Density prediction modeling and mapping of common minke, sei and Bryde's whales distribution in the western North Pacific using JARPN II (2000-2007) data set

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ABSTRACT

Spatial distribution patterns are important information for management of highly mobile animals. Baleen whales migrate long distance from tropical reproduction areas to high latitude feeding areas, and they are known as important consumers because of their large biomass. We developed density prediction models for common minke, sei and Bryde's whales in the Western North Pacific in their feeding season. To make these prediction models, the densities of each whale species calculated using dedicated sighting survey data in JARPN II and satellite information were used. We used Non-parametric Multiplicative regression model (NPMR) which can examine the interactions among ecological factors multiplicatively. The regression results showed sea surface temperature ("SST") and "Longitude" were selected as predictors in each best model, and "Latitude", "Chlorophyll", "Year", "Month" and "sea surface height ("SSH") were also selected as predictor variables in some cases. The predicted density distributions by NPMR showed spatial distribution patterns of whales and difference and characteristics among whale species. This study demonstrated that this habitat model technique gave useful information.

KEYWORDS: BALAENOPTERA; MINKE WHALE; WHALE DENSITY; NONPARAMETRIC MULTIPLICATIVE REGRESSION; SCIENTIFIC PERMITS

INTRODUCTION

The Second Phase of Japan Whale Research Program in the Western North Pacific (JARPN II) has conducted since 2000 with one of the objectives as contribution to the feeding ecology of whales and ecosystem studies for conservation and sustainable use of marine living resources including whales. Baleen whales seasonally migrate from tropical to high latitude feeding area, and these latitudinal movements continues throughout their feeding season (Nemoto and Kawamura 1977, Masaki 1977). To consider and discuss the role of these baleen whales, their distribution and migration patterns are important information to understand the results of stomach contents and sighting survey from the spatial aspects. For management purpose, meanwhile, the predictions of whale distribution patterns provide geographical importance in ecosystem in some specific environment. From these background, the spatial analyses are getting important in ecological study, and the habitat modelling of whales with covariates has become standard technique throughout small to large scale areas (Okamura *et al.* 2001, Kaschner *et al*. 2006, Laran and Gannier 2008). Satellite information, such as sea surface temperature, chlorophyll concentration, provide snap-shot like data in a broad scale which are useful and suitable to make prediction of distribution in migrating baleen whales. The predictions of whale distributions using sighting survey and satellite information were reported in fin whale (Laran and Gannier 2008). JARPNII has continued dedicated sighting surveys since 2000 in addition to lethal samplings. The main objective of this study was to examine the quantitative interactions among environmental factors and distribution patterns of the common minke, sei and Bryde's whales in JARPN II research area in their feeding season.

MATERIALS AND METHODS

Environmental parameters

Satellite data of sea surface temperature (SST), Chlorophyll *a*, and sea surface height (SSH) vary spatially and seasonally. JARPN II offshore sighting survey was conducted from May to September. To combine the data from the whale sighting survey and satellite information, we prepared 1 by 1 degree girded monthly dataset for survey and satellite data. The data used in this study were SST from Terra-Modis, Chl from the Sea WIFS (NASA/Gollard sensor (NOTT/NASA) both from Ocean Color Web (http://oceancolor.gsfc.nasa.gov/). Sea Surface Height (SSH) anomaly data were obtained from the Jason, TOPEX/Poseidon, Geosat Follow-On (GFO), ERS-2 and Envisat altimetry processed by Colorado Center for Astrodynamics Research. Daily SSH data of daily 10th and 20th at each moth were pooled to make monthly datasets.

Sighting data

We conducted dedicated whale sighting surveys using a vessel from 2000 to 2007. Two survey procedures were conducted, that is, “ASP mode” which the vessel approach whales for precise identification of whale species or “NSP mode” which keeps track line and ship speed during the identification process. Experienced observer recorded the position of findings, species and etc. Density index (DI) is calculated as the number of whales seen per effort in 100 n. miles. The three baleen whales have different distributions and, so sighting surveys were conducted in different manner of courses and date by years. We also used whale findings and efforts on track lines by sighting and sampling vessels to overlay with estimated DI on maps.

Model development and selection

We used nonparametric multiplicative regression (NPMR) to predict whale densities. This modelling technique has been applied to some organisms (Jovan 2003, Yost 2008, Potapova and Winter 2006, Grundel and Pavlovic 2007). NPMR models can build up a species response surface to the interactions among ecological factors multiplicatively. Hyperniche version 1.38 (McCune and Mefford 2004) was used to make NPMR models and selected best models.

Build species performance y_i from m predictors as:

$$y_i = f(x_1, x_2, x_3, \ldots, x_m) \qquad (1)$$

Gaussian weighting with local-mean function was used to make smooth the neighbourhood of the target point as:

$$w_{ij} = e^{-\frac{1}{2}\left[\left(x_{ij} - v_j\right)/s_j\right]^2} \qquad (2)$$

where x_{ij} is the value of a predictor variable j at sample unit i, v_{ij} the value of the predictor variable j at the target sample unit, and s_j is the value of the tolerance (standard deviation) for predictor variable j.

Estimate the response variable (species performance) y at target point v as:

$$\hat{y}_v = \frac{\sum_{i=1, i \neq v}^{n} y_i \left(\prod_{j=1}^{m} w_{ij} \right)}{\sum_{i=1, i \neq v}^{n} \left(\prod_{j=1}^{m} w_{ij} \right)} \qquad (3)$$

Main point of this model is if any w_{ij} equal to zero results in failure of a response y. The $i \neq v$ means that if the target point v is one of the calibration data points, then it is excluded from the basis for the estimate of y_v (leave-one-out cross-validation).

Neighborhood size (the amount of data bearing on that particular estimate) is:

$$n_v^* = \sum_{i=1, i \neq v}^{n} \left(\prod_{j=1}^{m} w_{ij}^* \right) \quad (4)$$

where $0 < n_i^* <= n$, then no estimate is possible for that point. Setting a minimum n_i^* required for an estimate protects against estimating a response in a region of the predictor space with insufficient data. We used 0.05% as minimum average neighbourhood size for acceptable model.

Model evaluation choice of predictors and their tolerances are based on the results of cross-validation.

$$xR^2 = 1 - \frac{RSS}{TSS} = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y}_i)^2} \quad (5)$$

where RSS is the size of the cross-validated residual sum of squares, TSS is the total sum of squares.

Sensitivity Analysis (evaluation of the predictors)

To nudge up and down observed values for individual variables, and measure the resulting change in the estimate for that point. The greater the sensitivity, the more influence that variable has in the model.

$$\text{Sensitivity} = \frac{\left(\sum_{i=1}^{n} (\hat{y}_{i+} - \hat{y}_i)^2 + \sum_{i=1}^{n} (\hat{y}_{i-} - \hat{y}_i)^2 \right)}{2n \left| y_{\max} - y_{\min} \right| \Delta} \quad (6)$$

where

$\hat{y}_{i+}$ = estimate of the response variable for case I, having increased the predictor by an arbitrarily small value Δ (say 0.1 of the range of the predictor).

$\hat{y}_{i-}$ =estimate of the response variable for case I, having decreased the predictor by an arbitrarily small value Δ (say 0.1 of the range of the predictor)

Δ = A small difference applied to a predictor, expressed as a constant proportion of the range of a predictor (5% of the range of the predictor).

Sensitivity range is from 0 to 1.0. A value of 1.0 means that on average, nudging a predictor results in a change in response of equal magnitude, and a value of 0 means no detectable effect on the response.

RESULTS

Model selection

NPMR constructed habitat models and identified best modes with the highest $xR^2$for each year datasets (Table 1). The predictors and the values of xR^2 differed among whale species and datasets. Latitude, Longitude, SST and Chlorophyll concentration were included in the models of minke whale. Year, Longitude, and SST were included as predictors. In the model of Bryde’s whale, Year, Month, Latitude, Longitude, SST, SSH and Chlorophyll a were included. Table 2 shows the sensitivities of the models. The DI of minke whale showed high sensitivity to Latitude, Longitude and SST, and small sensitivity to Chlorophyll a. The DI of sei whale showed high sensitivity to SST followed by Longitude and year. NPMR included many predictors in the model of Bryde’s whale, and the DI of the whale showed relatively high sensitivity to Longitude, SST and SSH followed by Latitude, Year, Month and Chlorophyll a. The model showed the minke whale occur 10-20°C with SST, and coastal and peak around 45°N with high chlorophyll concentration. The model showed high density peak around 18°C and longitudinal gradient and year.

Species response curves

NPMR shows the complex multiplicative relationship among predictors. Figures 1, 2 and 3 show three dimensional response curves from NPMR models for each whale species. Among predictors in best models, "SST" and "longitude" were selected in these models. So we compared these predictors among whale species to examine environmental factors which indicate feature of distribution patterns (Fig 4 and 5). These two predictors clearly demonstrated the difference of distribution pattern related to environmental factors in our study area. The range of SST overlapped between the DI of minke and sei whale, although the peak SST of DI in the minke whale was rather low temperature than that in sei whale. The range of SST to DI of Bryde's whale was clearly warmer than others.

Sensitivity tests

To examine the sensitivities of predictors to response DI, we conducted sensitivity tests (Table 2). SST was most sensitive predictors followed by Latitude and Longitude in minke whale, but the sensitivity of Chlorophyll a was small. The sensitivity of predictors in sei whale showed strong sensitivity of SST followed by Longitude and year. Among predictors in Bryde's whale, the sensitivity of longitude was relatively high followed by SST and SSH, however these values were smaller than that in other baleen whales. The sensitivities of other predictors were small.

GIS outputs

To illustrate model performance, the monthly predictions of DI distributions were estimated using monthly satellite datasets with finding positions and efforts on track lines (Fig. 6, 7 and 8). The area where we estimated the DI of whales covered the 32-55°N and 140-175°E without Okhortsk Sea. Estimated DI showed monthly latitudinal migration patterns in all three whale species, and finding positions overlapped the estimated high density area. The estimated DI distributions differed among different years, such as latitudinal migration and distribution pattern. The matches of estimated DI with finding positions are interesting. Most of monthly distribution patterns matched the real finding position by sighting vessels, although some showed findings in low estimated DI area.

DISCUSSION

This study demonstrated the NPMR models performed spatial distribution patterns, and SST and Latitude were most important limiting factors for the distribution of three baleen whales in addition to time scale, such as year and month. Our study firstly showed precise habitat model development from long-term comprehensive dedicated sighting survey in broad study area.

Minke whale has strong segregation to coastal area in early summer and the minke whale occur in offshore around 45°E and 160°E where they feed intensively on Pacific saury (Tamura *et al*. 1998, Tamura and Fujise 2002, Konishi *et al*. in preparation). The distribution pattern of minke whale in this study showed similar pattern to the previous study (Okamura *et al.* 2001) and commercial catch (Hatanaka and Miyashita 1997).

The estimated distribution of sei whale covered most of JARPN II survey area without coastal area, and high density distribution was estimated in eastern most. In later summer the distribution extend to around 50°N at eastern coast of the Kamchatka Peninsula where sei whales were exploited in commercial whaling period (Nemoto 1959, Kawamura 1973, Masaki 1977, Kawamura 1982). Large number of catch were also reported around 170°E in commercial whaling period from 1952 to 1972 (Masaki 1977), although same paper reported the large number of catches off the Pacific coast of Japan.

Bryde's whales prefer warm waters rather than sei and minke whales. Our study demonstrated the distribution patterns can be determined by environmental factors and NPMR models. The prediction of distribution pattern suggested that Bryde's whale move to JARPNII study area later than other two species. This estimated spatial distribution pattern will contribute to the evaluation of consumption by Bryde's whale in our study area.

The environmental limiting factors are also means habitat preference of whales, and this information can focus on specific important area. Since the DI distribution in JARPN II survey varied both seasonally and geographically, these habitat preferences can contribute to the study of feeding ecology and ecosystem management.

This study could show the spatial distribution pattern of the three baleen whales with environmental factors, however the number of environmental factors we used in this study were small. To make more dependable models and estimation, we need to take into account information which is related to temperature gradient, water depth and some biological factors.

Acknowledgements

We would like to thank all the captains, crews and member of ICR who were involved in JARPN II surveys. Thanks are also due to Yokota for her kindly support to organize data set. We would also like to thank SeaWiFS and Colorado Center for Astrodynamics Research for remote sensed imagery.

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Table 1 Summary of best NPMR models selected by the value of cross-R^2 (xR^2) from 2000 to 2007 dataset year.

Response	Evaluation	Average	Pred	Variable 1		Variable 2		Variable 3		Variable 4		Variable 5		Variable 6		Variable 7	
Variable	xR^2	neighborhood size	Count	Predictor	Tolerance	Predictor	Tolerance	Predictor	Tolerance	Predictor	Tolerance	Predictor	Tolerance	Predictor	Tolerance	Predictor	Tolerance
DI_Mi	0.0260	244.3874	1	Longitud	1.4500												
DI_Mi	0.0566	177.4518	2	Longitud	2.9000	SSTterra	2.5435										
DI_Mi	0.0754	98.4377	3	Latitude	2.4000	Longitud	2.9000	SSTterra	2.5435								
DI_Mi	**0.0757**	**97.5775**	**4**	**Latitude**	**2.4000**	**Longitud**	**2.9000**	**SSTterra**	**2.5435**	**Chl9km**	**4.7181**						
DI_Mi	0.0747	99.0187	5	Month	2.0000	Latitude	3.2000	Longitud	2.9000	SSTterra	2.5435	Chl9km	4.7181				
DI_Sei	0.0026	833.1682	1	Longitud	5.8000												
DI_Sei	0.0050	313.4554	2	Longitud	5.8000	SSTterra	2.5435										
DI_Sei	**0.0066**	**182.6707**	**3**	**Year**	**2.1000**	**Longitud**	**5.8000**	**SSTterra**	**2.5435**								
DI_Sei	0.0066	182.2451	4	Year	2.1000	Longitud	5.8000	SSTterra	2.5435	Chl9km	10.1102						
DI_Br	0.0047	691.1324	1	SSTterra	2.5435												
DI_Br	0.0107	249.8734	2	Longitud	4.3500	SSTterra	2.5435										
DI_Br	0.0137	138.0588	3	Longitud	2.9000	SSTterra	2.5435	SSHcolor	129.5127								
DI_Br	0.0153	121.5576	4	Latitude	3.2000	Longitud	2.9000	SSTterra	3.8152	SSHcolor	129.5127						
DI_Br	0.0157	99.9564	5	Year	3.1500	Latitude	4.0000	Longitud	2.9000	SSTterra	3.8152	SSHcolor	129.5127				
DI_Br	0.0157	97.9237	6	Year	3.5000	Month	3.5000	Latitude	4.0000	Longitud	2.9000	SSTterra	3.8152	SSHcolor	129.5127		
DI_Br	**0.0157**	**97.4611**	**7**	**Year**	**3.5000**	**Month**	**3.5000**	**Latitude**	**4.0000**	**Longitud**	**2.9000**	**SSTterra**	**3.8152**	**SSHcolor**	**129.5127**	**Chl9km**	**6.7402**

Tables 2 Sensitivity tests for NPMR models.

a) Minke whale

Predictor	Sensitivity	Range	N nudgings	NudgedEmpty	Empty Orig.
Latitude	0.3778	16	3896	0	0
Longitude	0.4846	29	3896	0	0
SST	0.5648	25.43	3896	0	0
Chlorophyll a	0.0203	13.48	3896	0	0

3.6805 = range in estimated values from original data

b) sei whale

Predictor	Sensitivity	Range	N nudgings	NudgedEmpty	Empty orig
Year	0.291	7	3896	0	0
Longitude	0.5279	29	3896	0	0
SST	0.9115	25.43	3896	0	0

12.041 = range in estimated values from original data

c) Bryde's whale

Predictor	Sensitivity	Range	N nudgings	NudgedEmpty	Empty Orig.
Year	0.0197	7	3896	0	0
Month	0.0039	5	3896	0	0
Latitude	0.0559	16	3896	0	0
Longitude	0.1796	29	3896	0	0
SST	0.1636	25.43	3896	0	0
SSH	0.1209	1295	3896	0	0
Chlorophyll a	0.0021	13.48	3896	0	0

96.428 = range in estimated values from original data

Sensitivity is the mean absolute difference resulting from nudging the predictors,
expressed as a proportion of the range of the response variable.
N nudgings = number of nudged values that contributed to the sensitivity calculation.
Nudged empty = number of nudged values that resulted in a missing estimate because of insufficient
data in that region of the predictor space, according to user-set minimum neighborhood size.
Empty orig. = number of actual data points with neighborhood size below user-set minimum.

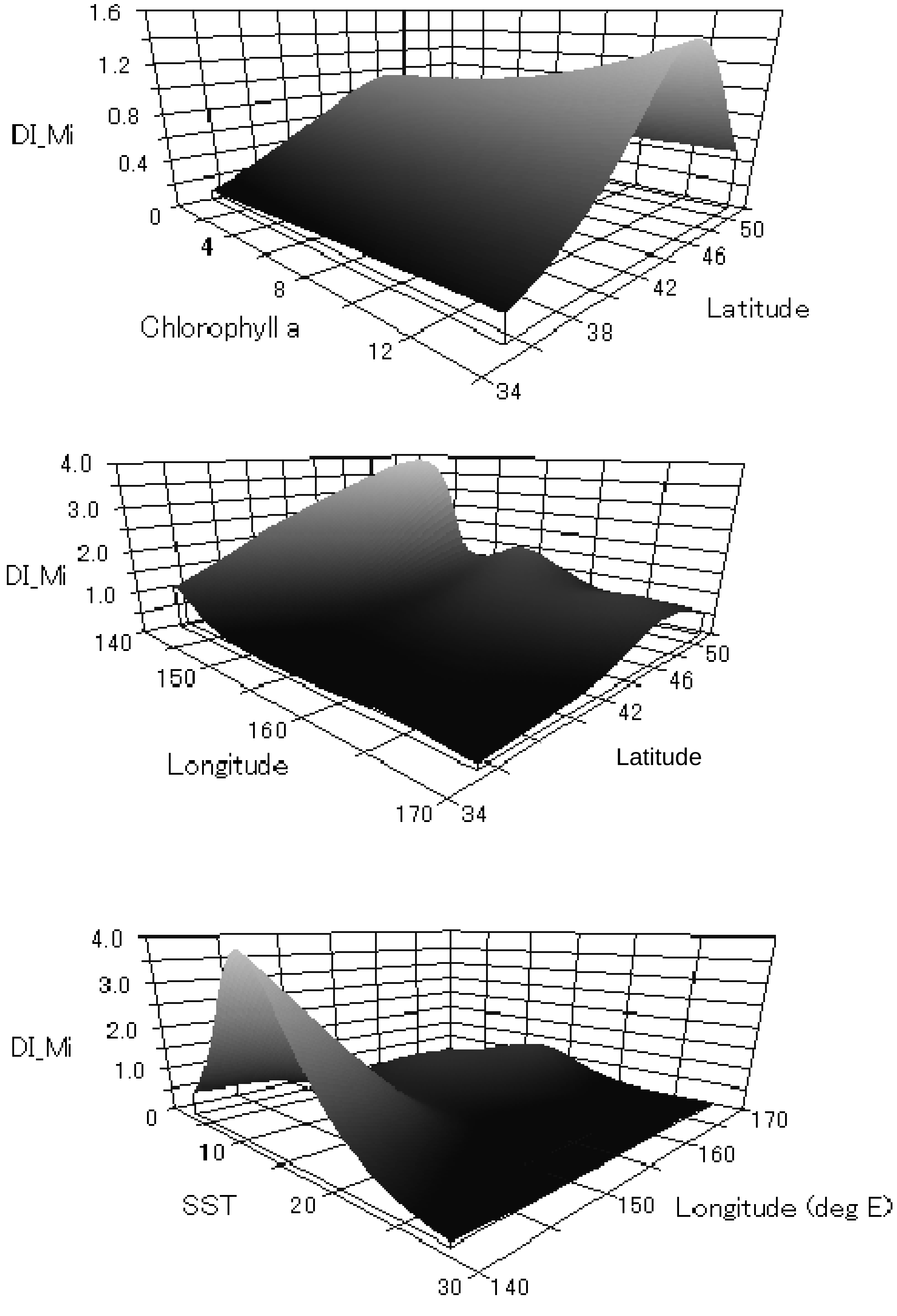

Figure 1 Species response and predictors interactions by NPMR model in minke whale.

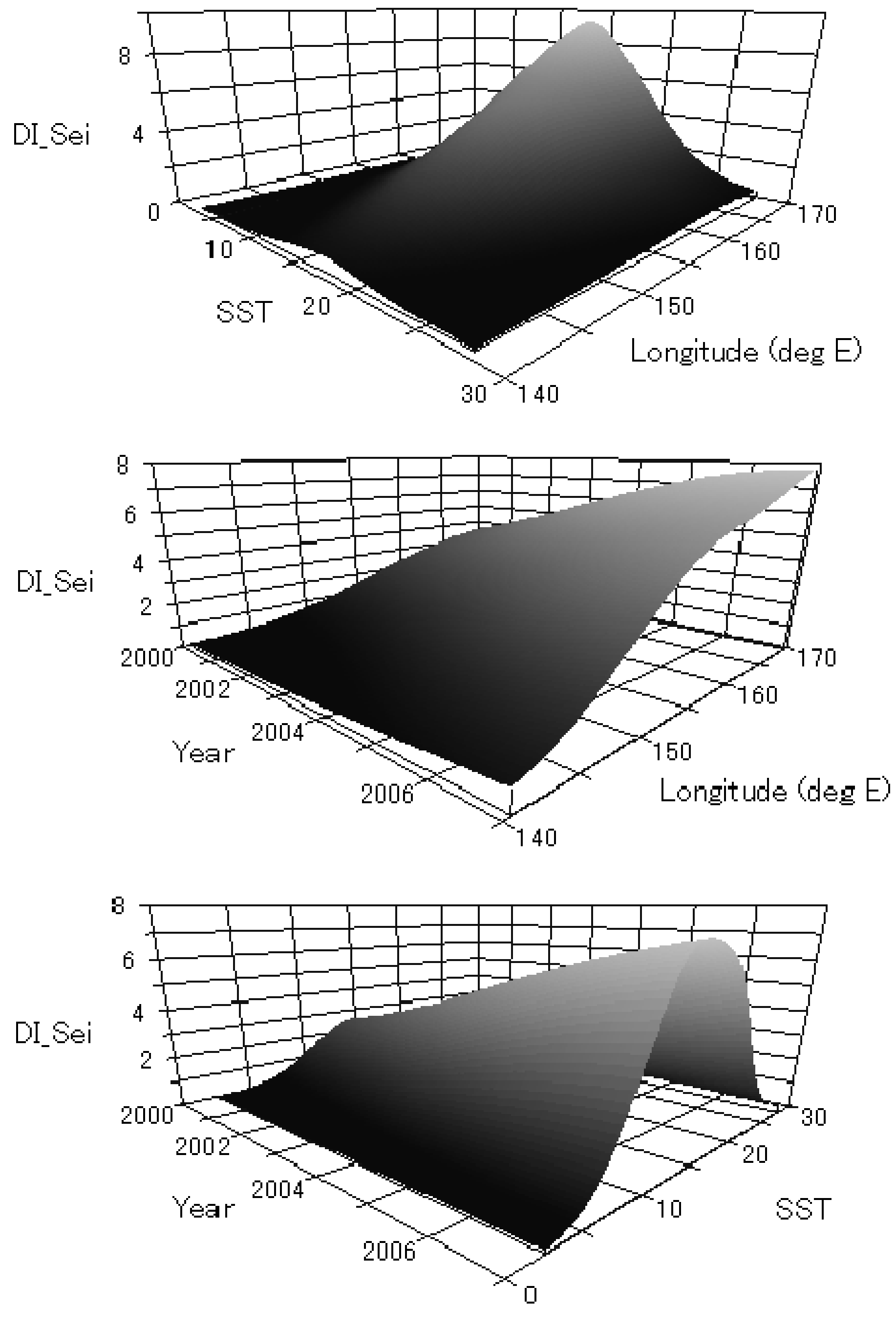

Figure 2 Species response and predictors interactions by NPMR model in sei whale.

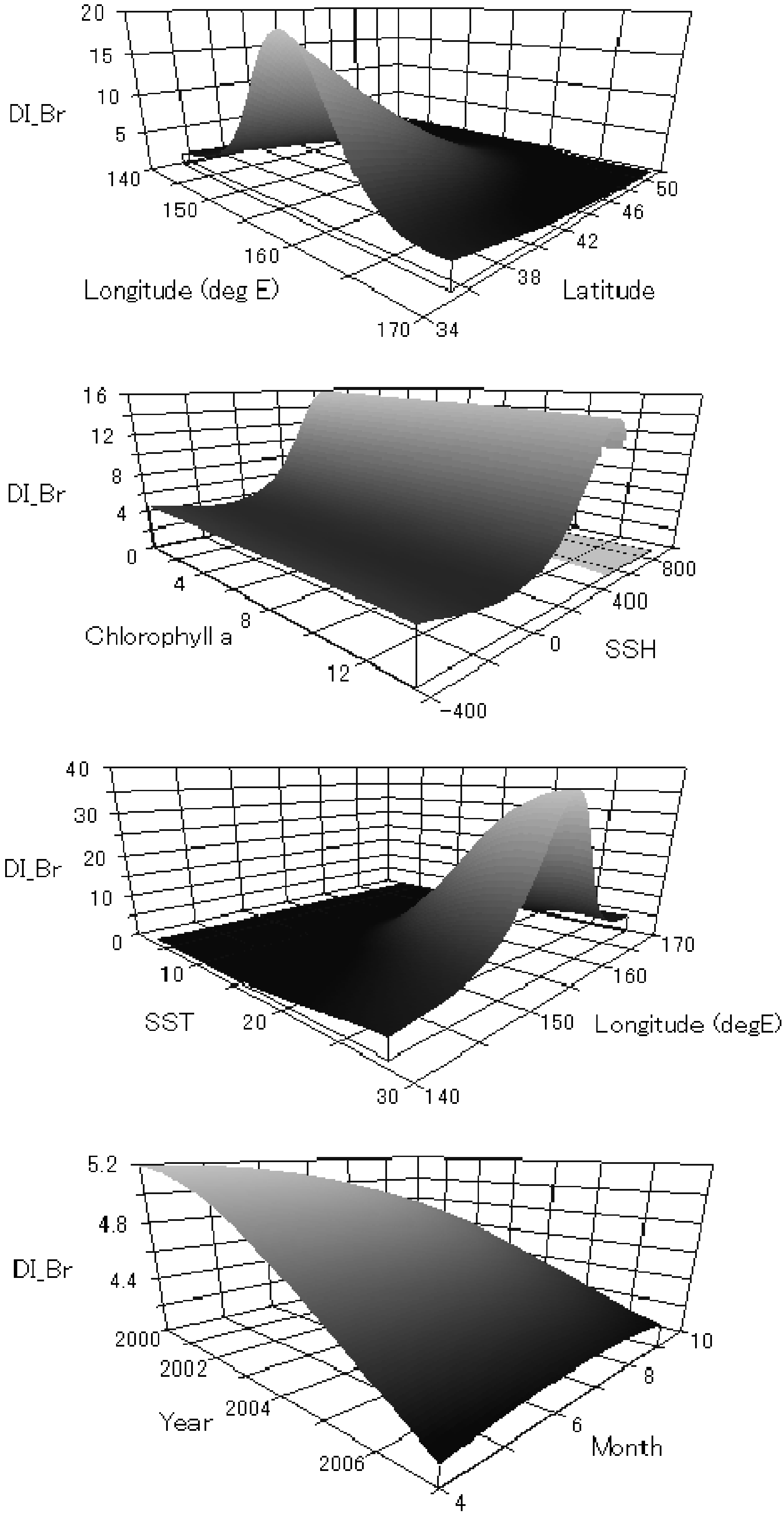

Figure 3 Species response and predictors interactions by NPMR model in Bryde’s whale

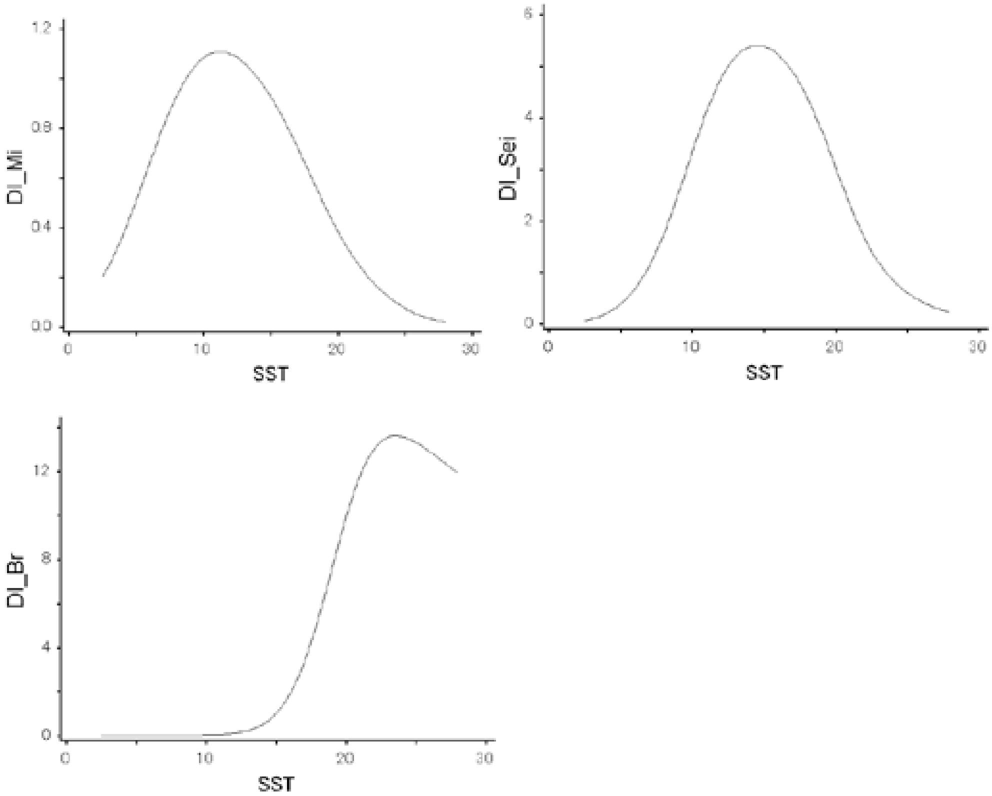

Figure 4 Response of DI and SST in minke, sei and Bryde's whales

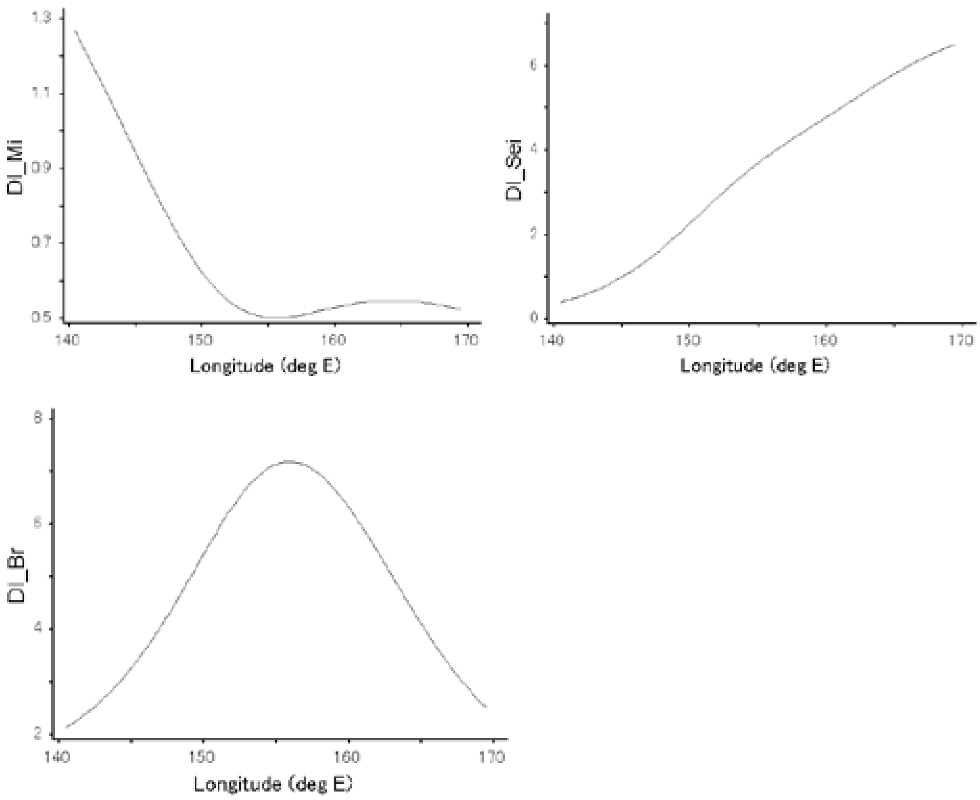

Figure 5 Response of DI and Longitude in minke, sei and Bryde's whales

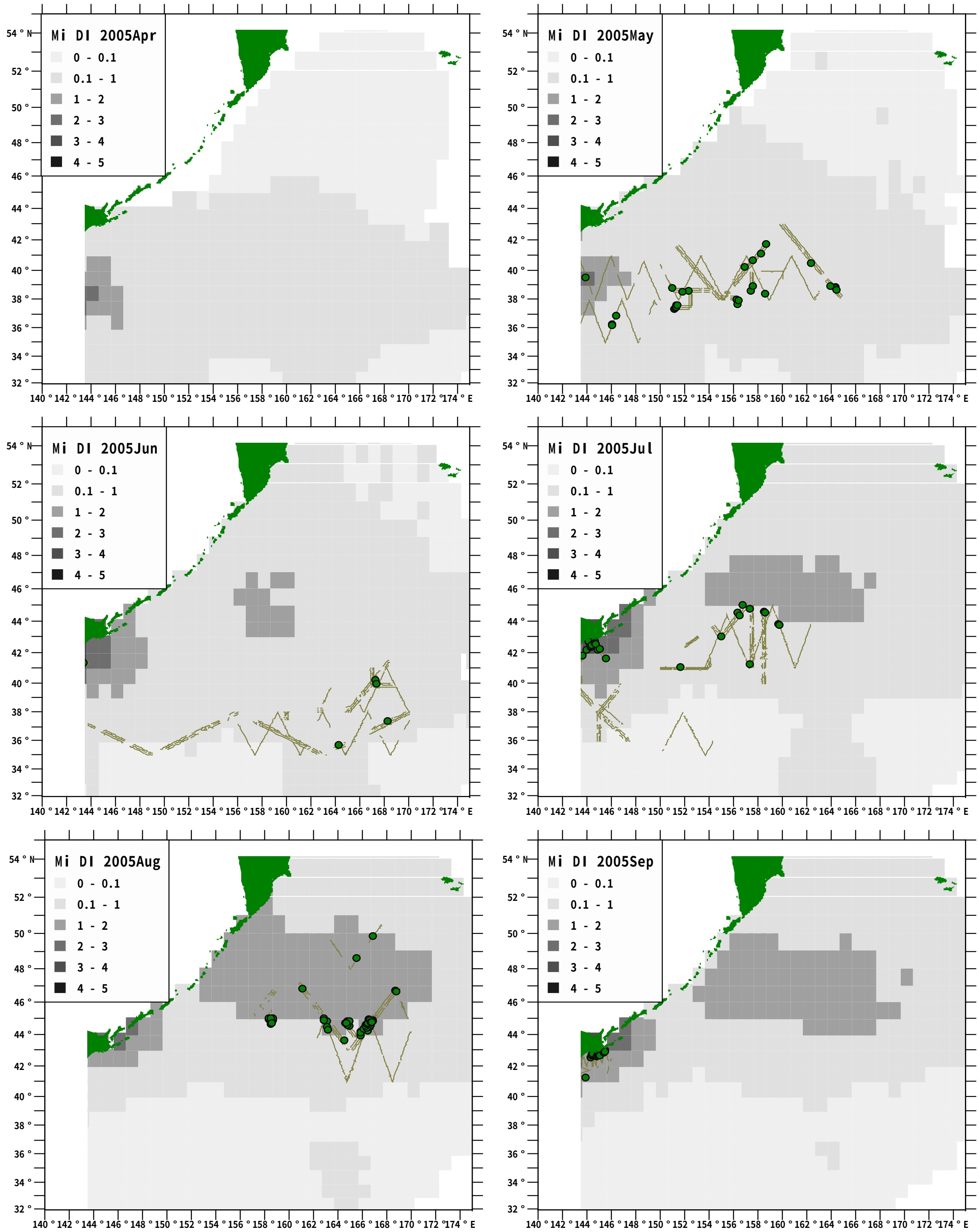

Figure 6-a Estimated DI of minke whale by NPMR model with sighting efforts and positions in 2005.

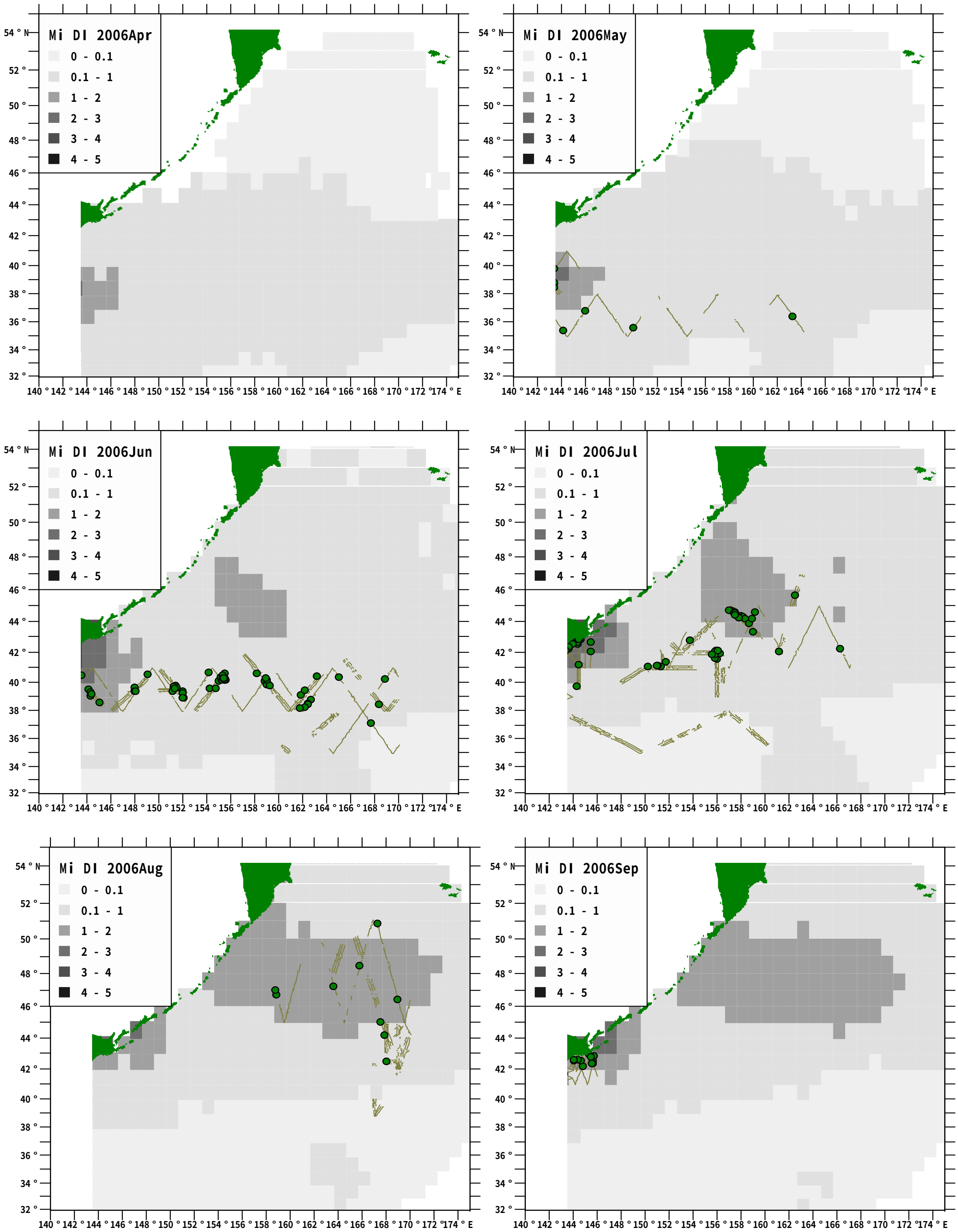

Figure 6-b Estimated DI of minke whale by NPMR model with sighting efforts and positions in 2006.

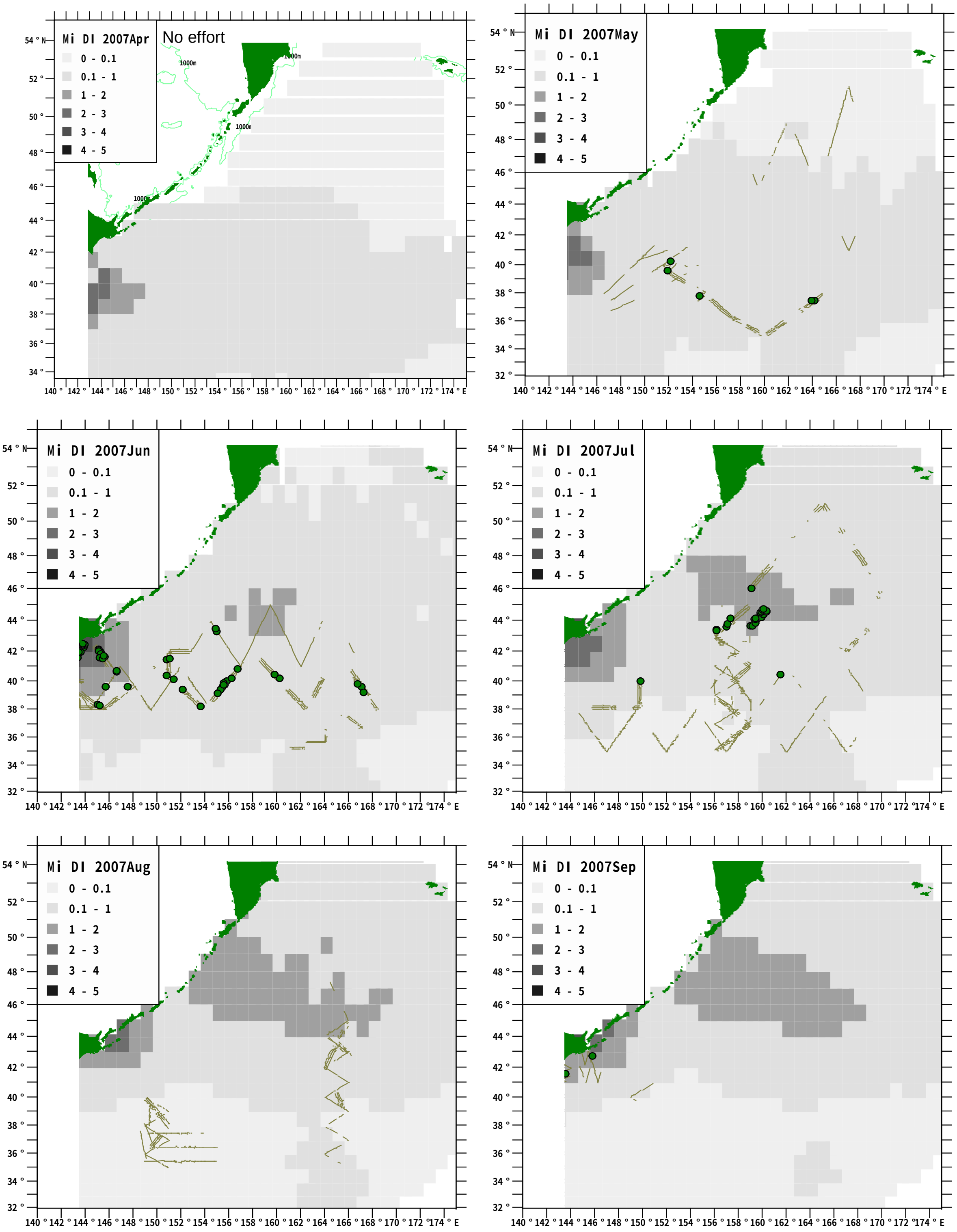

Figure 6-c Estimated DI of minke whale by NPMR model with sighting efforts and positions in 2007.

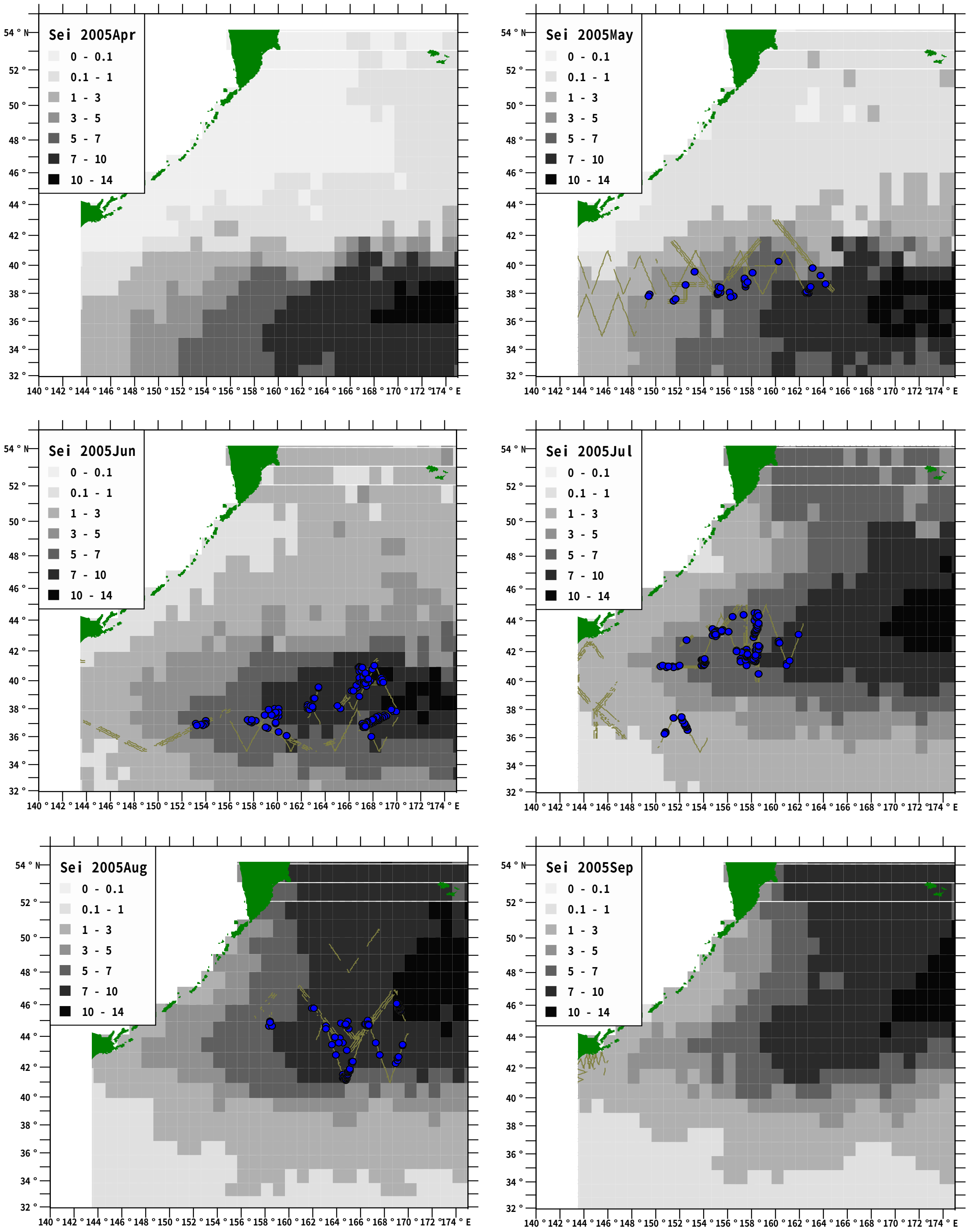

Figure 7-a Estimated DI of sei whale by NPMR model with sighting efforts and positions in 2005.

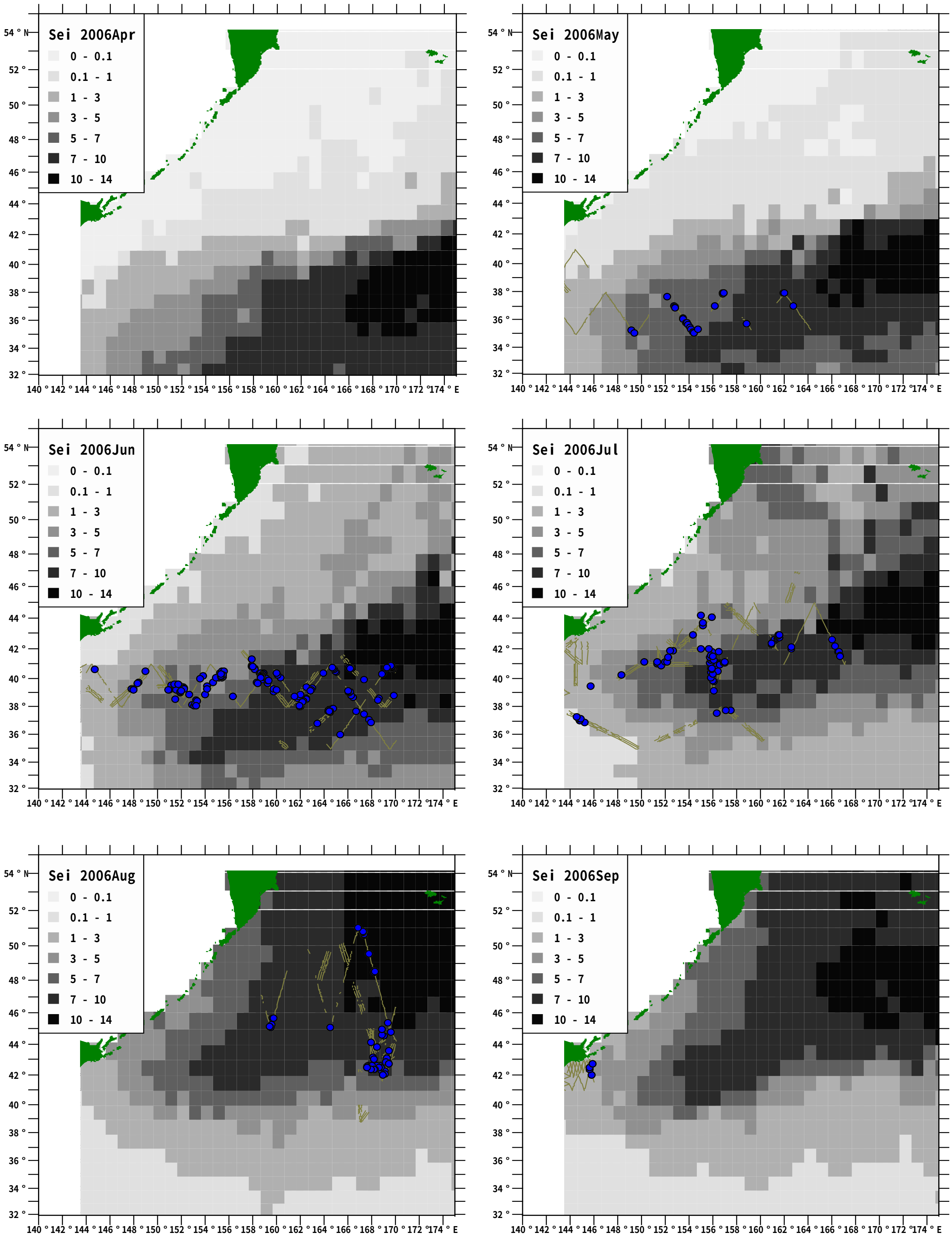

Figure 7-b Estimated DI of sei whale by NPMR model with sighting efforts and positions in 2006.

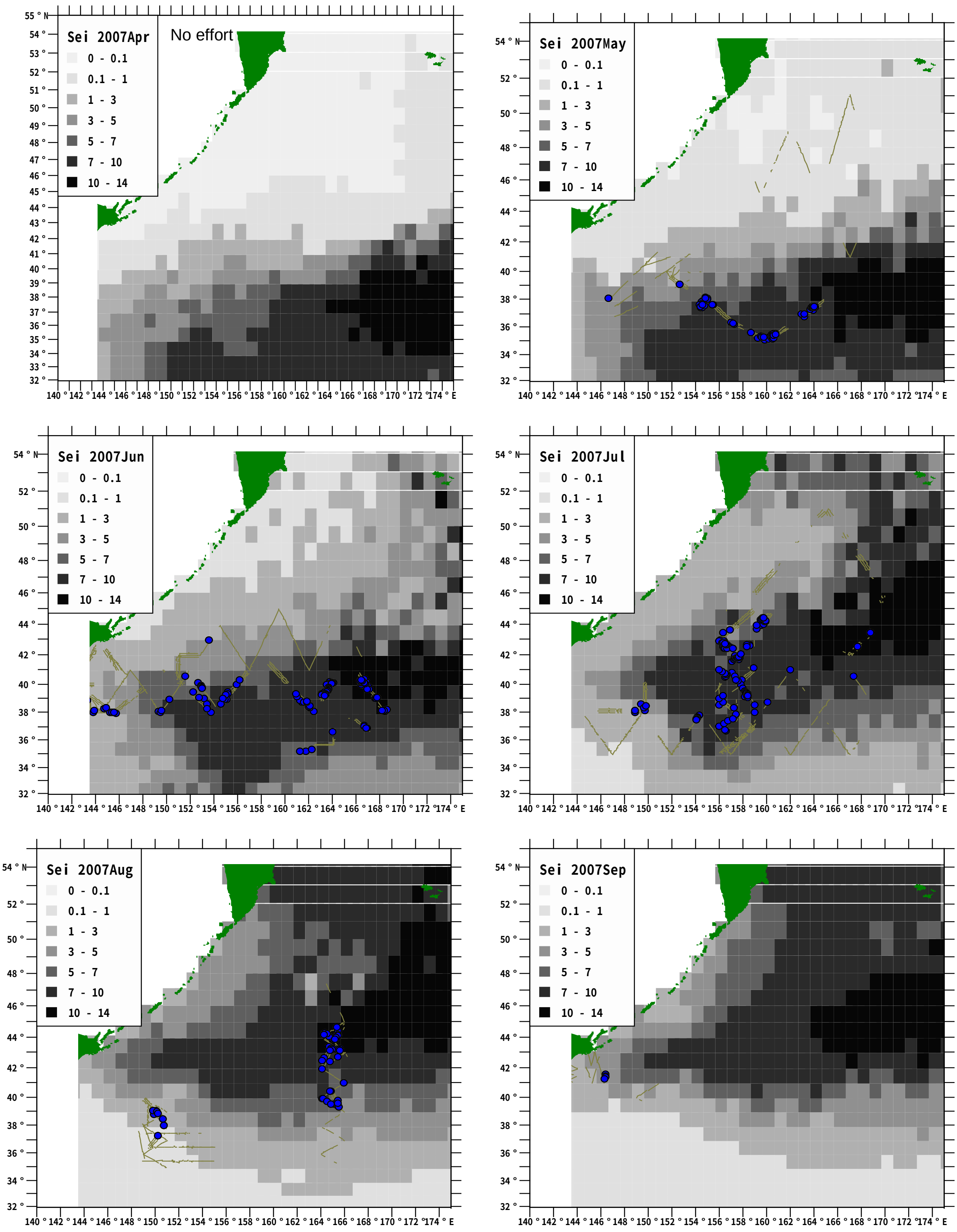

Figure 7-c Estimated DI of sei whale by NPMR model with sighting efforts and positions in 2007.

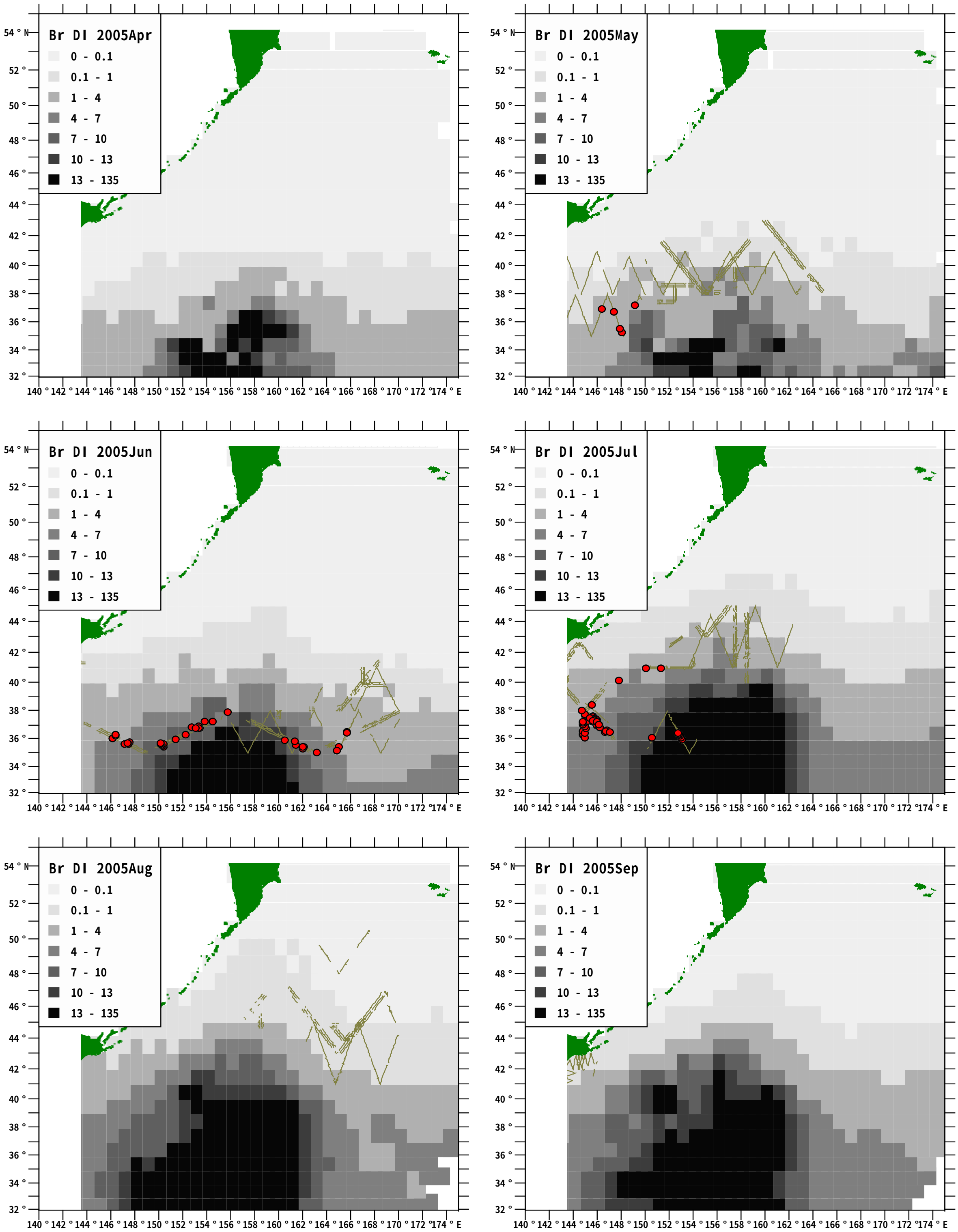

Figure 8-a Estimated DI of Bryde's whale by NPMR model with sighting efforts and positions in 2005.

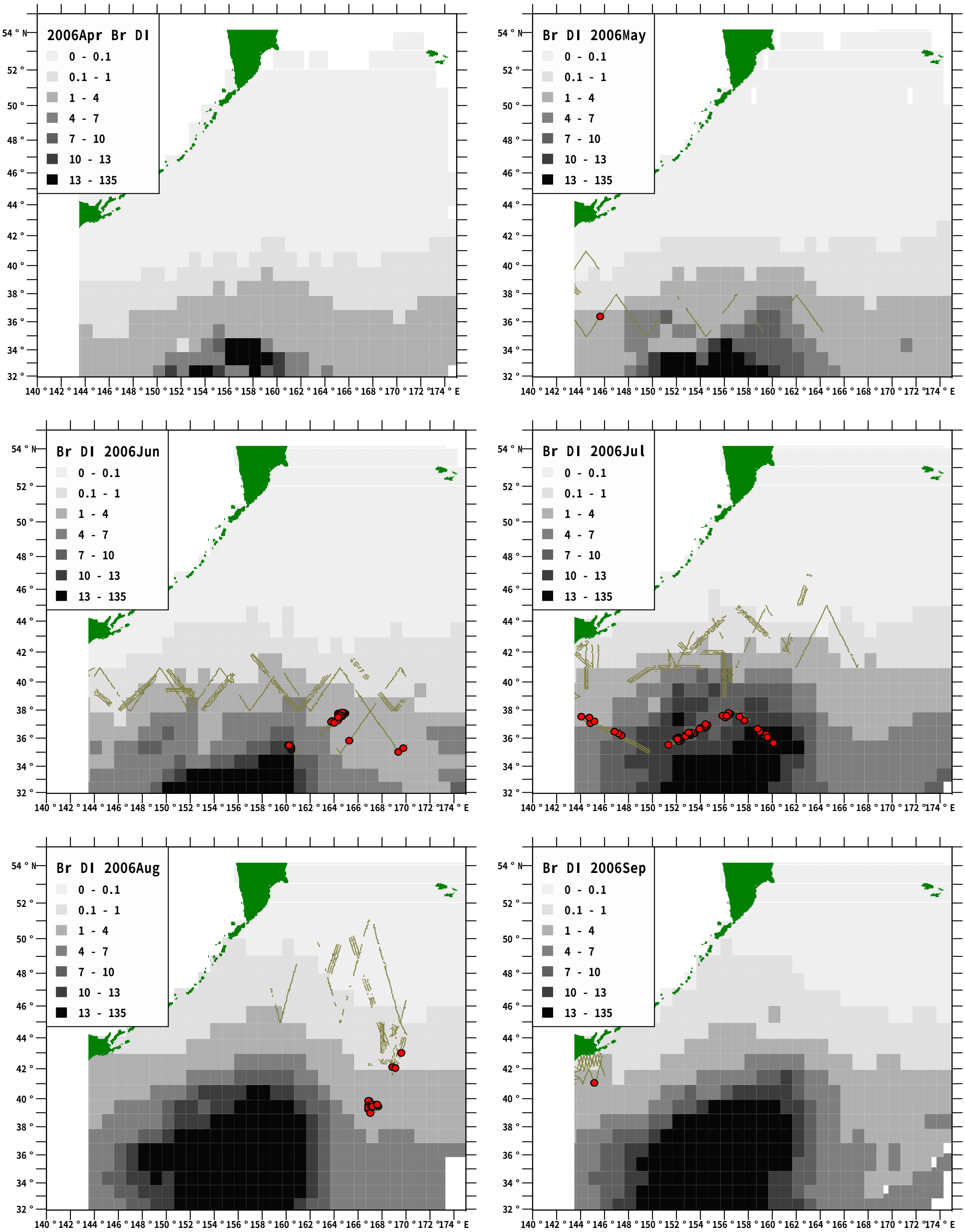

Figure 8-b Estimated DI of Bryde's whale by NPMR model with sighting efforts and positions in 2006.

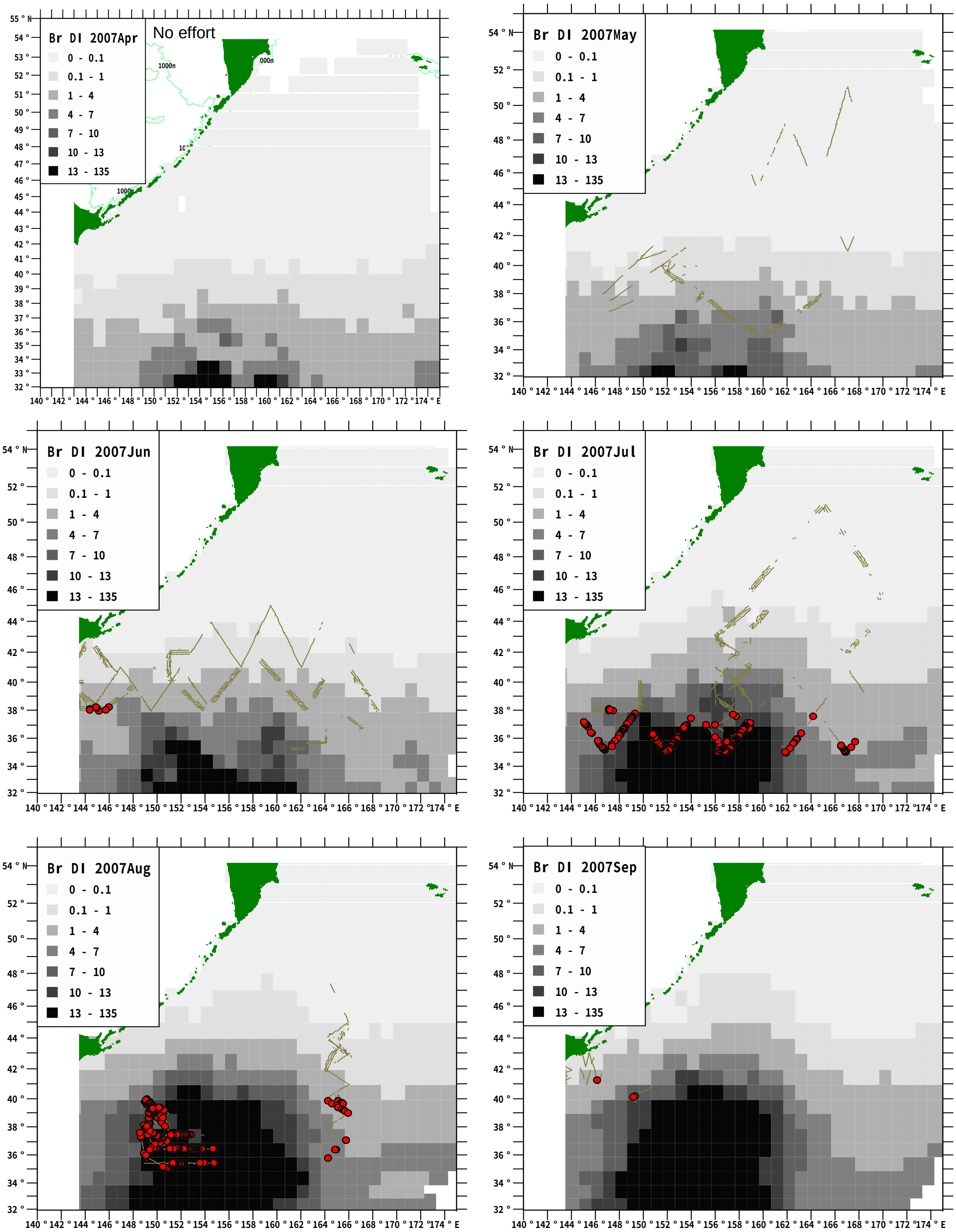

Figure 8-c Estimated DI of Bryde's whale by NPMR model with sighting efforts and positions in 2007.