Big Sur (35.75°N) (Evans 1998), Half Moon Bay (37.5°N) (Johnson 1982), the Farallon Islands (37.1°N) (Rice & Fiscus 1968) and San Clemente Island (33°N) (Carretta et al. 1994). All sightings occurred close to shore and none included a calf. Historic records from this area discuss a vibrant whale fishery for gray whales. Right whales are known to migrate close to shore both en route to calving areas but especially when traveling back from a calving ground accompanied by a calf. It is possible that at some point along the west coast of the U.S. or Mexico optimal calving habitat turns into a migratory corridor for mother/calf pairs. In light of this, sightings of right whales along the California coast may represent right whales traveling to a more southerly calving ground. Or the whales may use the area south of Point Conception where the predicted habitat is more robust as a calving ground off California.

Since the early 1970s, researchers have observed several right whales in Hawaiian waters off Maui (Herman et al. 1980; Rowntree et al. 1980; Salden & Mickelsen 1999). No sightings included a calf and in call cases the right whales were observed in the company of humpback whales (*Megaptera novaeangliae*). No recent observations of right whales exist for the northwestern islands but since that this section of the state is nearly uninhabited, opportunistic sightings are unlikely. All observations were documented in the more populous main Hawaii islands where the model identified limited but not robust habitat. Interestingly, all the sightings occurred between March 25 and April 10 which falls towards the end of the calving season in the Northern Hemisphere. March was the only month when conditions in the main Hawaiian islands were identified by the model as optimal for calving. It is possible that as the season progresses mother/calf pairs which may have arrived at the far northwestern islands make their way east along the archipelago as the surface temperatures become cooler and thus more favorable.

Historically, whalers targeted humpback whales in Hawaiian waters during winter or passed through the islands en route to other hunting grounds. A recent re-analysis of data from whaler logbooks in the 1800s demonstrates a high right whale encounter rate in an area that encompasses the three most western islands in the Hawaiian Archipelago: Kure, Midway, and Pearl and Hermes. This is also the area identified by the model as having the most robust calving habitat in the Hawaiian Islands.

In the western North Pacific, little data is available for either China or Vietnam regarding right whales. Historic records indicate a centuries long whale fishery active off Japan during the winter months (Omura 1986). Several species, including right whales, were taken in this fishery but the proportion of the catch made up of right whales dropped precipitously during the second half of the nineteenth century. This area was not selected by our model as optimal calving habitat and we speculate that this may be a migratory corridor for whales traveling to and from calving grounds in the south. Omura (1986) refers to the historic fishery as targeting migrating right whales. The most direct and coastal route for a whale to travel from southern China north to foraging grounds in the Okhotsk Sea would be through the Sea of Japan. Other historic records indicate right whales were targeted along the southern Chinese coast near Hainan Island (Ellis 1991). This closely matches up with areas identified as optimal habitat in the Gulf of Tonkin.

For all the regions examined, records of right whale observations or historic harvest exist which support our findings of optimal habitat. Additional analyses of historic records may yield further information about previous use of these areas by right whales; however, more field research is needed to verify whether these areas currently host right whales. It is imperative that attempts are made to conduct acoustic or visual surveys of potential calving grounds in winter to verify whether right whales currently travel there to calve. Based on twentieth century right whale observations and our modeled output, the Hawaiian Islands and the Baja Peninsula appear to be the most promising candidates. The North Pacific right whale remains critically endangered and in need of targeted protection. Reproductively active females require special attention as they are chiefly responsible for the future growth of the population. All due attention should be paid to locating the remaining calving habitat for this species and evaluating whether any anthropogenic threats persist in these areas.

Conclusions:

Using a right whale habitat model based on the environmental conditions preferred by calving right whales in the Atlantic we successfully identified 3 regions of either current or historic calving habitat in the North Pacific Ocean: Baja California, the Northwest Hawaiian Islands and the southern coast of China and northern Vietnam coast. These regions offer calving habitat that is both spatially and temporally robust. Our review of historic harvest records and right whale observations in winter identified supporting evidence for the existence of optimal calving habitat in areas predicted by the model. However, records are limited and new acoustic or visual survey work is needed to verify the presence or absence of right whales at these predicted sites. Locating calving habitat for the endangered North Pacific right whale is a critical step towards ensuring the species' protection and recovery.

Note: We completed the Hawaiian Islands portion of our model using only the bathymetry and sea surface temperature variables due to temporary data constraints. The Brigham Young University Center for Remote Sensing, which is the NASA provider for raw scatterometer data provided us with a custom product for Hawaii. Data for this region is not publically available and can only be obtained through special request. Unfortunately, the data we received from the Center was corrupted and they just provided us with a fresh working copy on 06/27. We had hoped to receive this data before our final report was due but we will incorporate the data into the Hawaiian portion of the model for publication. We do not anticipate that the addition of this data will substantively alter our findings as detailed in this report.

Publications:

We have a manuscript in preparation: Good, C.P., Read, A.J. and Johnston, D.W. A global model of right whale (*Eubalaena* spp.) calving habitats. We plan to submit the manuscript to Marine Mammal Science or the Journal of Cetacean Research and Management by September 2009.

Outreach:

Educational Presentation:

We made a presentation to middle and high school students from Carteret County as part of a Marine Science Exploration Day using this project as an example of how researchers can employ high tech tools (i.e. satellite data, modeling) to answer ecological questions. The children participating in the program were interested in careers in marine science.

Educational Materials:

We have completed an educational poster for the Papahānaumokuākea Marine National Monument in Hawaii. The Monument encompasses the most likely calving habitat identified by our models in U.S. waters. We are currently making plans to transport the poster to Hawaii. We will also send a copy of the poster to the Pacific Islands Fisheries Science Center for the Protected Species Division to use for outreach.

Conference Presentation:

We plan to present our findings at the Biennial Conference of the Society for Marine Mammalogy in Canada this October.

Acknowledgements:

We wish the thank Dr. David Long from the BYU Center for Remote Sensing for generating a customized Hawaiian Islands scatterometer product for this analysis. We also wish to thank Jason Roberts of Duke University for making available code for processing portions of our data.

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Figures:

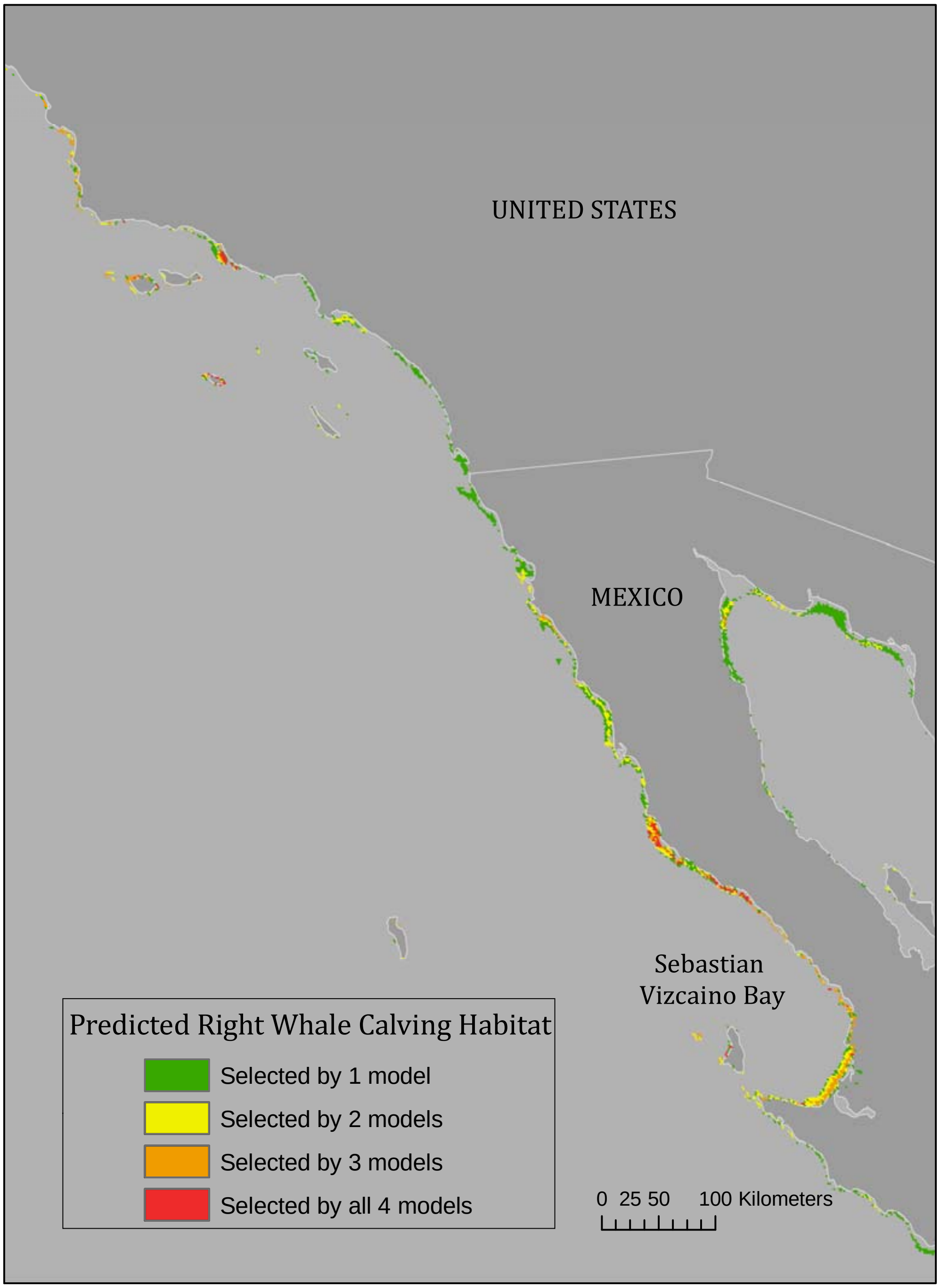

Figure 1: Optimal North Pacific right whale (*Eubalaena japonica*) calving habitat in the eastern Pacific as identified by the habitat model. Green areas were identified by the model in one month, yellow areas were identified by the model during two months, orange areas were identified by the model over three months and red areas were selected as optimal habitat over all four months evaluated.

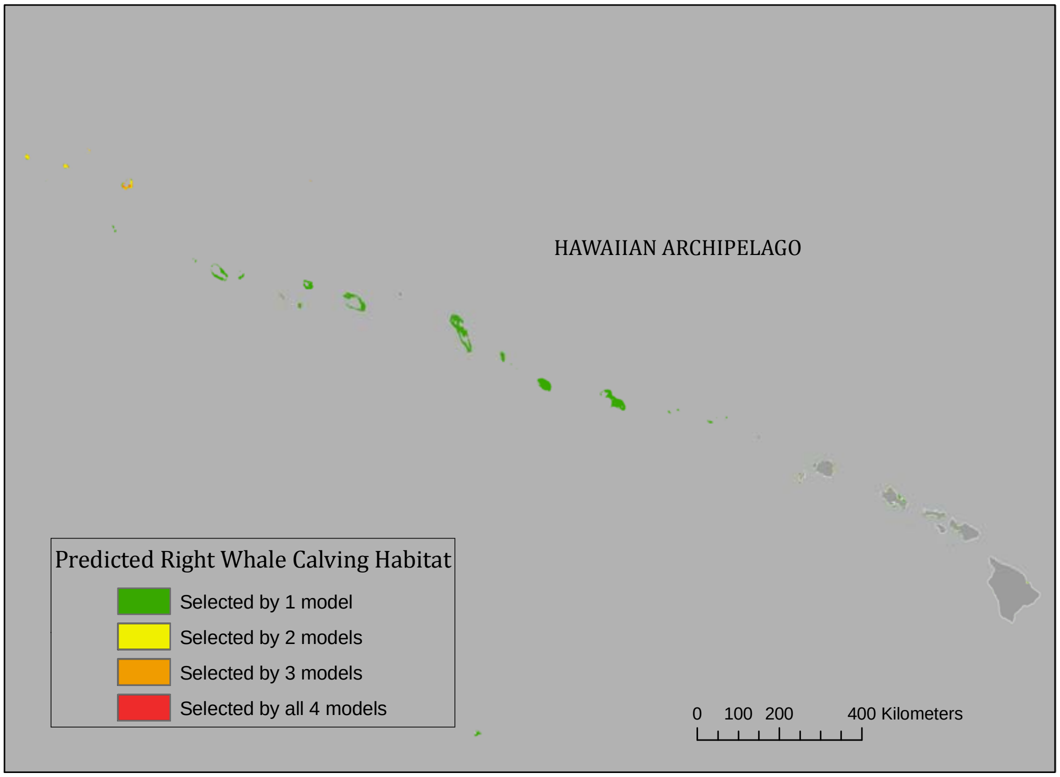

Figure 2: Optimal North Pacific right whale (*Eubalaena japonica*) calving habitat in the Hawaiian Islands as identified by the habitat model. Green areas were identified by the model in one month, yellow areas were identified by the model during two months, orange areas were identified by the model over three months and red areas were selected as optimal habitat over all four months evaluated.

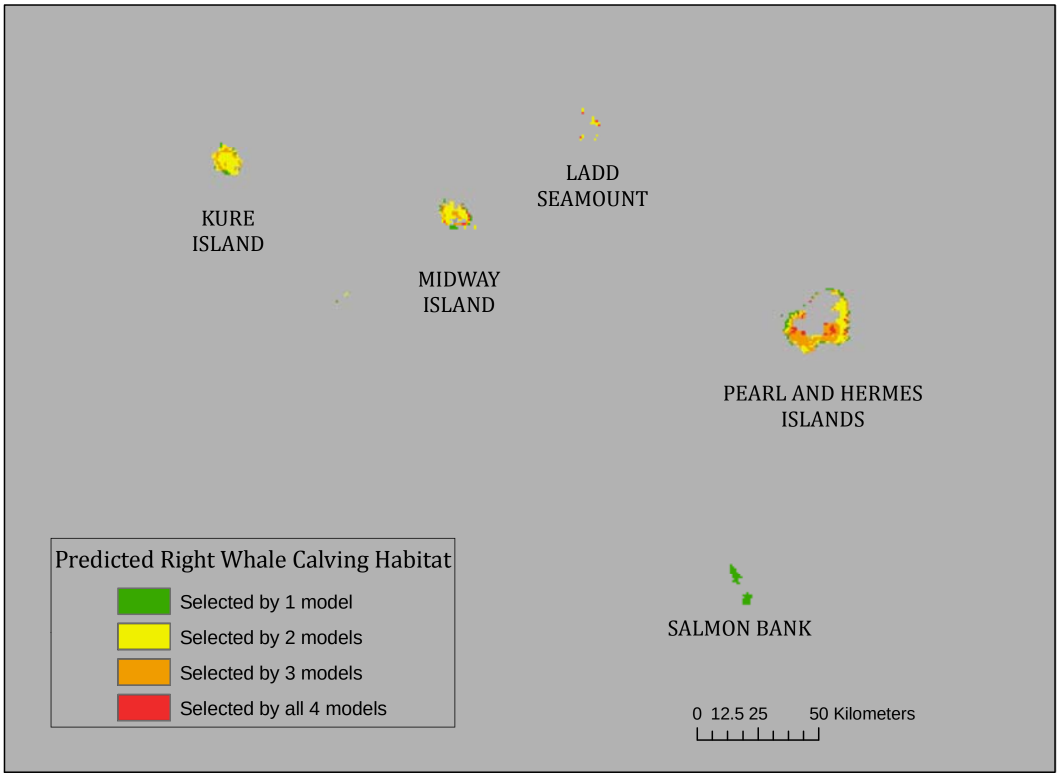

Figure 3: Optimal North Pacific right whale (*Eubalaena japonica*) calving habitat in the far Northwest Hawaiian Islands as identified by the habitat model. Green areas were identified by the model in one month, yellow areas were identified by the model during two months, orange areas were identified by the model over three months and red areas were selected as optimal habitat over all four months evaluated.

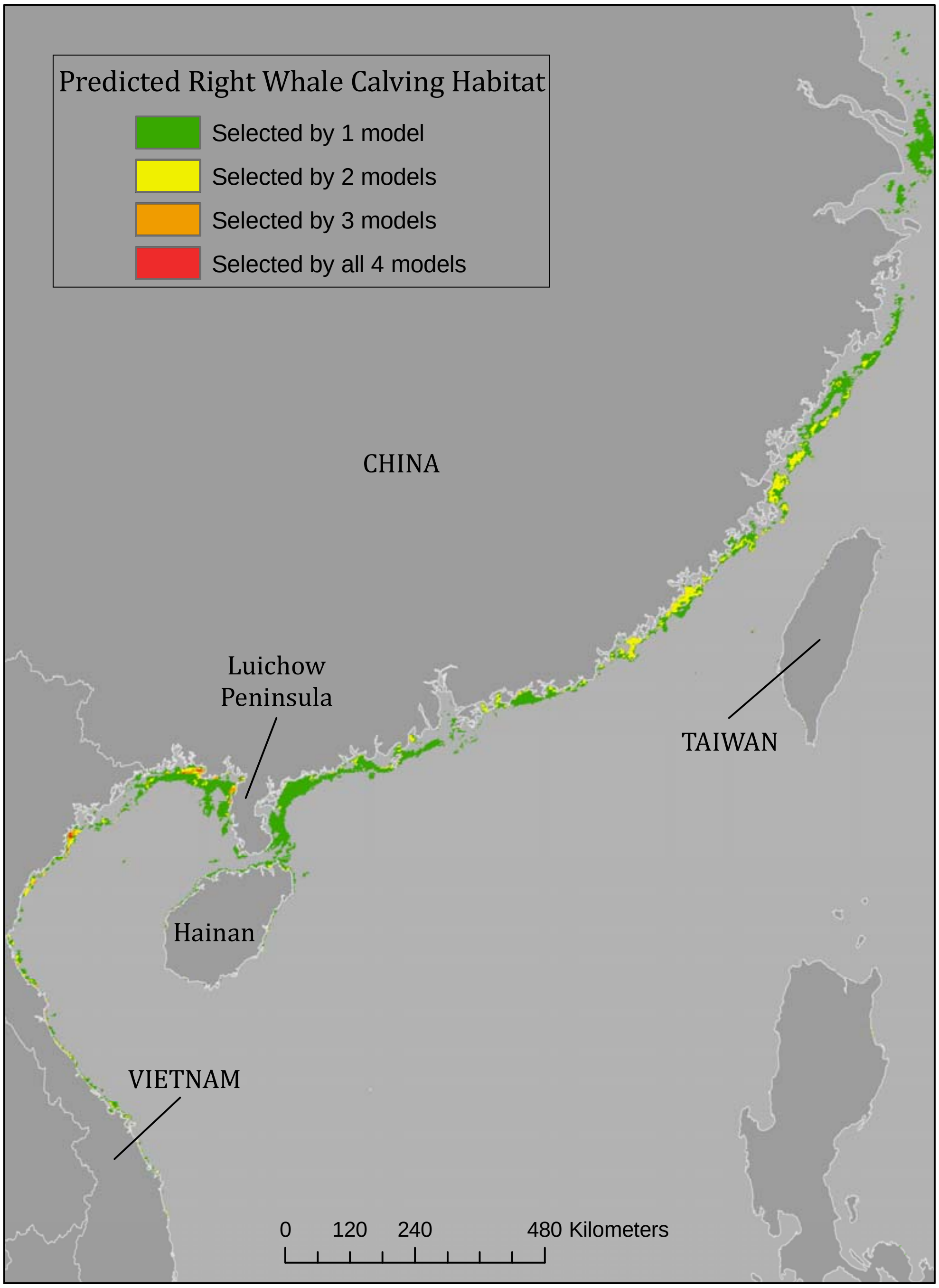

Figure 4: Optimal North Pacific right whale (*Eubalaena japonica*) calving habitat off China and Vietnam as identified by the habitat model. Green areas were identified by the model in one month, yellow areas were identified by the model during two months, orange areas were identified by the model over three months and red areas were selected as optimal habitat over all four months evaluated.

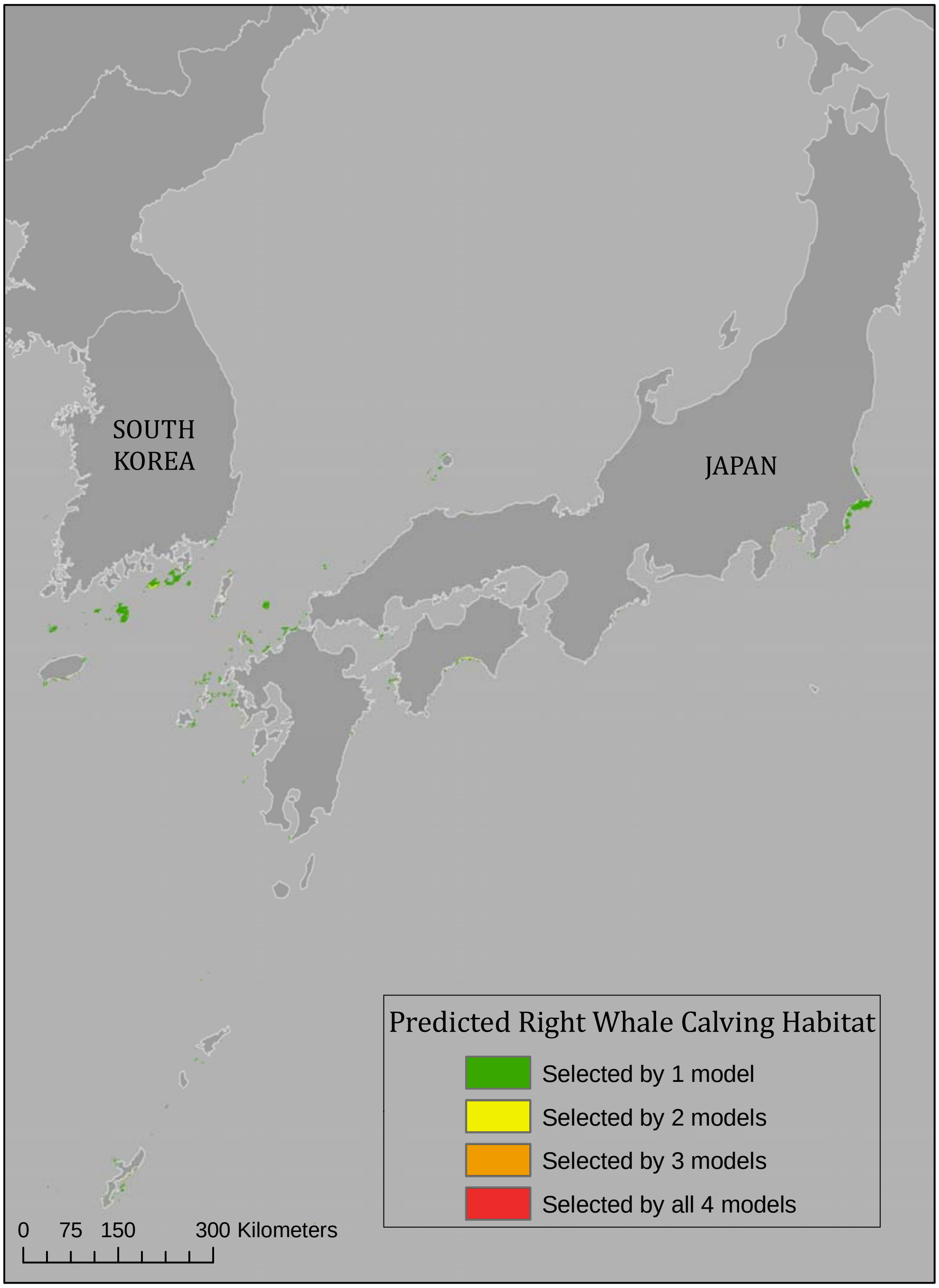

Figure 5: Optimal North Pacific right whale (*Eubalaena japonica*) calving habitat off South Korea and Japan as identified by the habitat model. Green areas were identified by the model in one month, yellow areas were identified by the model during two months, orange areas were identified by the model over three months and red areas were selected as optimal habitat over all four months evaluated.