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Gulf of Mexico Marine Assessment Program for Protected Species (GoMMAPPS): Marine Mammals

Volume 3: Appendix D: Gulf of Mexico Sea Turtle Spatial Density Models

US Department of the Interior
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Gulf of Mexico Sea Turtle Spatial Density Models

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DISCLAIMER

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ABOUT THE COVER

Marine mammal photographs were collected during GoMMAPPS vessel surveys under NMFS ESA/MMPA Permit No.14450.

Contents

List of Figures

List of Tables

D.1 Gulf of Mexico Shelf Leatherback Turtles Spatial Density Models

Photo credit: NOAA Fisheries

Leatherback turtles (*Dermochelys coriacea*) occur in the Gulf of Mexico (GOM). This section describes the development of spatial density models (SDMs) for leatherback turtles occurring over the continental shelf based on seasonal aerial surveys conducted in 2011–2012 and 2017–2018, including average abundance prediction maps generated using monthly environmental parameters for the period of 2015–2019. In addition, this section includes density prediction maps for shelf waters of the entire GOM.

D.1.1 Survey Data and Sightings

Aerial line-transect surveys were conducted over the continental shelf of the northern Gulf of Mexico (NGOM) in a survey region extending from the shoreline to the shelf break (approximately the 200 m isobath) between Key West, Florida and the US/Mexico border near Brownsville, Texas. Each survey was conducted in a NOAA Twin Otter flying at a survey altitude of 183 m (600 ft) and an approximate speed of 100 knots. Survey tracklines were spaced approximately 20 km apart and were oriented so as to be perpendicular to the shoreline. The aircraft was equipped with two large bubble windows in the forward portion of the aircraft (left and right sides) and one right bubble window and a belly window in the aft portion of the aircraft to allow effective visualization of the trackline (see Figure 2 in the GoMMAPPS project final report). Surveys were conducted using two independent teams to allow estimation of detection probability within the surveyed strip and on the trackline using Mark Recapture Distance Sampling (MRDS) approaches. Aerial surveys were conducted in spring 2011, summer 2011, fall 2011, and winter 2012 as part of the Natural Resource Damage Assessment (NRDA) associated with the *Deepwater Horizon* oil spill. Additional surveys were conducted in the summer of 2017, winter 2018, and fall 2018 as part of the Gulf of Mexico Marine Assessment Program for Protected Species (GoMMAPPS) project. Additional details about the survey design and execution are contained in Garrison et al. (2022). The total number of leatherback turtles sighted is shown in Table D.1-1.

Table D.1-1. Leatherback turtles observed for each survey included in this analysis

Survey	Groups	Individuals
TOSE11F	57	58
TOSE11Sp	10	10
TOSE11Su	83	86
TOSE12W	26	28
TOSE17Su	36	37
TOSE18F	5	5
TOSE18W	7	7

Leatherback turtles were observed in the NGOM in the continental shelf waters, east of latitude 94.5°W in all seasons with higher densities of animals typically occurring in the central NGOM in 2011 and 2012 (Figure D.1-1).

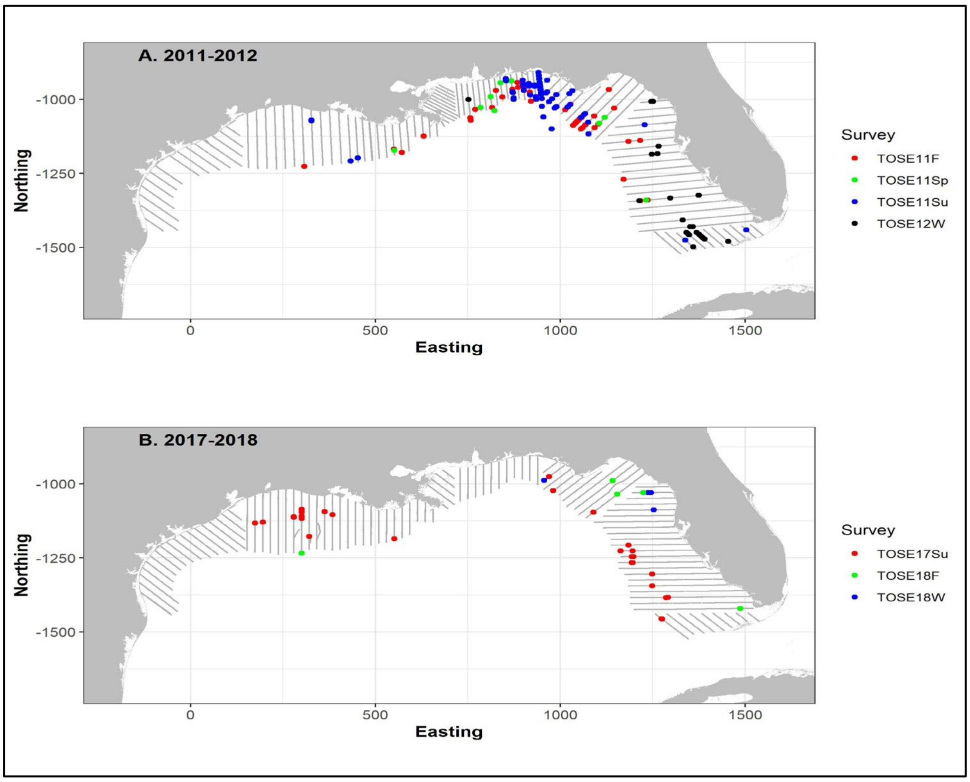

Figure D.1-1. Survey effort and leatherback turtle sightings during (A) 2011–2012 and (B) 2017–2018.

D.1.2 Distribution of Sightings and Physical Oceanography during Each Survey

Leatherback turtles were seen during all seasons but almost all sightings in winter and spring were east of the mouth of the Mississippi River. Sightings tended to occur more frequently in offshore waters with lower chlorophyll-a concentrations. The spatial pattern in the winter 2018 survey reflects incomplete survey effort where tracklines in the northeastern GOM were not completed due to poor weather conditions. The distribution of sightings and surface temperature and chlorophyll-a concentrations are shown in Figures D.1-2–D.1-8.

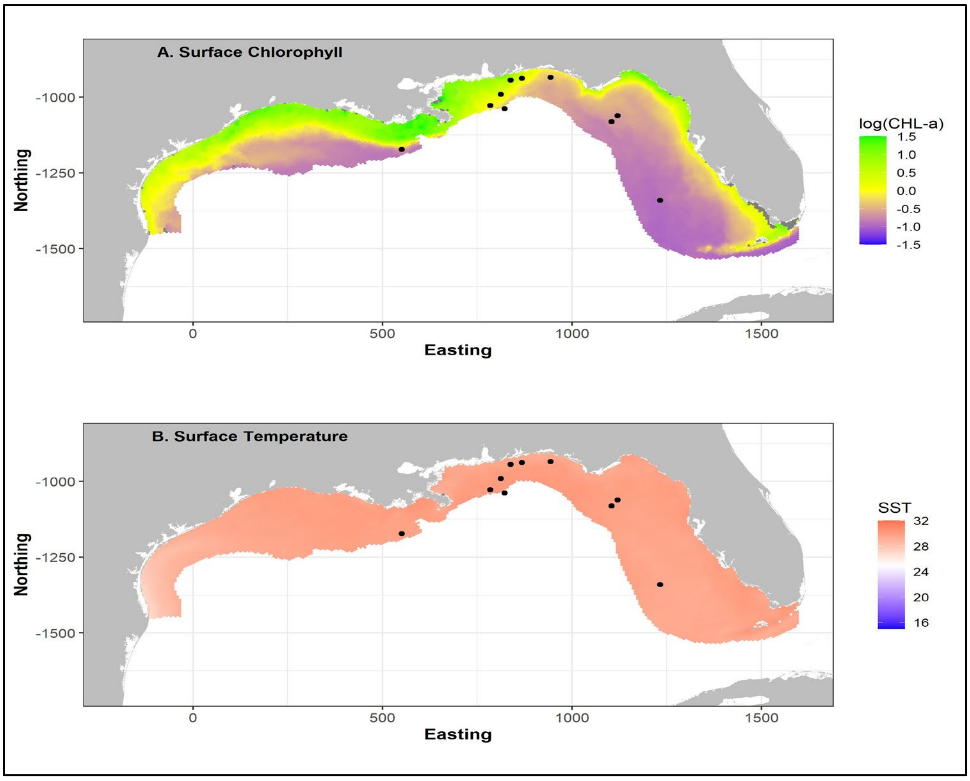

Figure D.1-2. Leatherback turtle sightings during spring 2011.

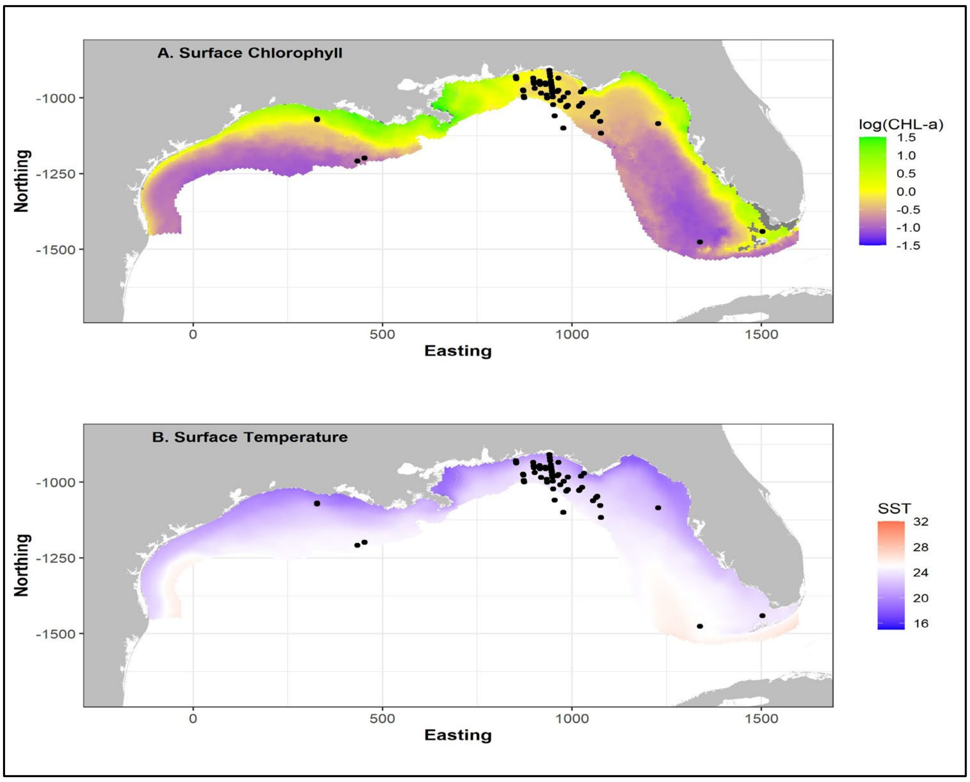

Figure D.1-3. Leatherback turtle sightings during summer 2011.

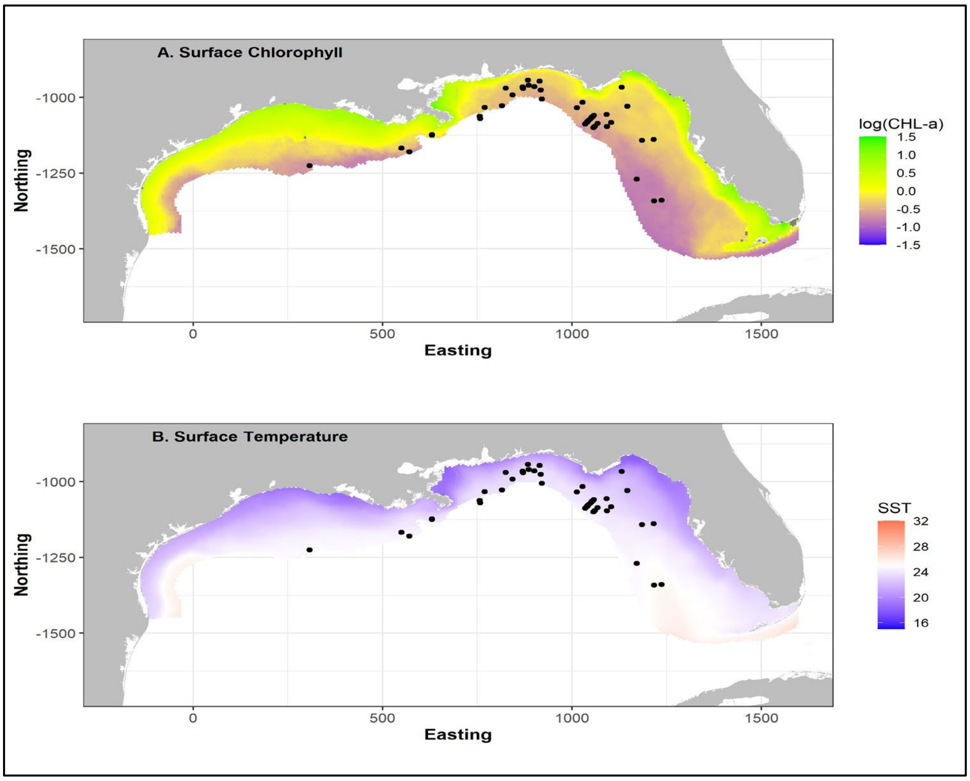

Figure D.1-4. Leatherback turtle sightings during fall 2011.

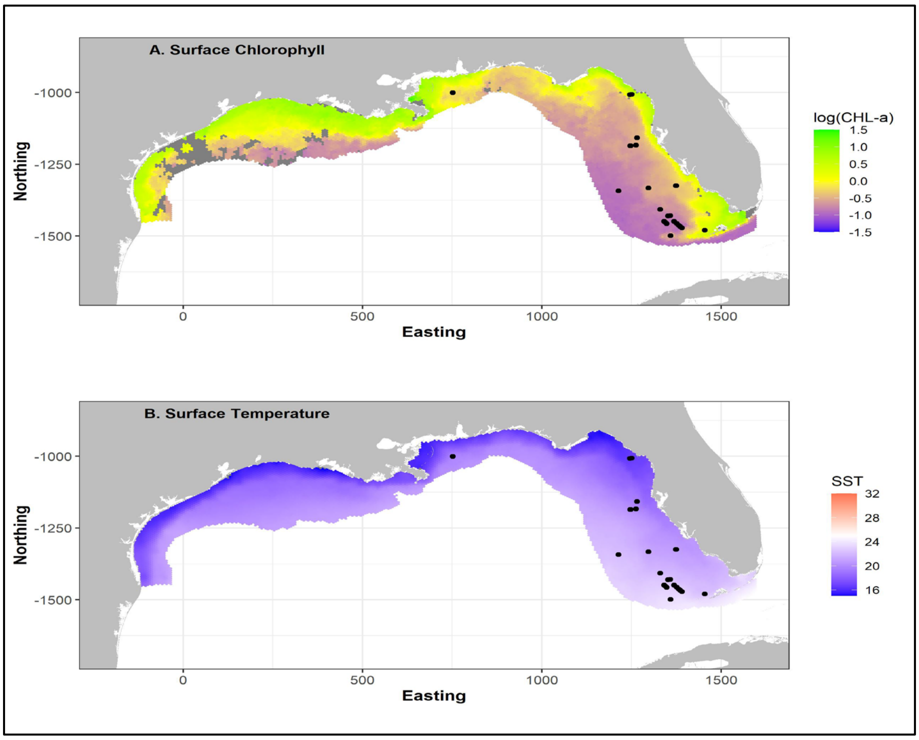

Figure D.1-5. Leatherback turtle sightings during winter 2012.

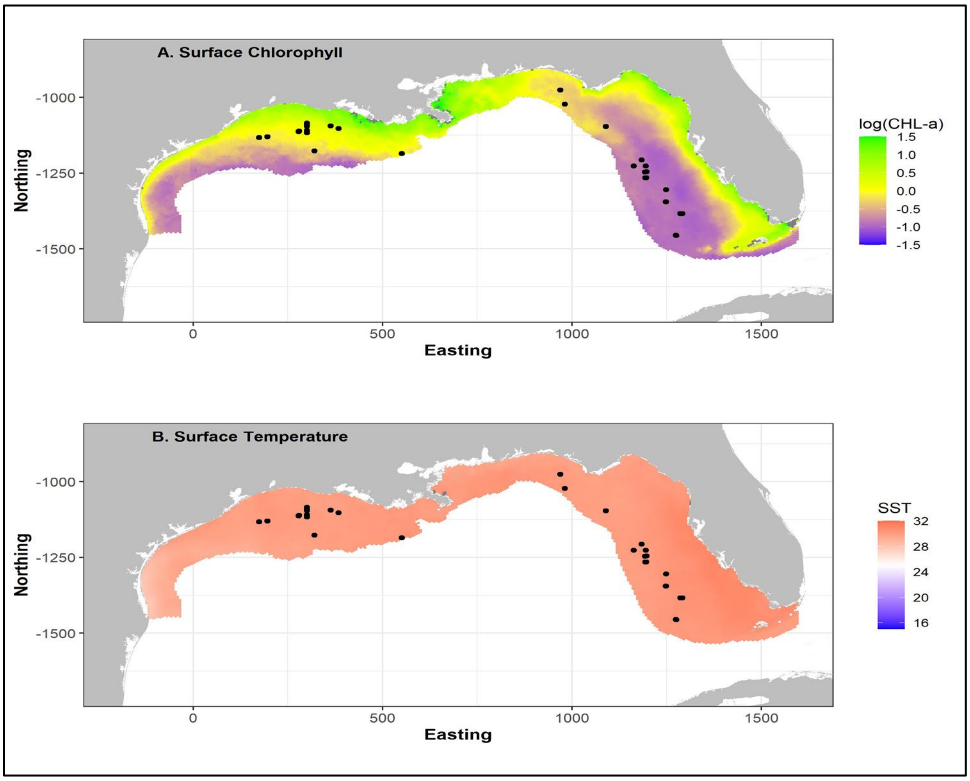

Figure D.1-6. Leatherback turtle sightings during summer 2017.

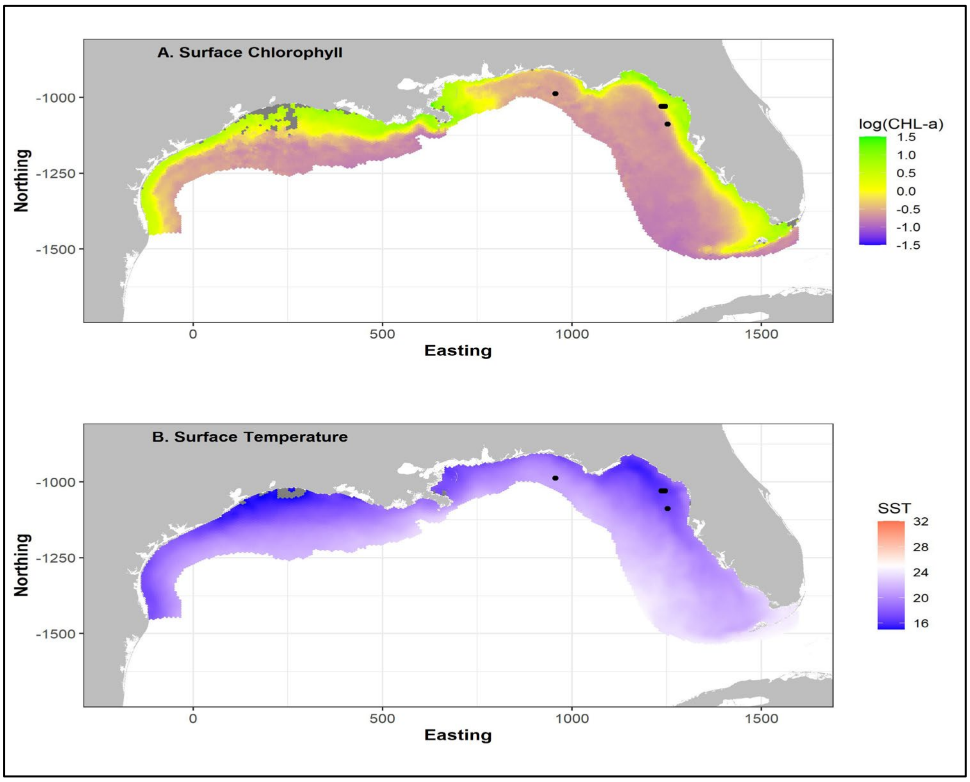

Figure D.1-7. Leatherback turtle sightings during winter 2018.

Note that survey effort was incomplete in the northeastern GOM during this survey.

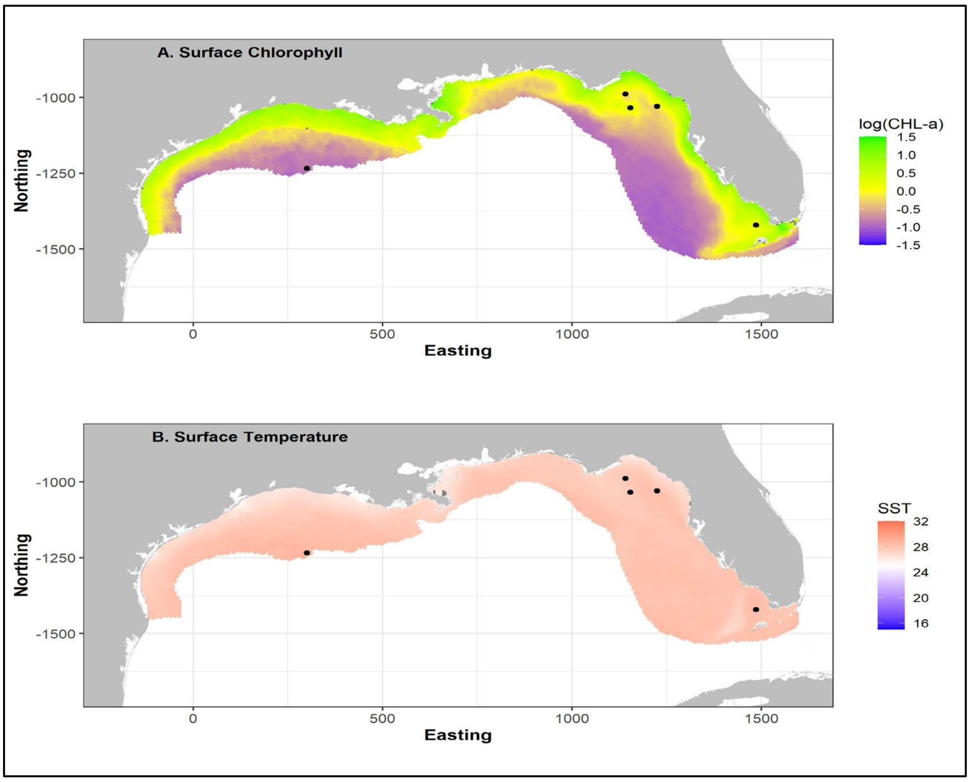

Figure D.1-8. Leatherback turtle sightings during fall 2018.

D.1.3 Distance Analysis and Detection Probability

Detection probability within the surveyed strip was estimated using MRDS approaches. Covariates considered for inclusion in the detection function included sea state, cloud cover, water turbidity, and sun penetration. In addition, the correlation between the ln(group size) and perpendicular sighting distance (PSD) was examined, but there was no relationship between group size and detection distances, so group size was not considered for inclusion in the model.

The best model was selected by first examining the distribution of PSD and selecting an appropriate right truncation distance and key function. Then, all combinations of detection covariates were considered for both the detection function and mark-recapture portion of the model, and the model with the lowest Akaike's Information Criterion (AIC) was selected. The best model used a hazard-rate key function with a right truncation distance of 300 m. Sea state was included as covariate in the distance component of the model. Turbidity and an interaction term with observer position were included in the mark-recapture component of the model (Table D.1-2).

Table D.1-2. Parameters included in the detection probability function

(MCDS = Multiple covariate distance sampling)

Model	Parameter	Estimate	SE
MCDS	MCDS Intercept	5.3807	0.2643
MCDS	Sea State	-0.2159	0.1099
MRDS	MRDS Intercept	2.7269	1.3550
MRDS	Distance	-0.0012	0.0048
MRDS	Observer	-0.7756	0.3215
MRDS	Turbidity	-0.9546	0.6317
MRDS	Distance x Observer	0.0006	0.0025

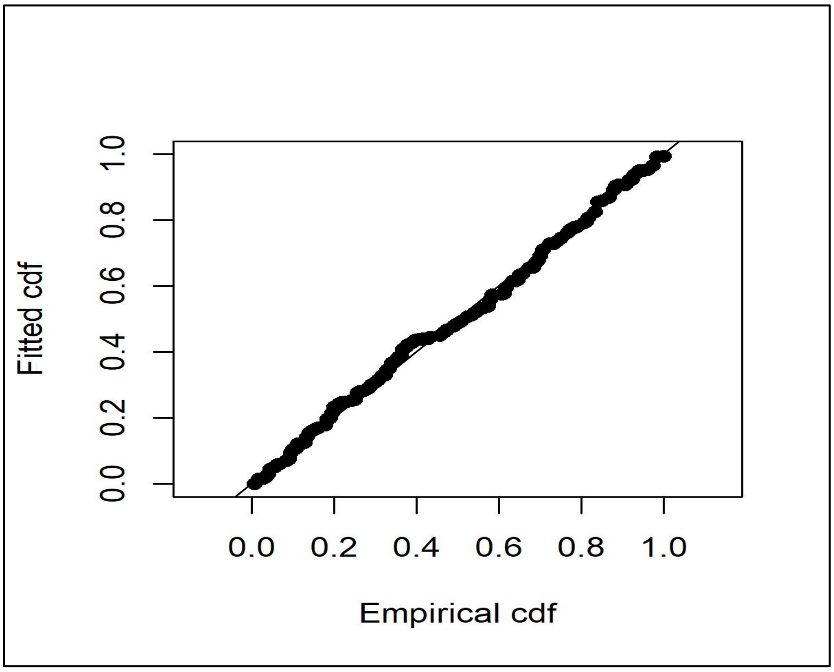

Figure D.1-9. MRDS detection function Q-Q plot

(cdf = cumulative distribution function).

The resulting detection probability function had a good overall fit as indicated by the linear Quantile-Quantile (Q-Q) plot (Figure D.1-9). The Chi-square goodness of fit test p-value was 0.02 (Chi-square = 19.66, df = 9) indicating some deviation from the expected model especially in the mark-recapture component at high PSD. However, the Cramer-von Mises test p-value was 0.839 (test statistic = 0.056) suggesting an adequate model fit overall.

The estimated detection probability on the trackline is shown in Table D.1-3, and the detection probability function is shown in Figure D.1-10.

Table D.1-3. Estimated detection probability and number of detections in the surveyed area from Multiple Covariate Distance function

Parameter	Estimate	SE	CV
Detection probability	0.588	0.048	0.082
Team 1 p(0)	0.521	0.092	0.177
Team 2 p(0)	0.335	0.070	0.209
Combined p(0)	0.679	0.086	0.127
Overall Avg. Detection Prob.	0.399	0.060	0.150

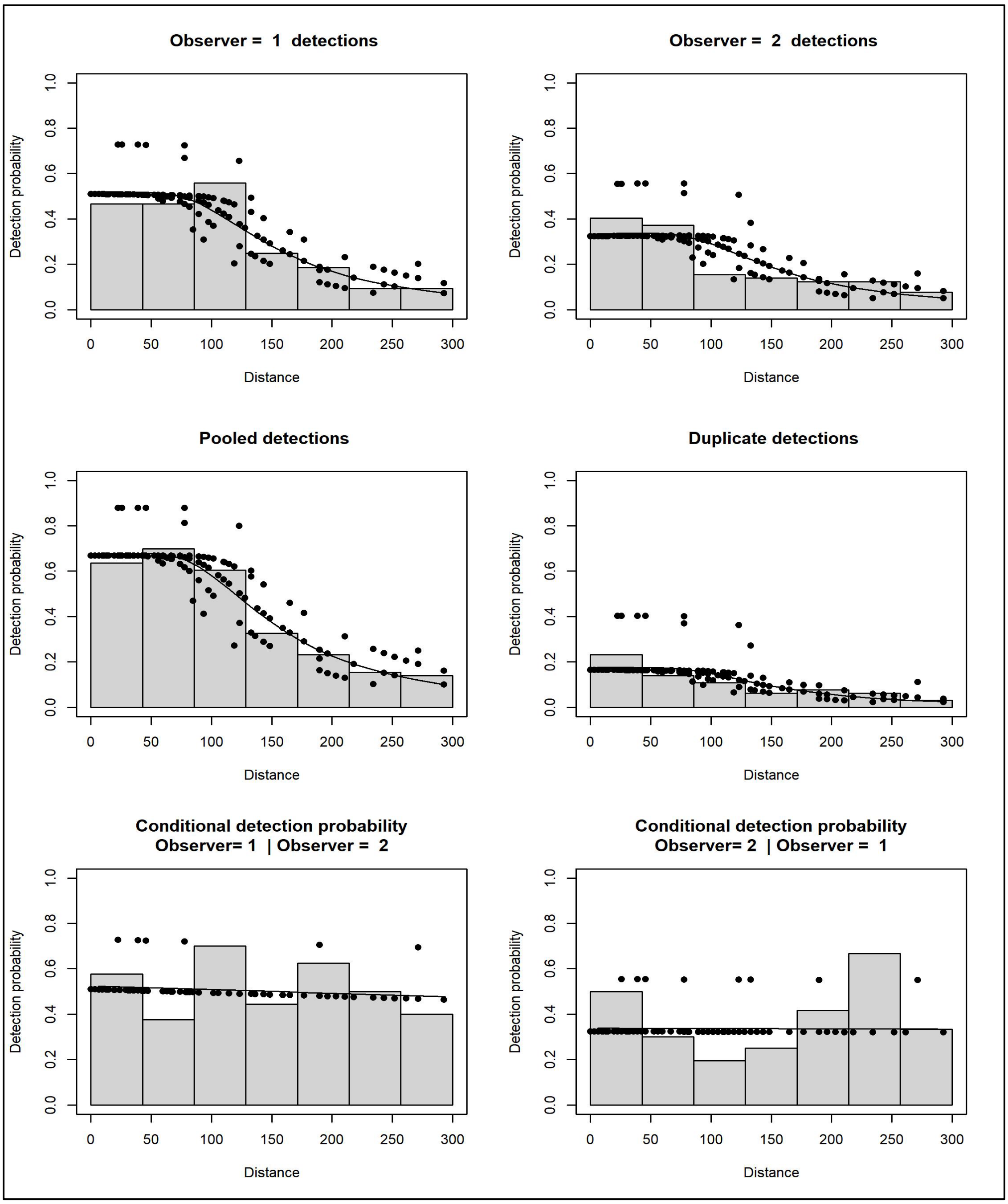

Figure D.1-10. Mark-recapture distance sampling detection probability.

D.1.4 Spatial Density Model Selection

A generalized additive model (GAM) was used to develop a spatial density model to describe the effect of habitat variables on the density and abundance of leatherback turtles in the NGOM. Survey effort (kilometers of survey trackline) was partitioned into segments within a grid of hexagonal cells of 40 km^2 area and matched to physical oceanographic parameter values within each cell. Each resulting segment was considered a sampling unit within the GAM, and the number of animals observed on the segments was the response variable in a log count model assuming a Tweedie error distribution to account for overdispersed count data. An offset term (ln[strip area]) was included in the model to account for the effective area surveyed within each spatial cell based upon the detection probability function described above and covariates during the survey.

An initial GAM model was fit using all available oceanographic and physiographic variables. A reduced model was the selected including only model terms with p-value < 0.2. This reduced model was compared to the full model using AIC to ensure selection of the best fitting, most parsimonious model. Model fit was assessed through the examination of randomized quantile residuals and the associated Q-Q plot for deviance residuals.

For leatherback turtles, the selected model included Average Depth (AvgDepth), Distance from the Continental Shelf Edge (Dist2Shelf), Distance from Canyons (Dist2Canyo), log(chlorophyll-a concentration) (lAvgChl), Sea Surface Temperature (Avg_SST) and Mixed Layer Depth (Avg_CMEMS_MLD) (Table D.1-4). In addition, two factor variables were included in the model to reflect the overall higher density of leatherback turtles in the 2017–2018 surveys compared to prior years ("year") and the areas east and west of the mouth of the Mississippi River ("Shelf_EW"). The model fit to the data may have been affected by zero inflation as can be seen by the outlier residual values in the Q-Q plot (Figure D.1-11).

Table D.1-4. Parameter estimates for the selected Generalized Additive Model

(EDF = effective degrees of freedom)

Term	EDF	Max..EDF	F.Statistic	P.value
s(AvgDepth)	3.619	9	4.224	< 0.001
s(Dist2Shelf)	2.963	9	2.297	< 0.001
s(Dist2Canyo)	5.844	9	3.982	< 0.001
s(lAvg_Chl)	4.41	9	9.447	< 0.001
s(Avg_SST)	6.126	9	5.395	< 0.001
s(Avg_CMEMS_MLD)	0.924	9	1.132	< 0.001

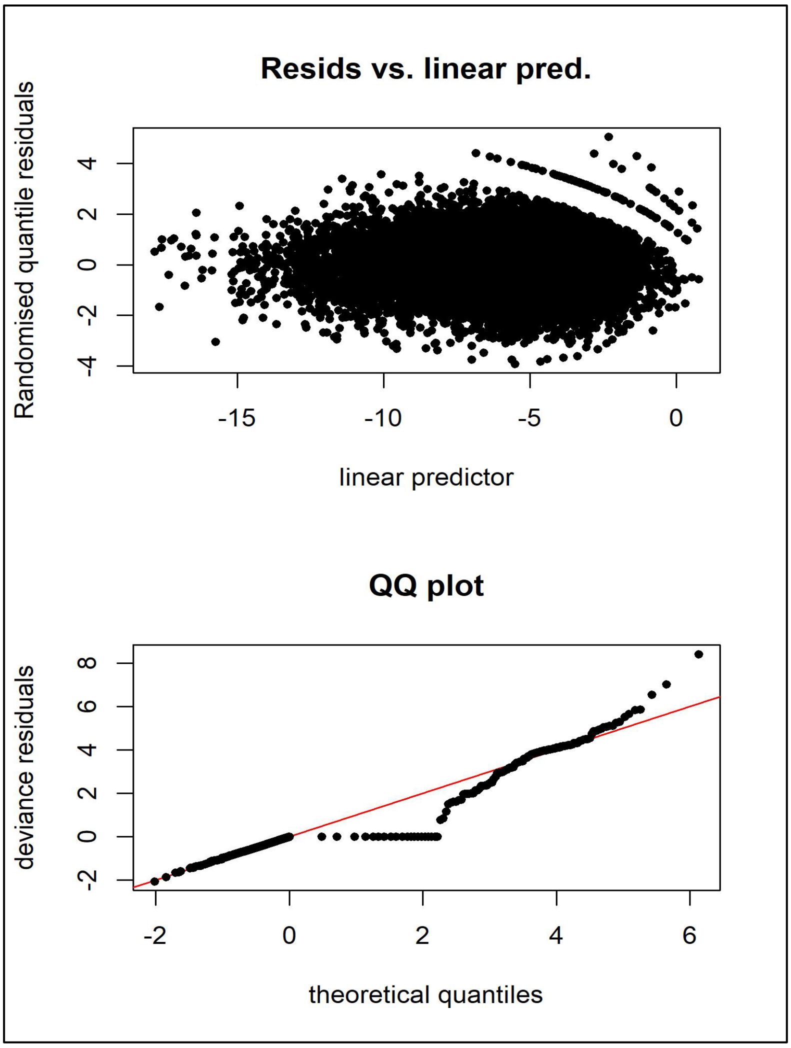

Figure D.1-11. GAM residual plots.

The selected model indicated that leatherback turtle density was higher in offshore waters deeper than 50 m. The effect of distance from continental shelf edge shows higher density in the middle of the continental shelf. The sea surface temperature effect reflects the higher densities and wider distribution throughout the area observed in the summer and fall with lower density in the central NGOM during the winter. Leatherback turtle density was higher in areas with a shallower mixed layer depth. A year class factor indicated higher overall density in more recent surveys. The regional east-west shelf factor indicated differences in leatherback turtle densities between the areas east and west of the mouth of the Mississippi River, with overall density being higher in the eastern area (Figure D.1-12).

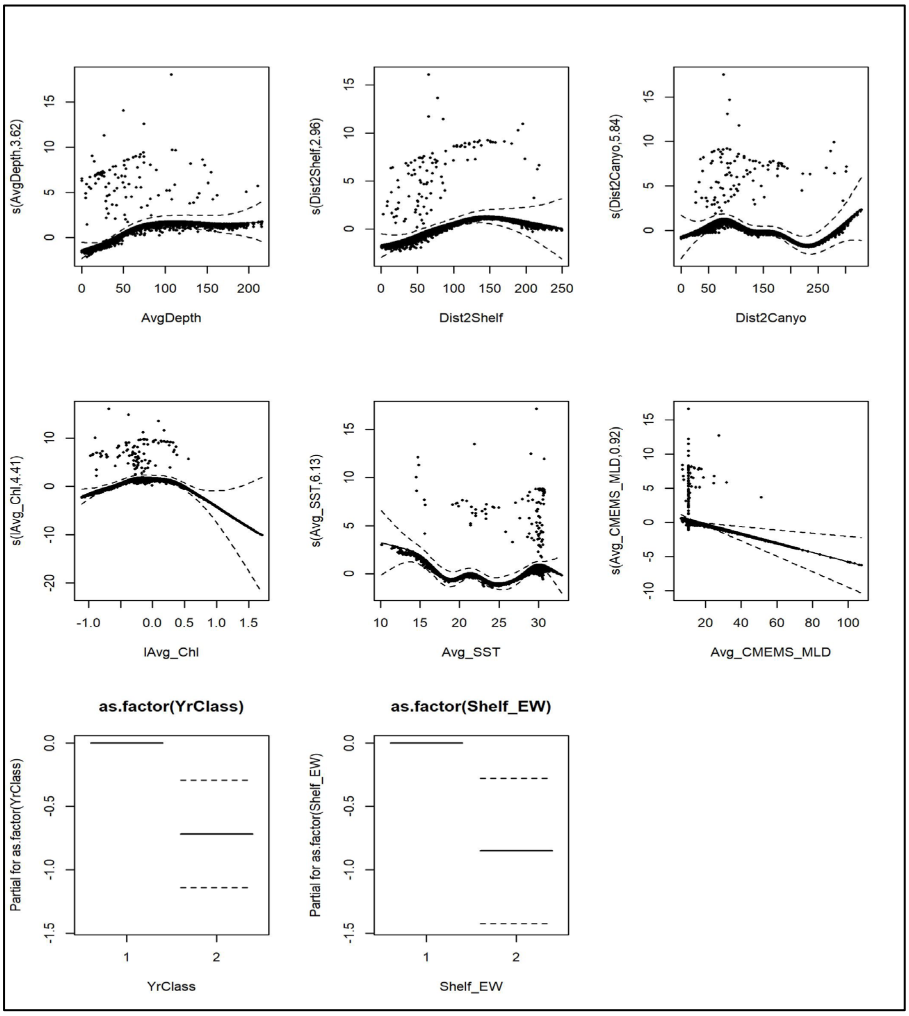

Figure D.1-12. GAM partial plots.

D.1.5 Spatial Density Model Prediction Maps and Model Output

Based upon the selected model, prediction maps were developed using monthly average oceanographic variable values for 2018. The estimated uncertainty (coefficient of variation [CV]) reflects only uncertainty in the GAM model fit and does not account for uncertainty in the detection probability function.

D.1.5.1 Northern Gulf of Mexico

Monthly prediction maps demonstrate variability in animal density resulting from variability in the underlying physical oceanography. In particular, variability in temperature results in changes in the overall estimated population size with the highest population estimates in the summer months (Figures D.1-13–D.1-24).

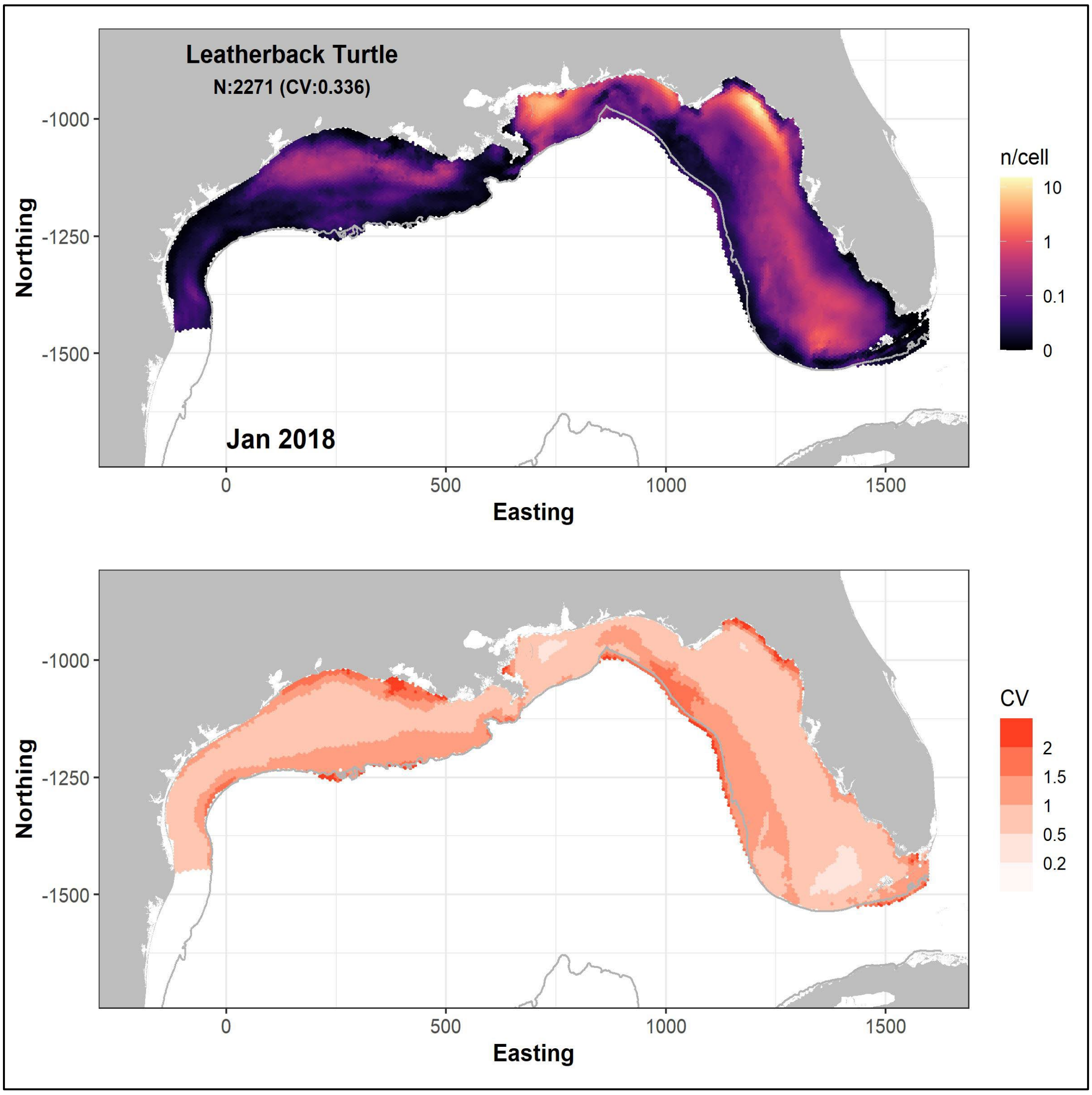

Figure D.1-13. Density model prediction for shelf leatherback turtles in the NGOM in January 2018.

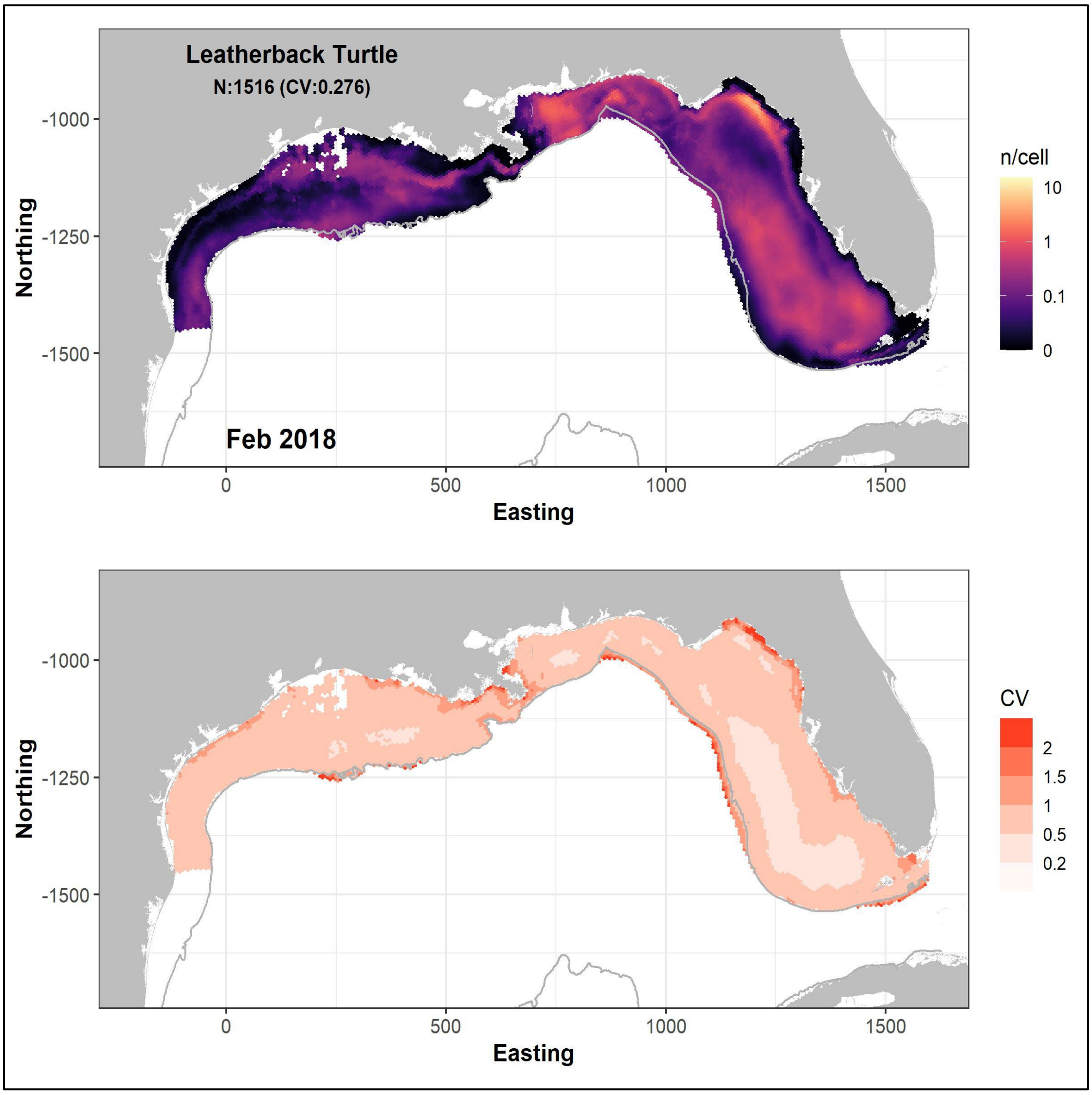

Figure D.1-14. Density model prediction for shelf leatherback turtles in the NGOM in February 2018.

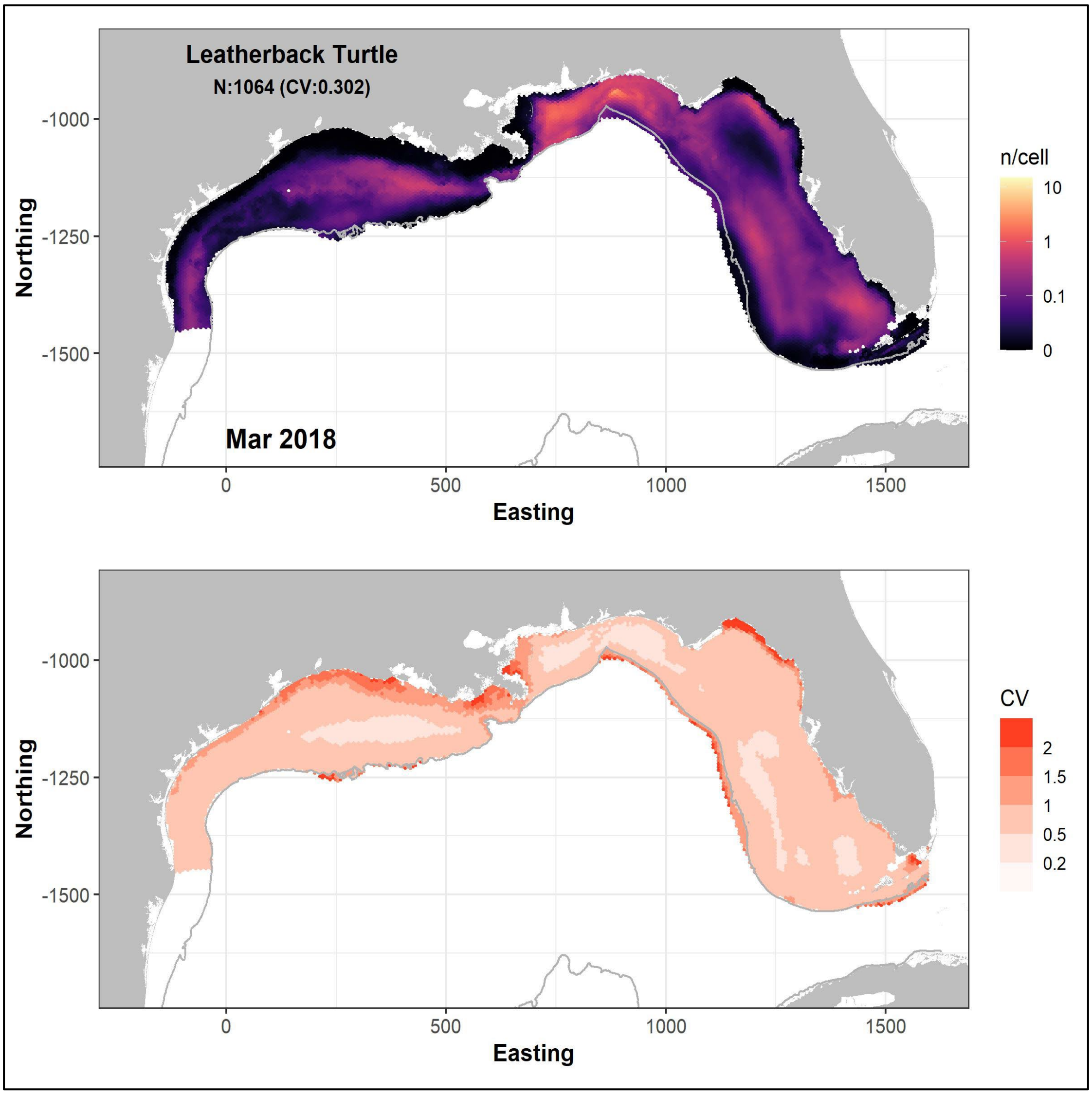

Figure D.1-15. Density model prediction for shelf leatherback turtles in the NGOM in March 2018.

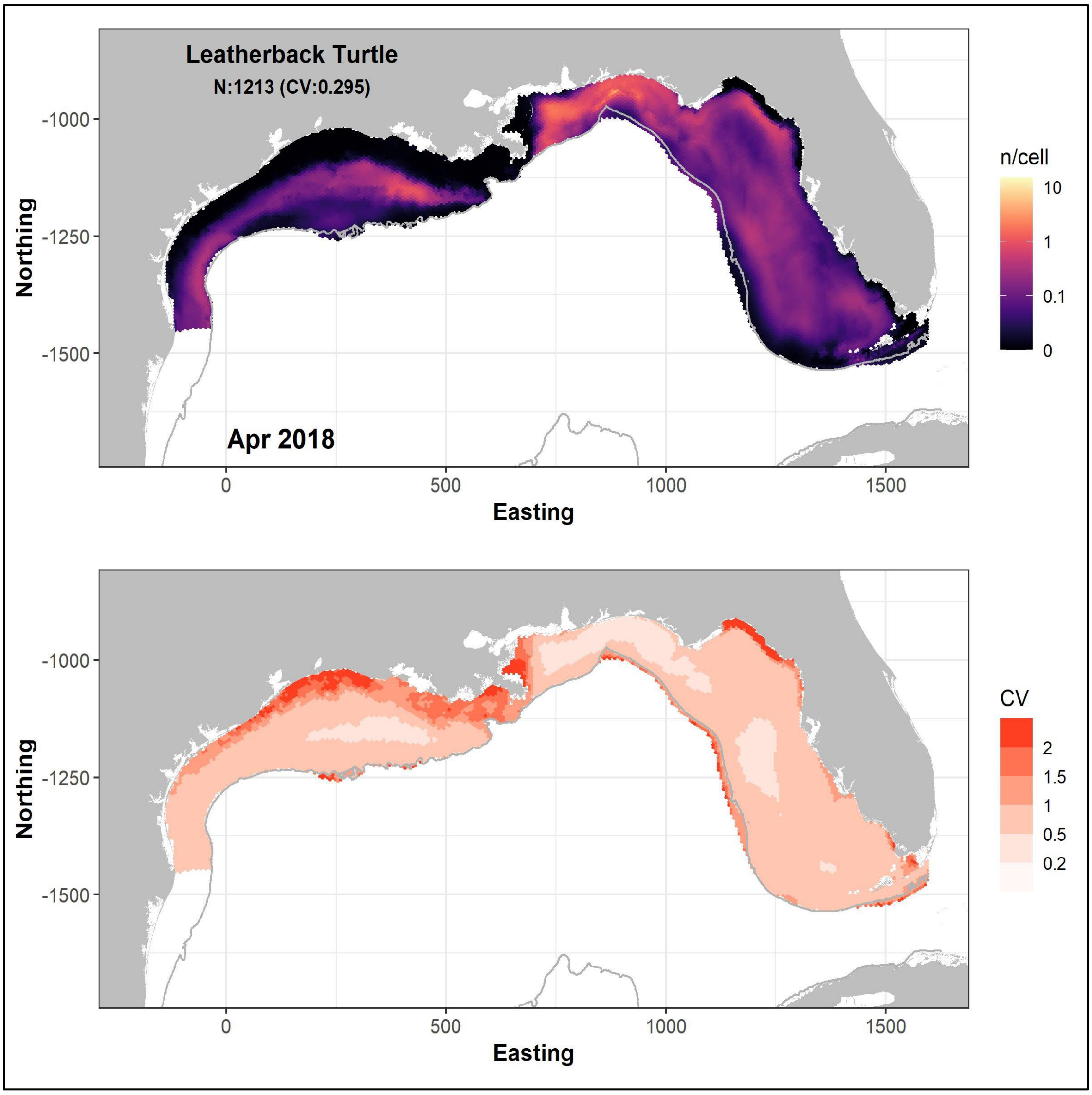

Figure D.1-16. Density model prediction for shelf leatherback turtles in the NGOM in April 2018.

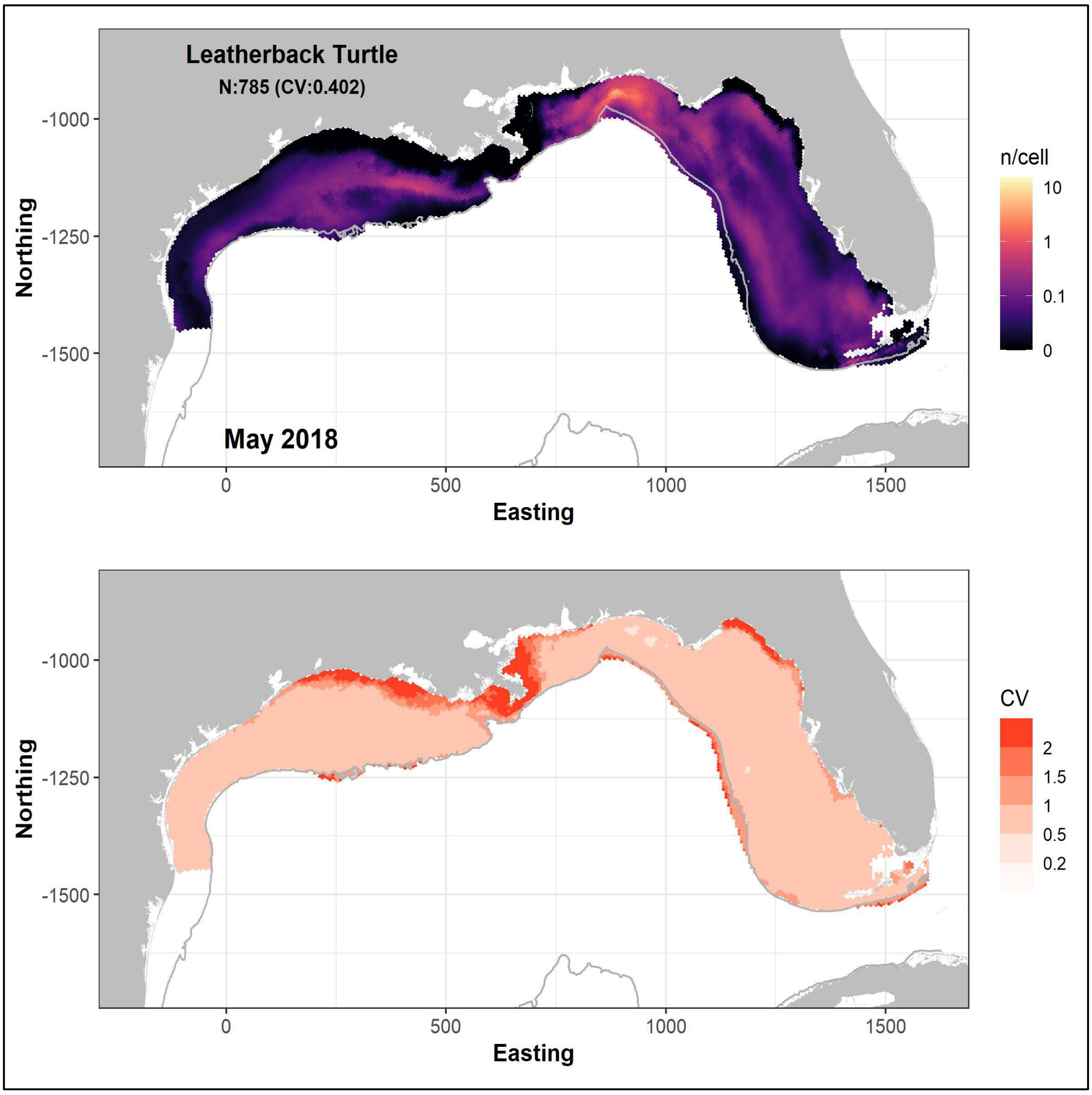

Figure D.1-17. Density model prediction for shelf leatherback turtles in the NGOM in May 2018.

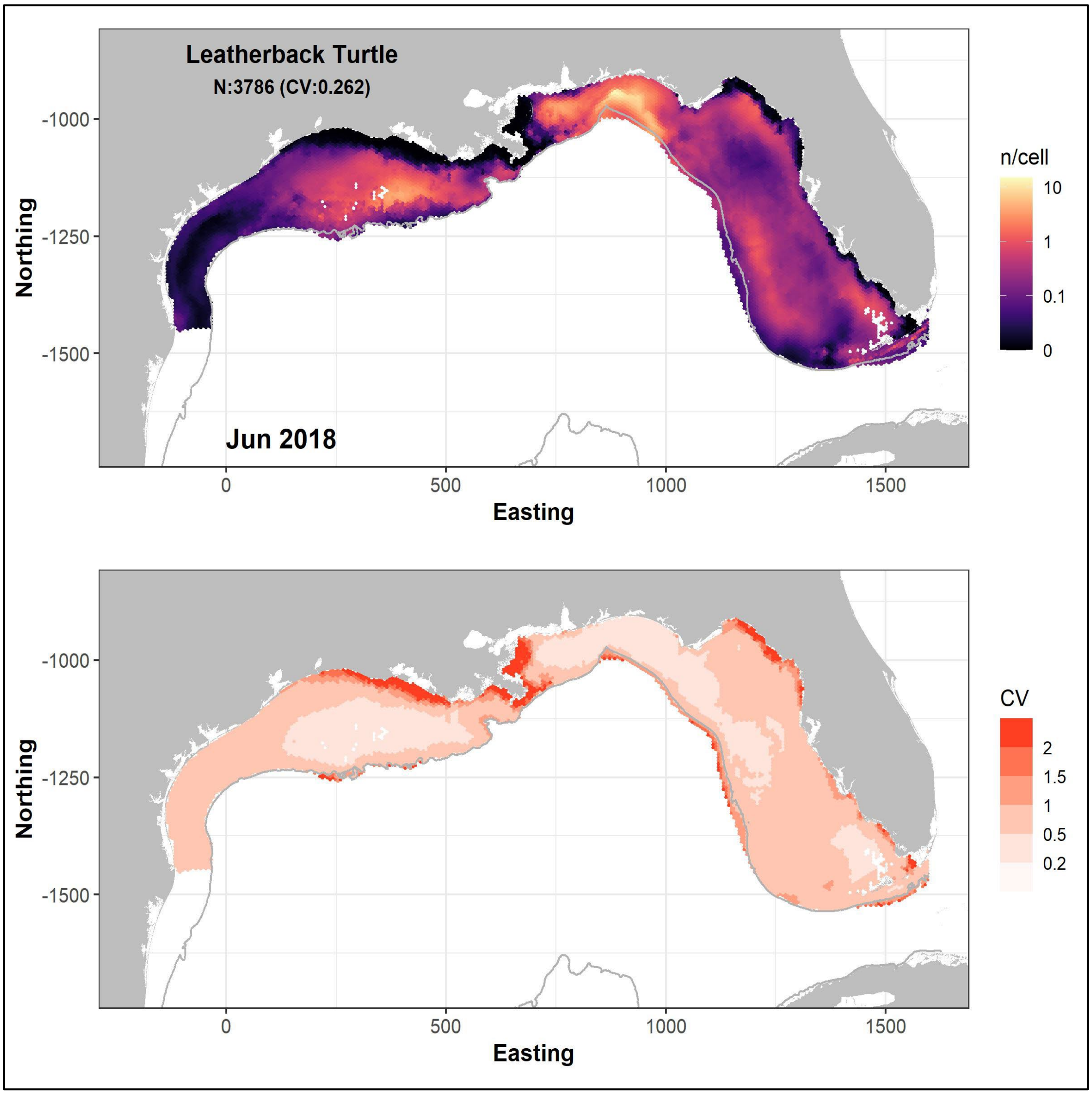

Figure D.1-18. Density model prediction for shelf leatherback turtles in the NGOM in June 2018.

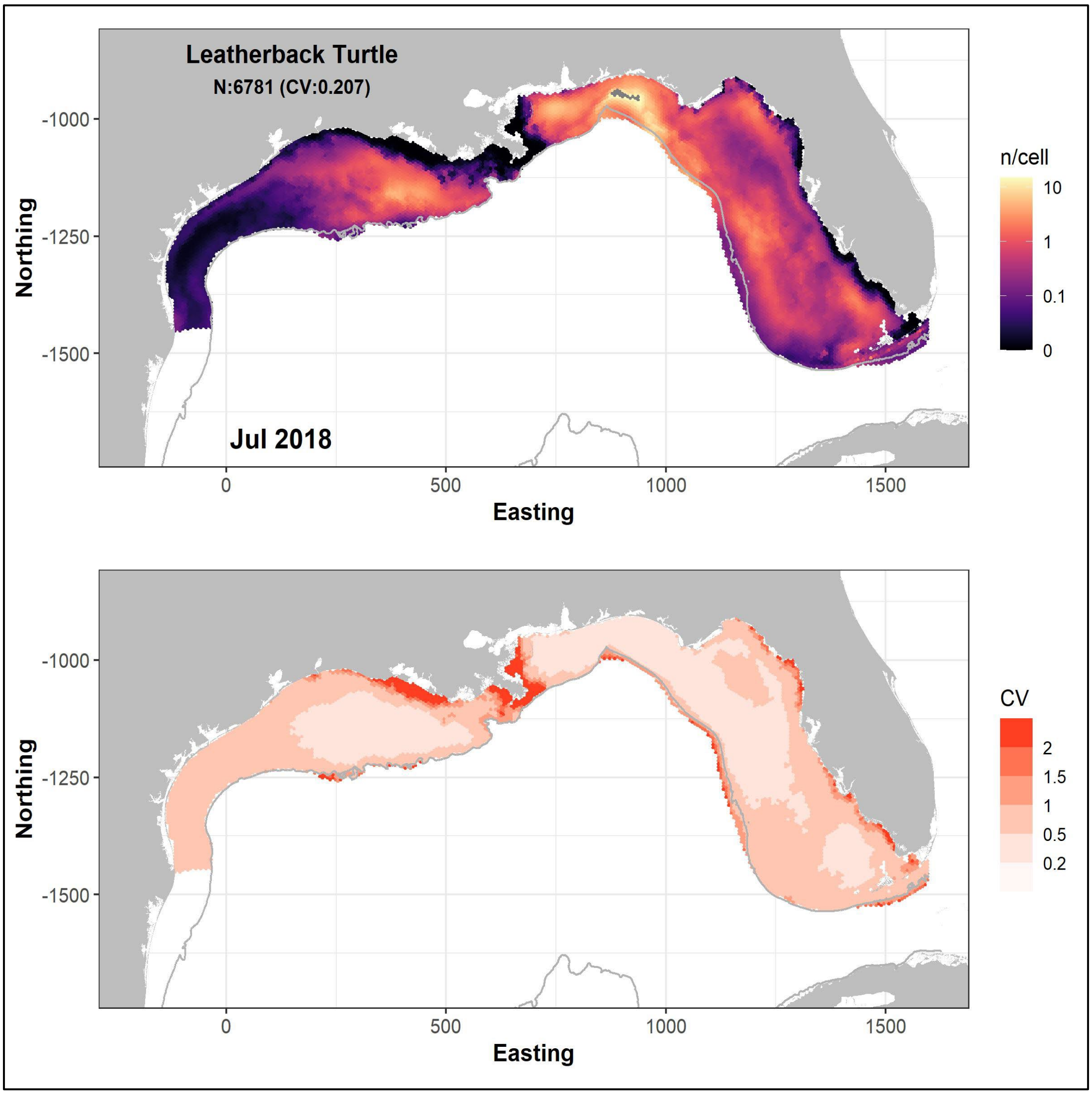

Figure D.1-19. Density model prediction for shelf leatherback turtles in the NGOM in July 2018.

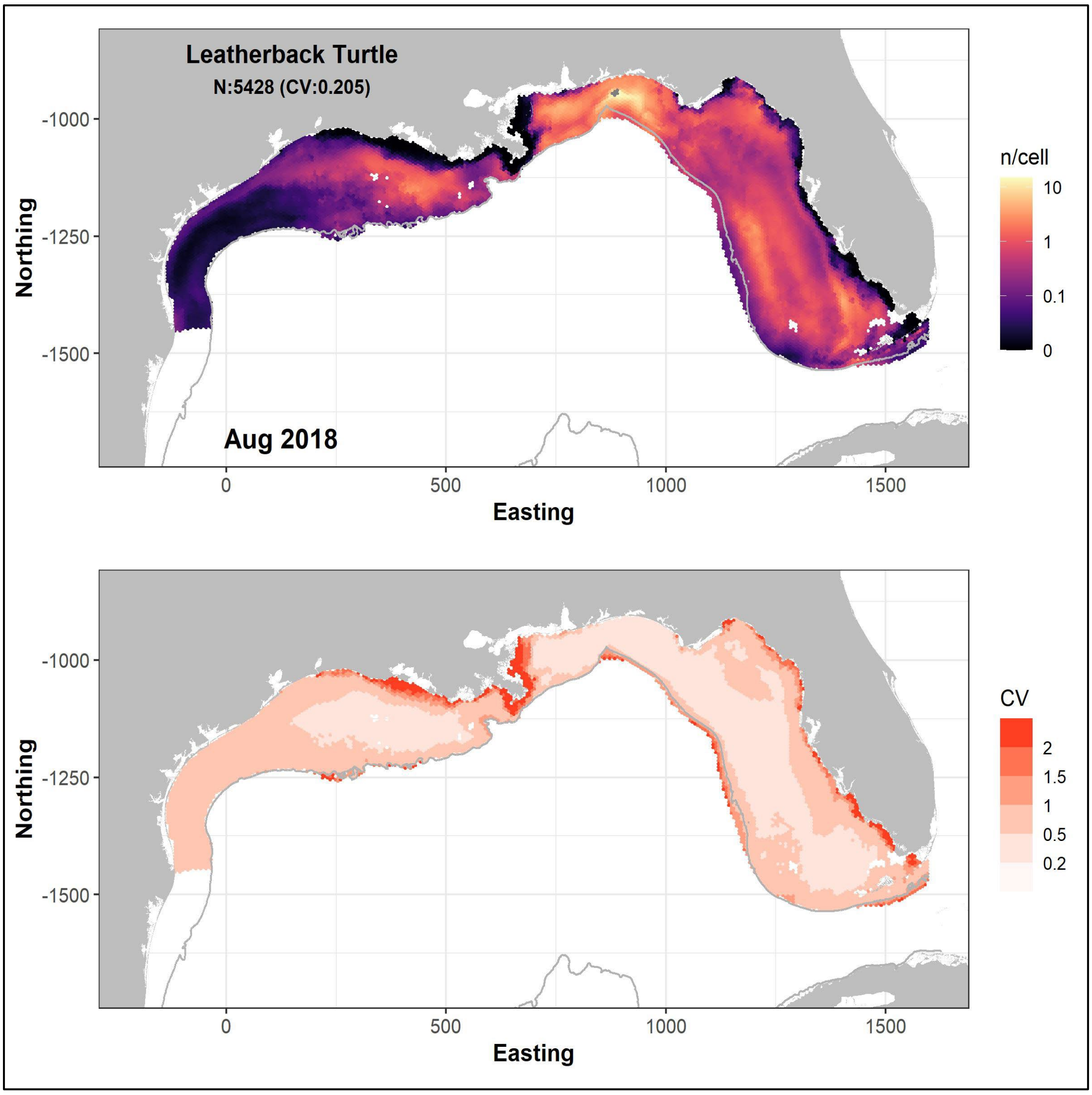

Figure D.1-20. Density model prediction for shelf leatherback turtles in the NGOM in August 2018.

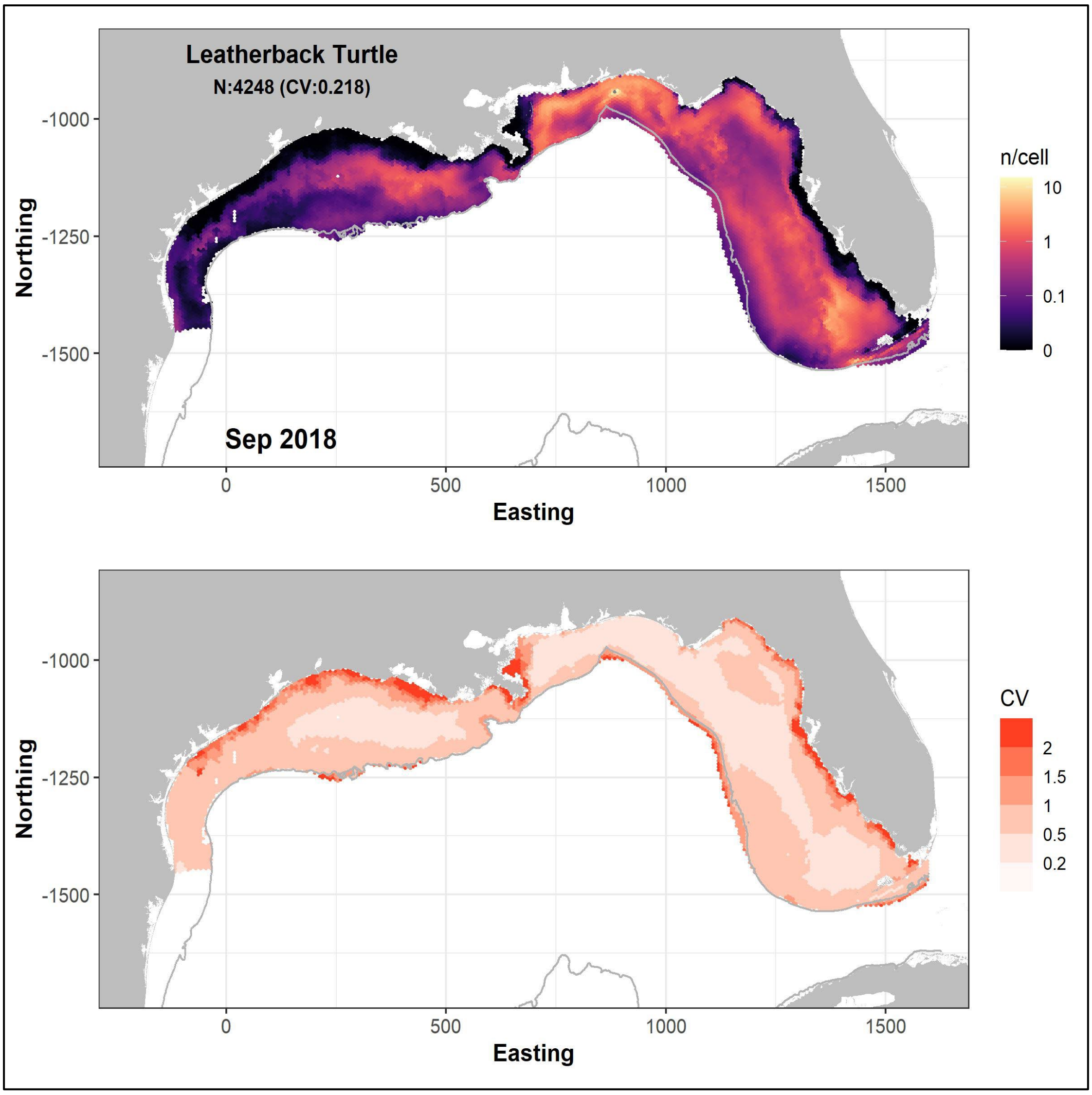

Figure D.1-21. Density model prediction for shelf leatherback turtles in the NGOM in September 2018.

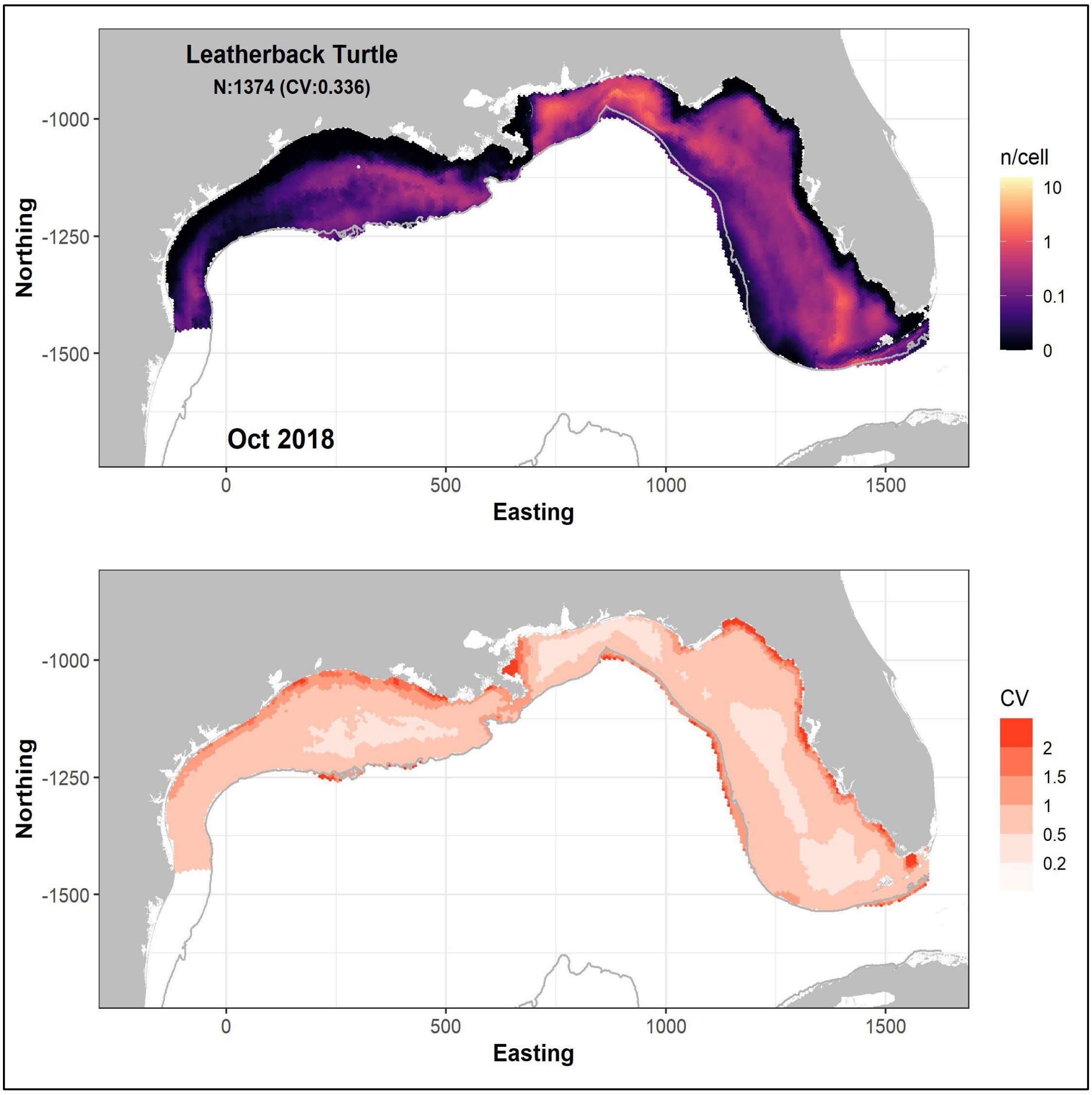

Figure D.1-22. Density model prediction for shelf leatherback turtles in the NGOM in October 2018.

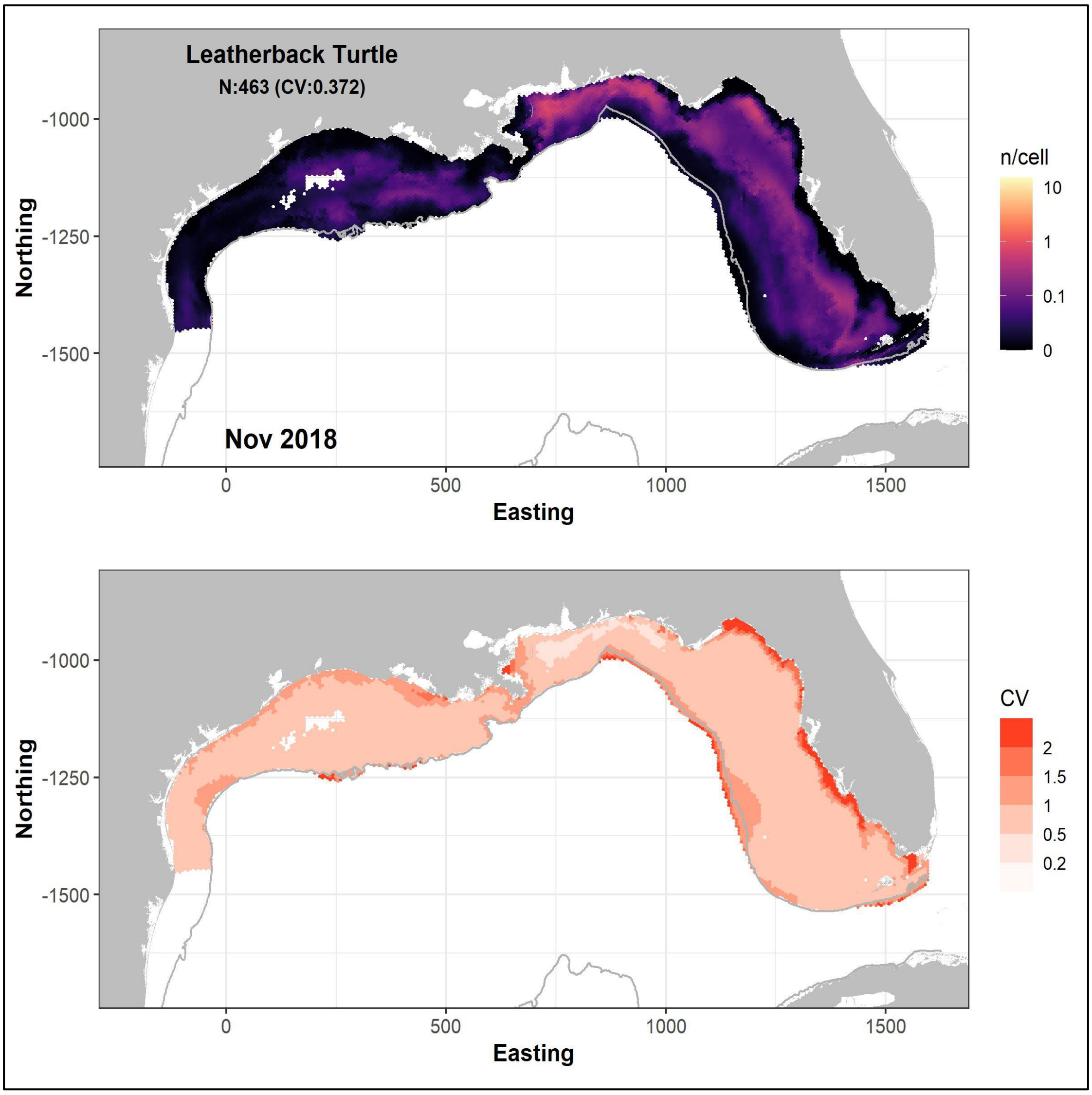

Figure D.1-23. Density model prediction for shelf leatherback turtles in the NGOM in November 2018.

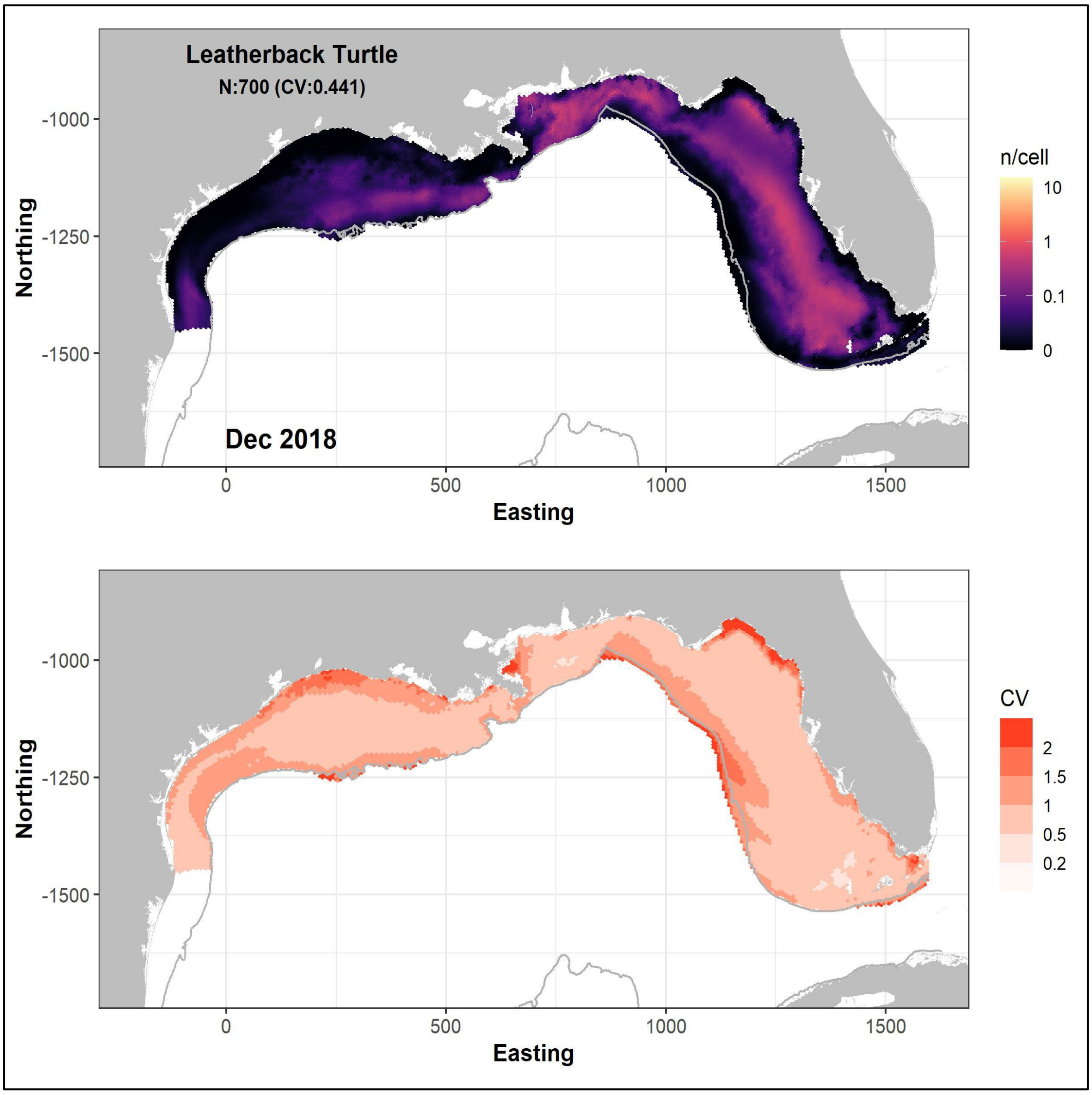

Figure D.1-24. Density model prediction for shelf leatherback turtles in the NGOM in December 2018.

D.1.5.2 Projected Density throughout the Gulf of Mexico

While aerial survey effort was restricted to the NGOM, leatherback turtles occur throughout the northern and southern GOM. The projection of the resulting SDM beyond the NGOM assumes that species-habitat relationships are consistent, and it is unknown if this assumption is reliable. To evaluate the potential density of leatherback turtles outside of the US Exclusive Economic Zone (EEZ), the SDM was projected throughout the GOM. These results should be interpreted with caution given the extrapolation outside of the surveyed area (Figures D.1-25–D.1-36).

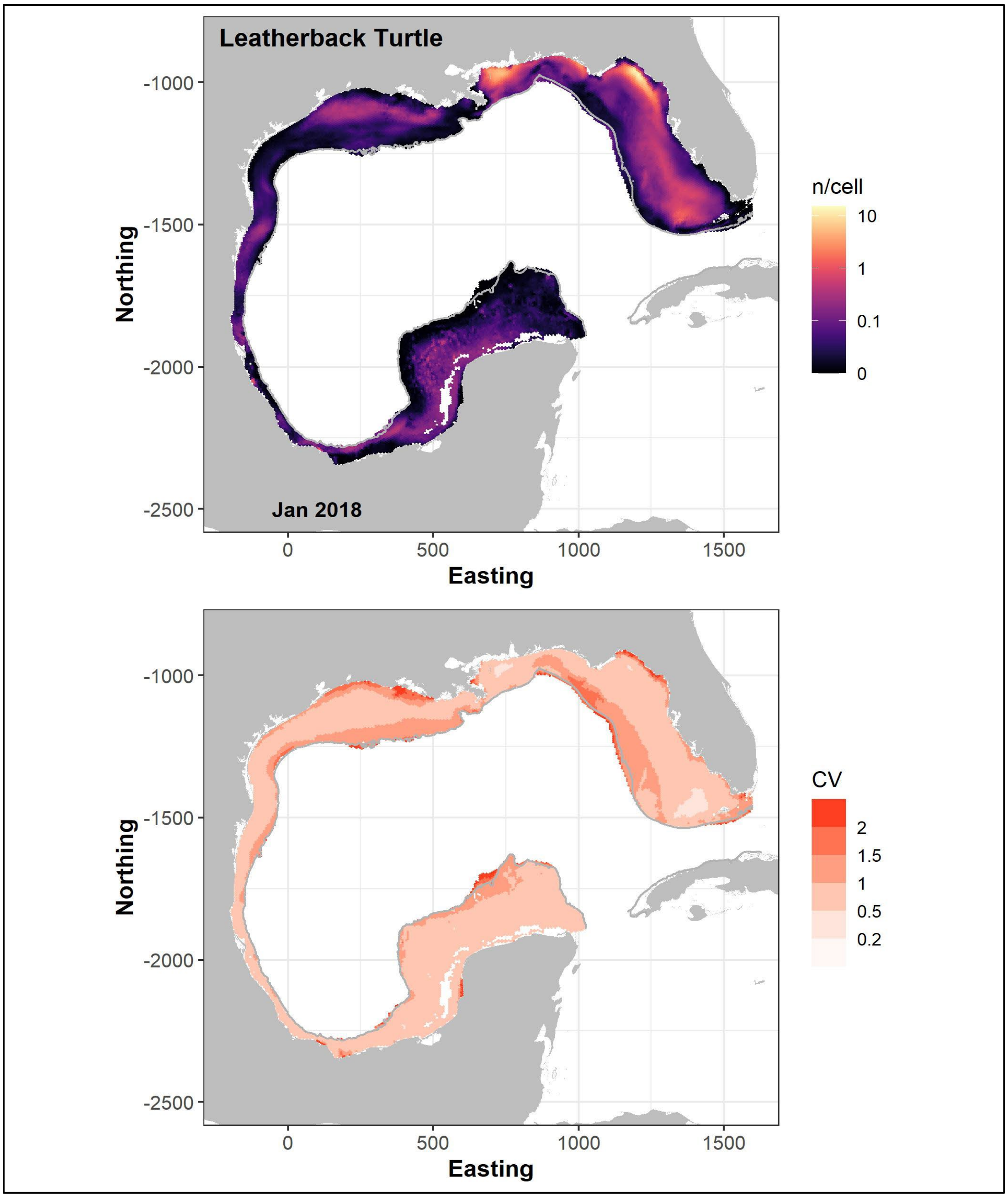

Figure D.1-25. Projected density model for shelf leatherback turtles in the entire GOM for January 2018.

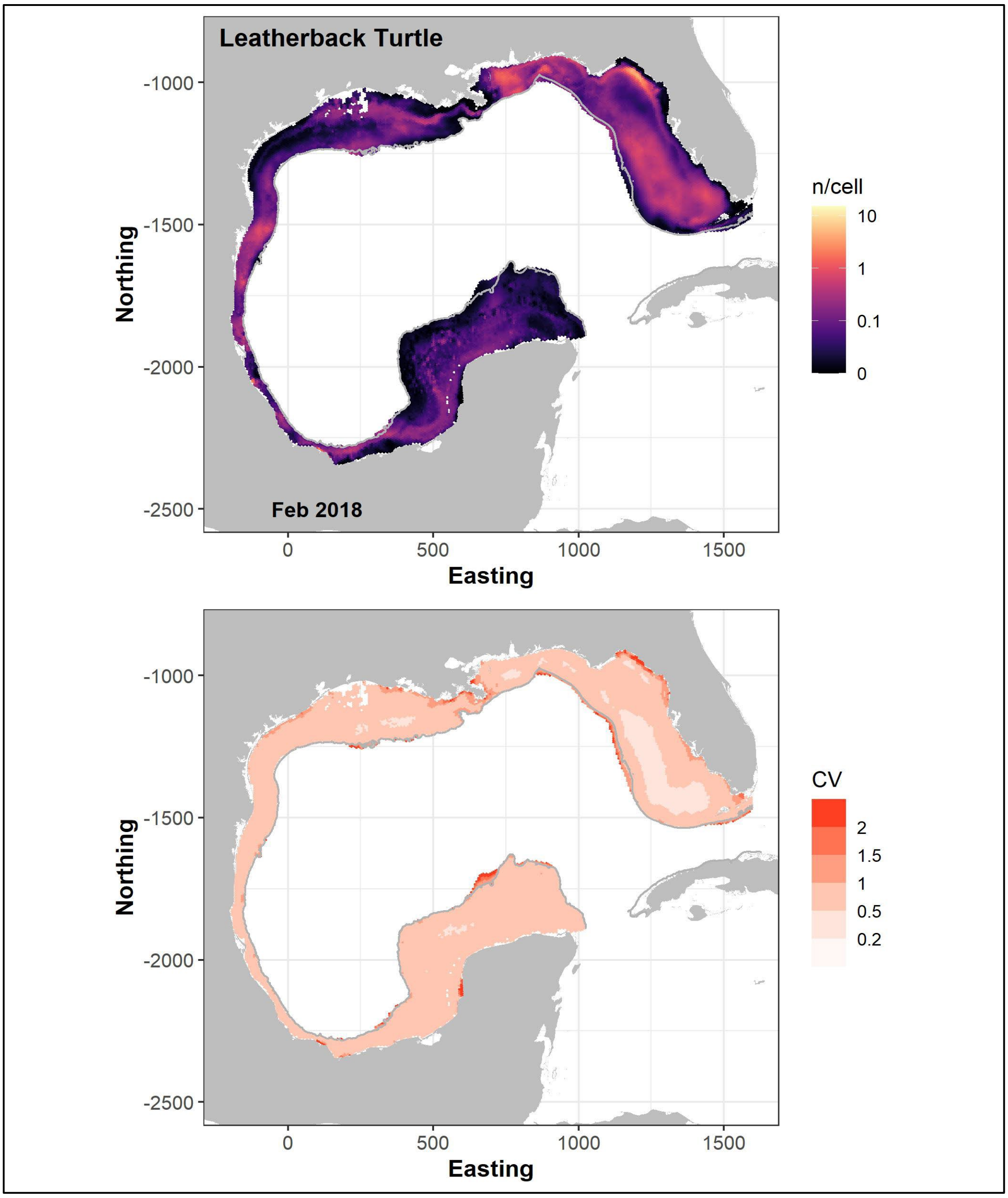

Figure D.1-26. Projected density model for shelf leatherback turtles in the entire GOM for February 2018.

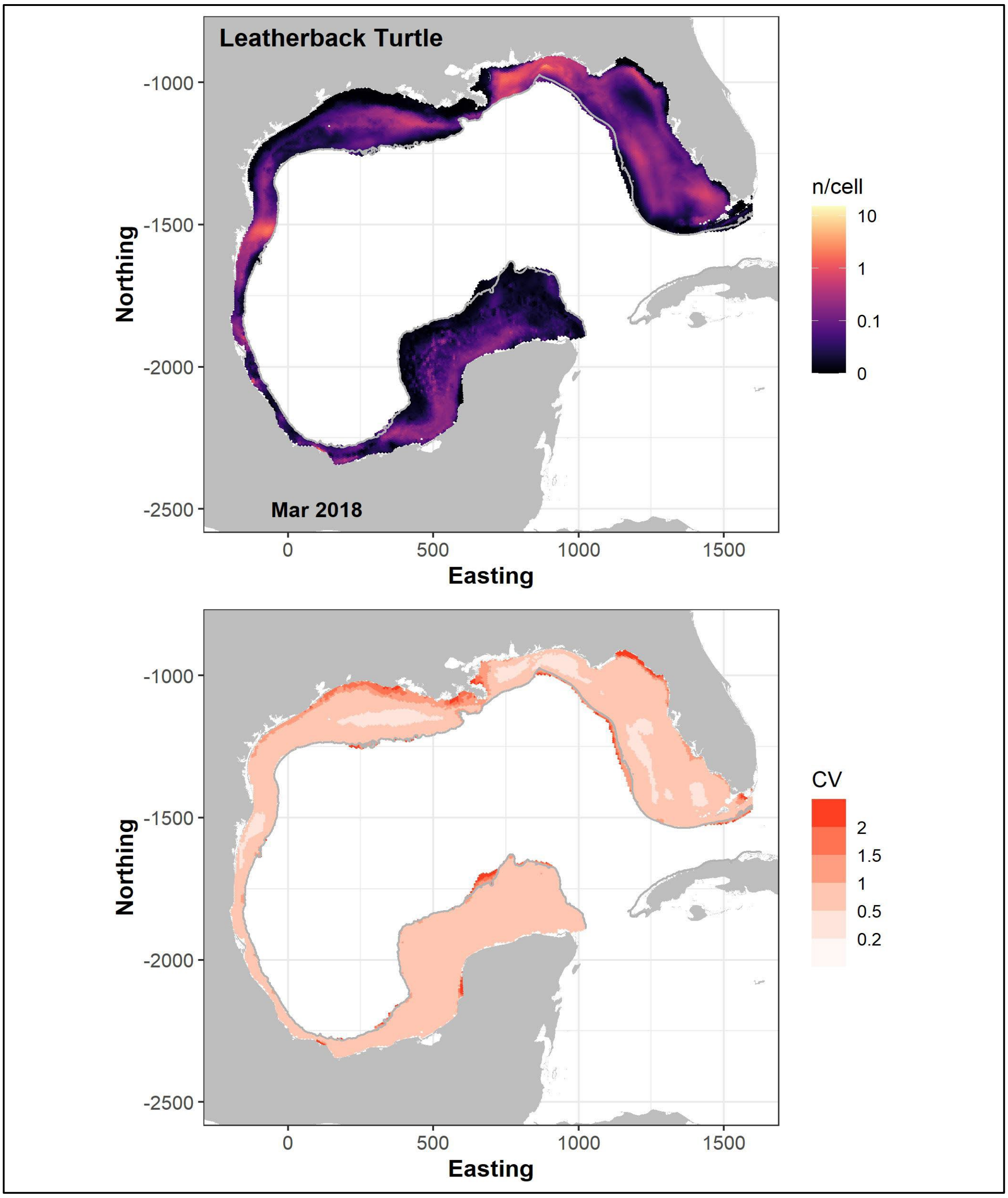

Figure D.1-27. Projected density model for shelf leatherback turtles in the entire GOM for March 2018.

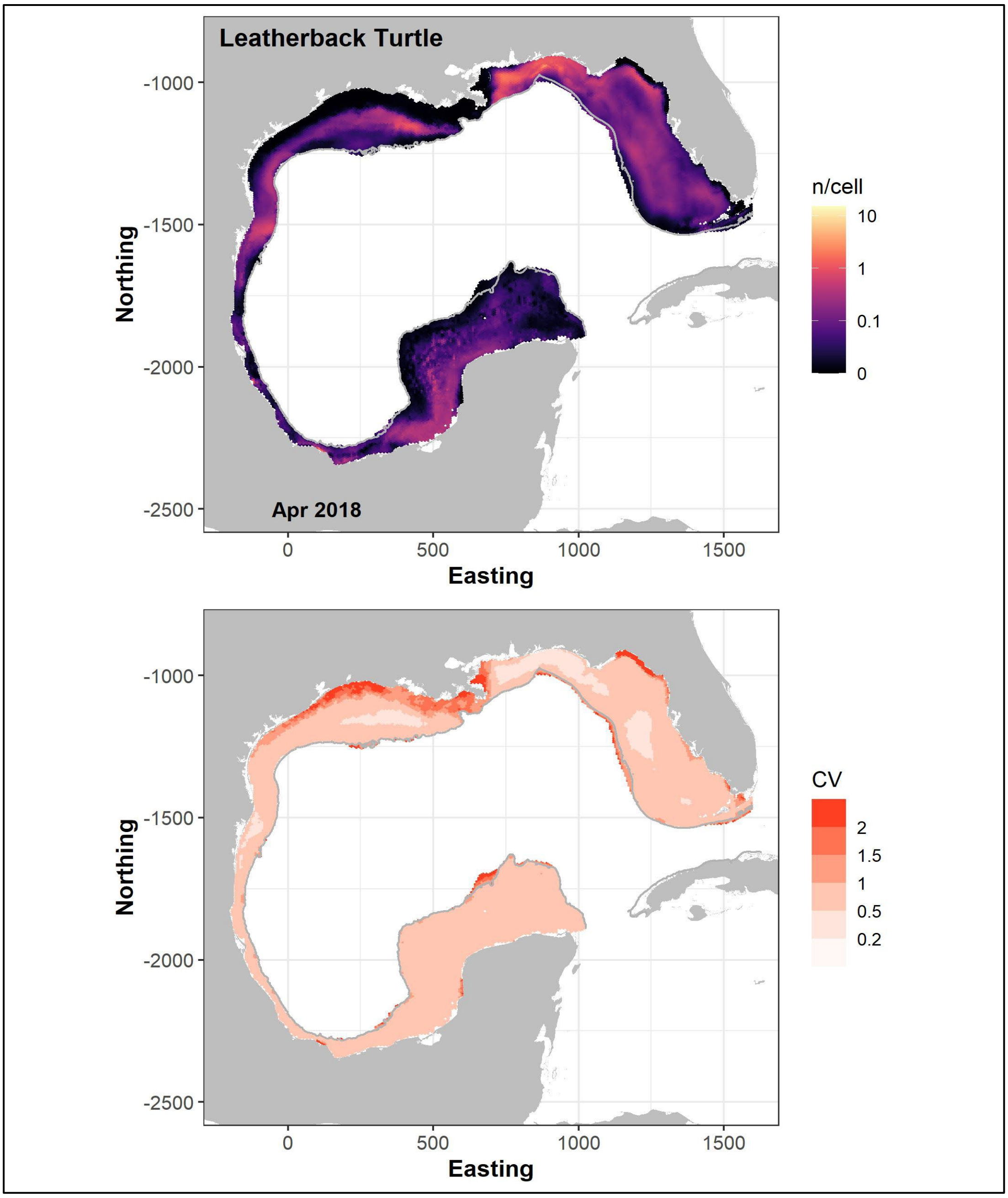

Figure D.1-28. Projected density model for shelf leatherback turtles in the entire GOM for April 2018.

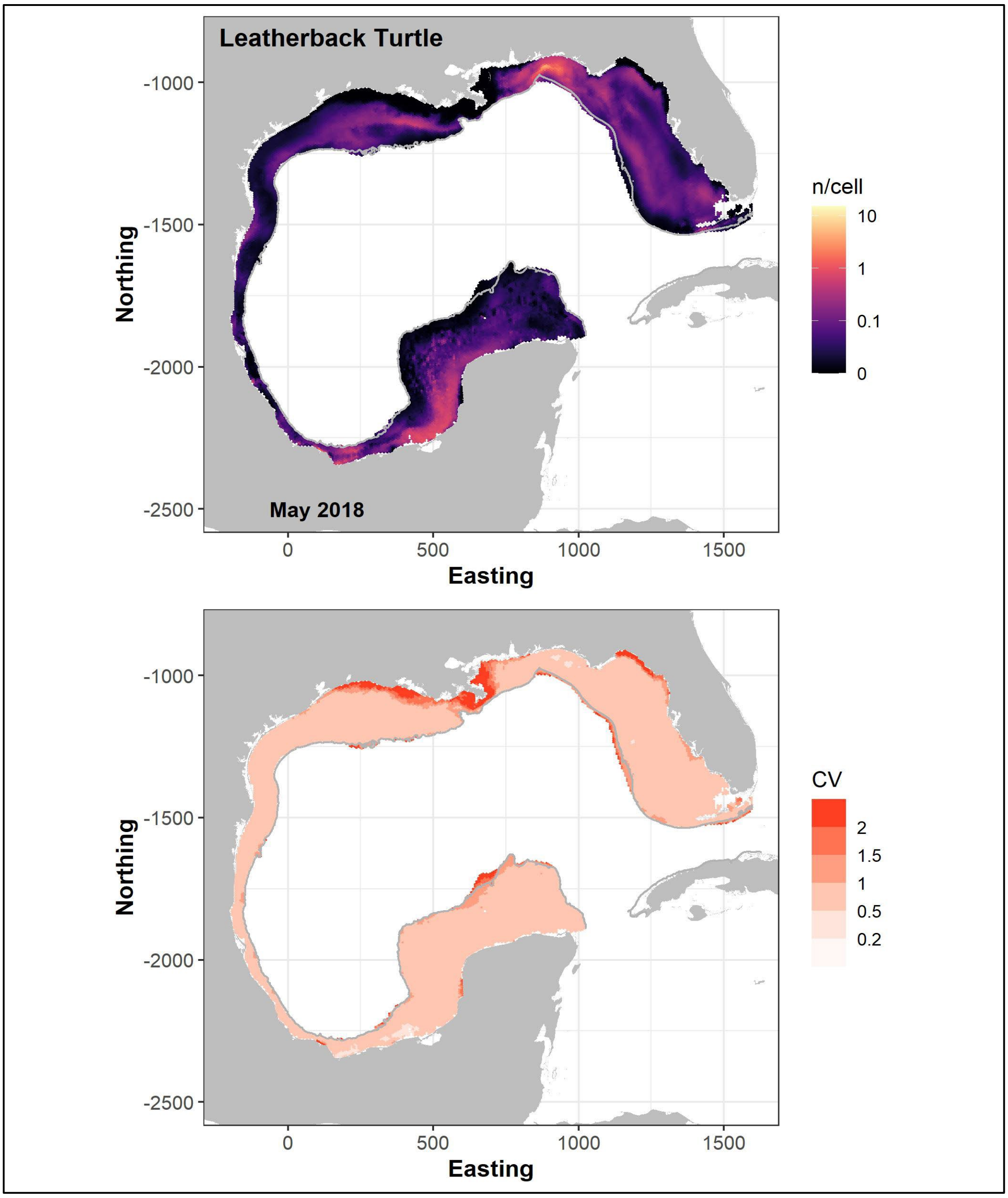

Figure D.1-29. Projected density model for shelf leatherback turtles in the entire GOM for May 2018.

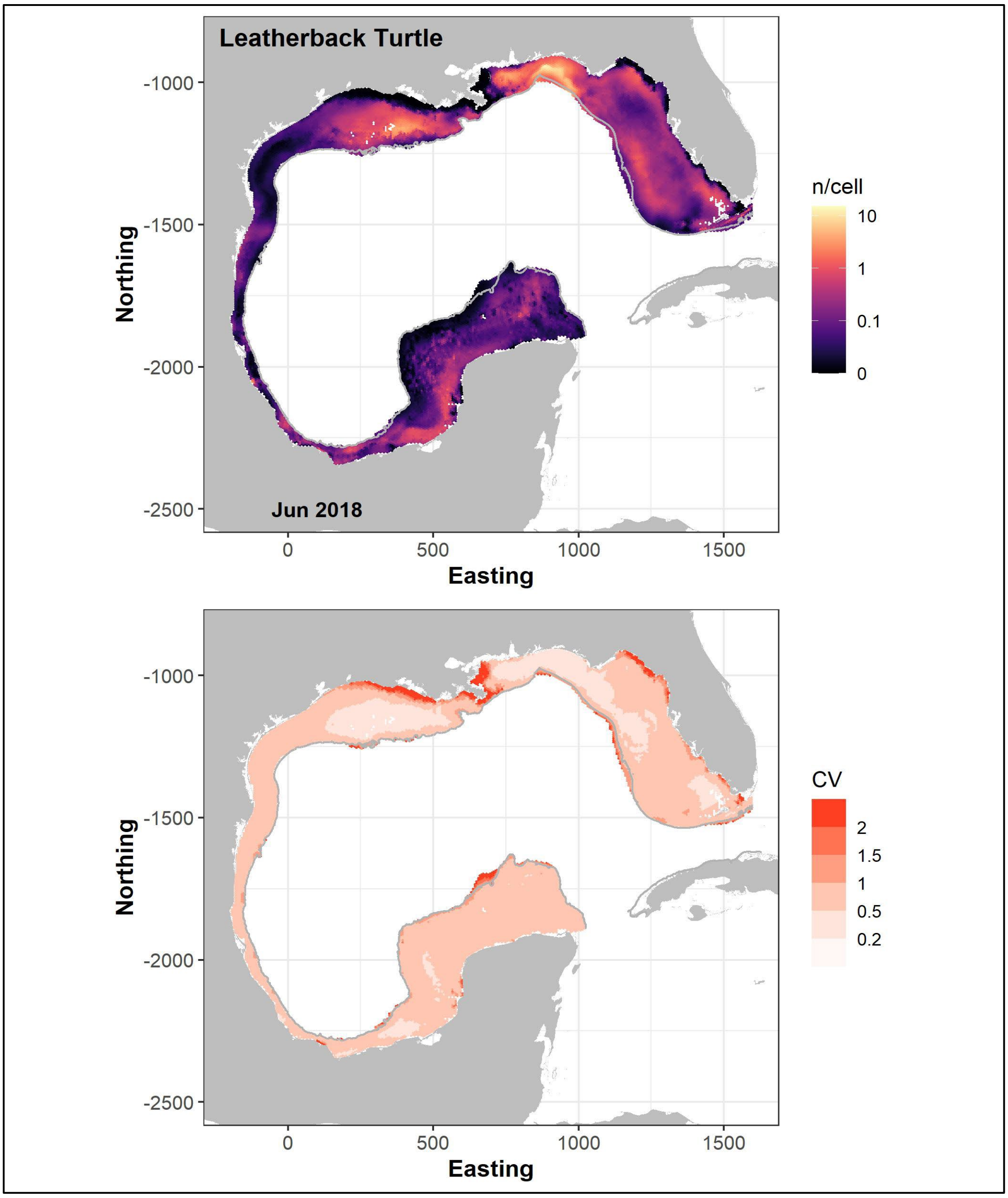

Figure D.1-30. Projected density model for shelf leatherback turtles in the entire GOM for June 2018.

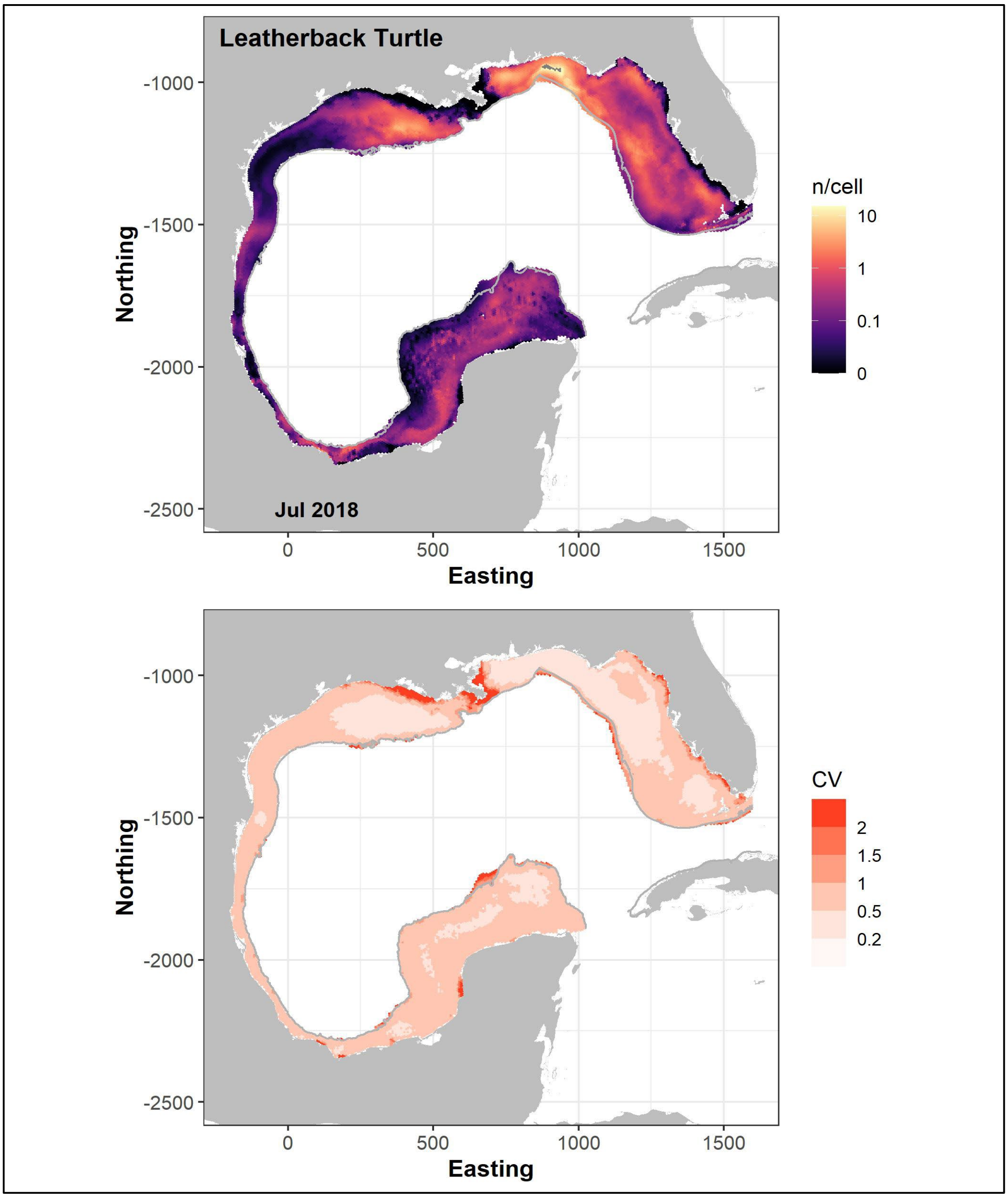

Figure D.1-31. Projected density model for shelf leatherback turtles in the entire GOM for July 2018.

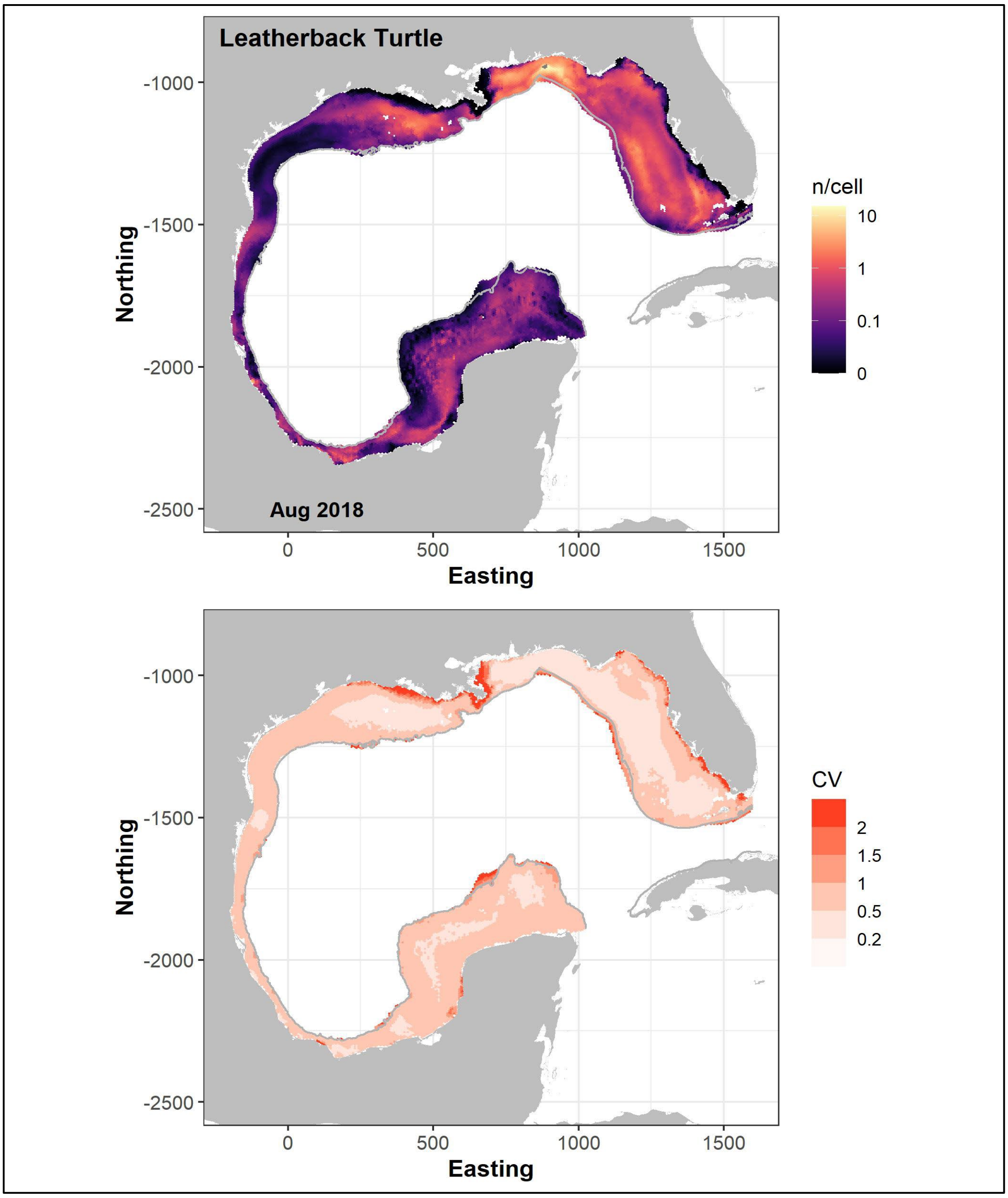

Figure D.1-32. Projected density model for shelf leatherback turtles in the entire GOM for August 2018.

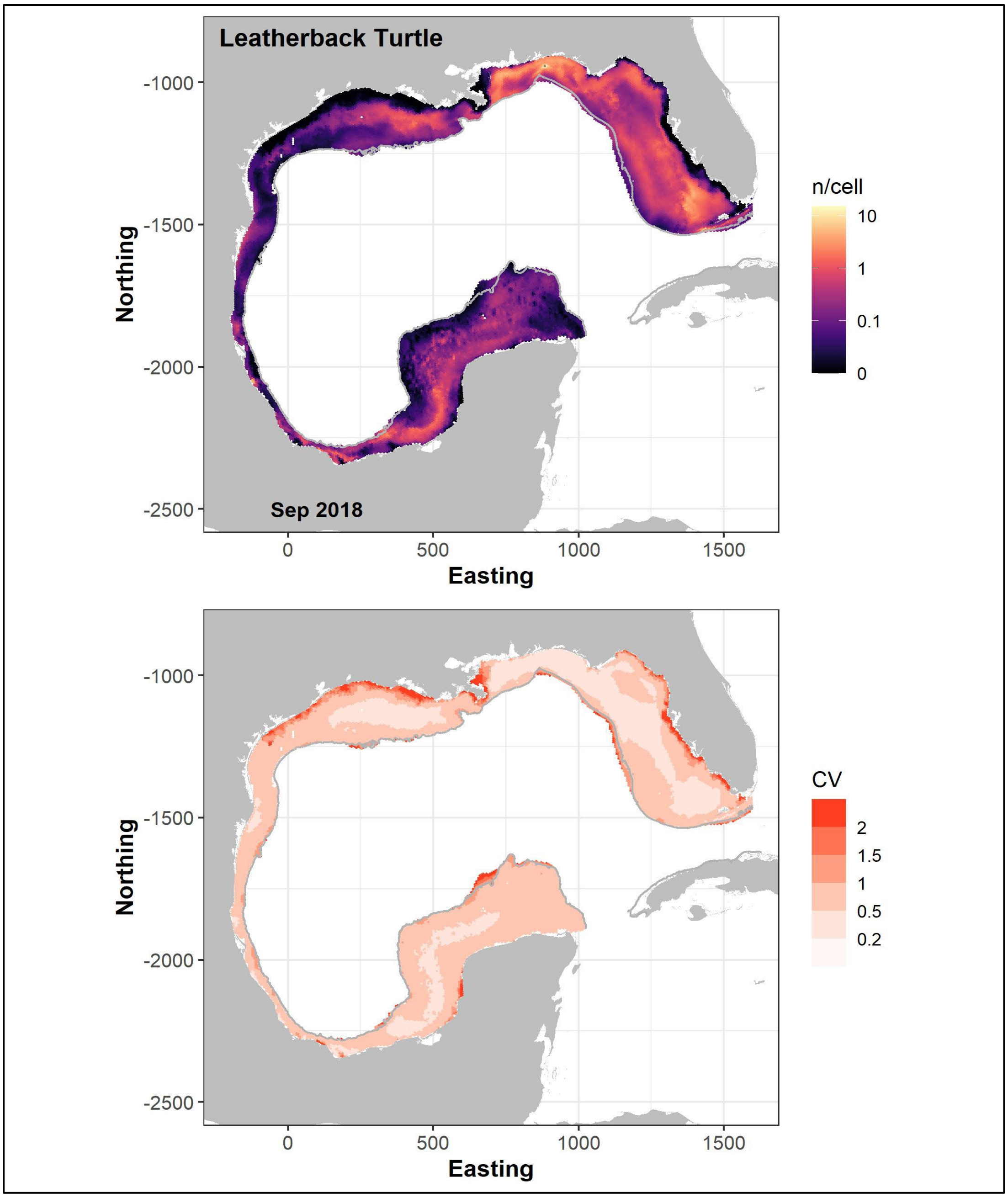

Figure D.1-33. Projected density model for shelf leatherback turtles in the entire GOM for September 2018.

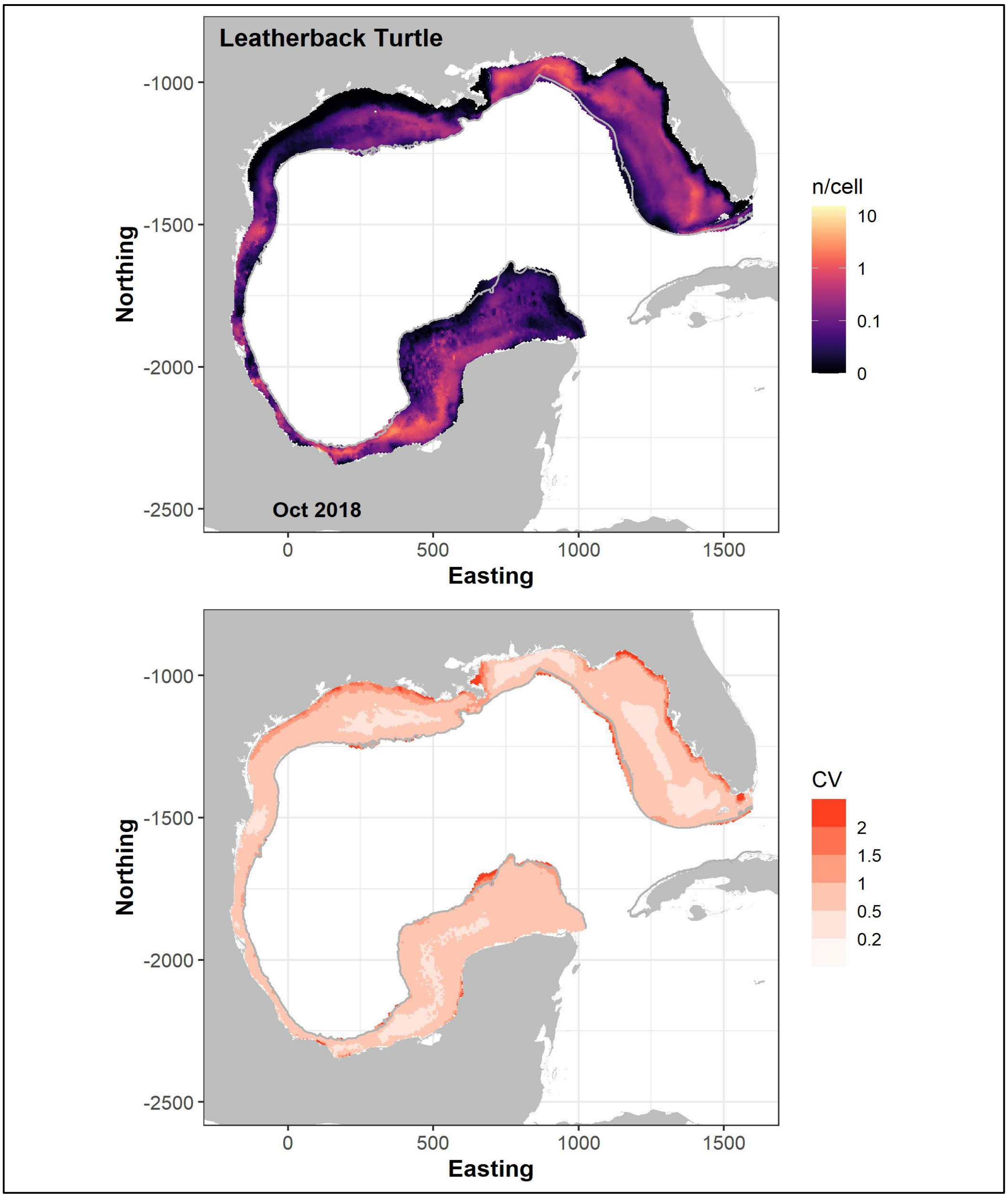

Figure D.1-34. Projected density model for shelf leatherback turtles in the entire GOM for October 2018.

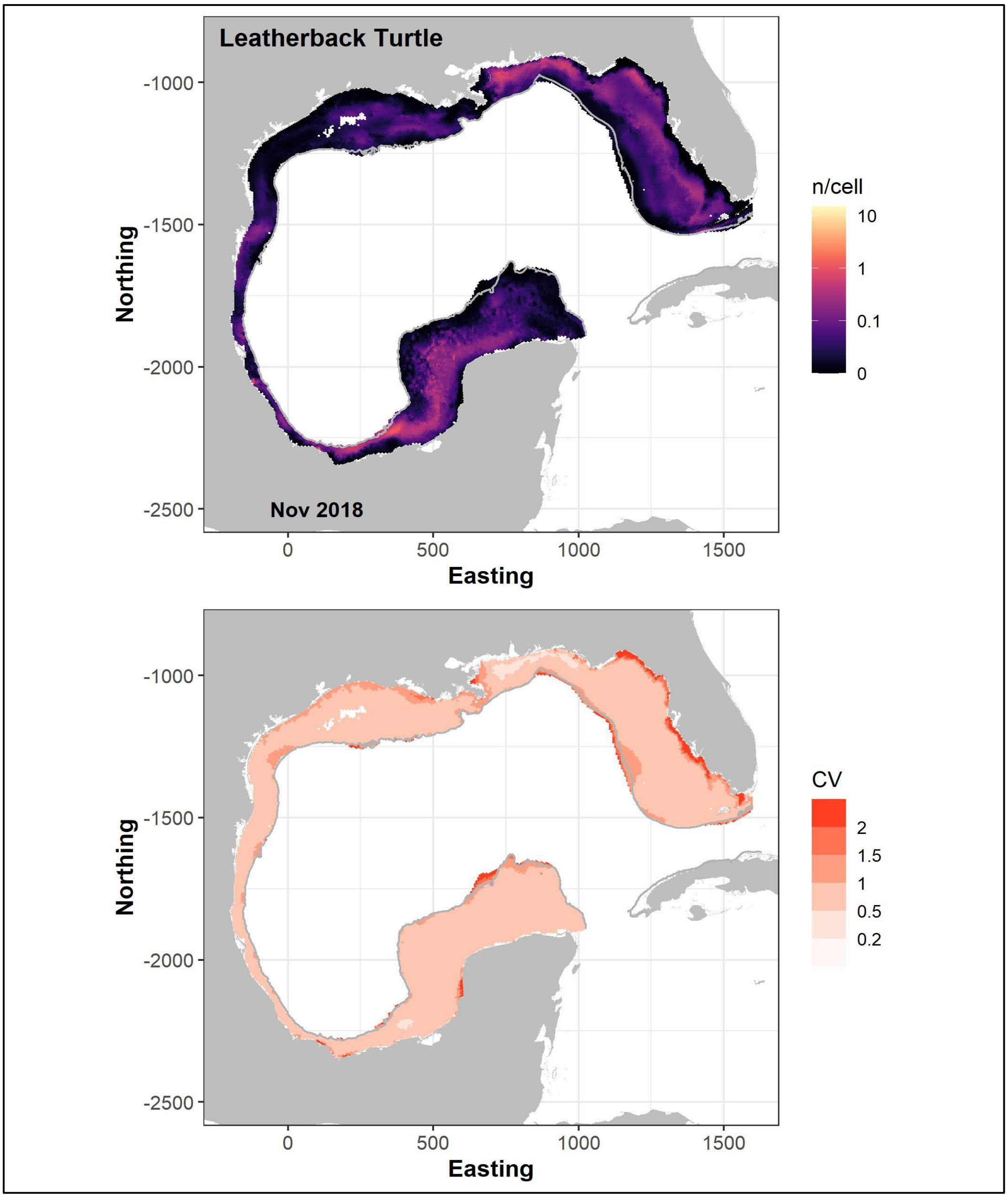

Figure D.1-35. Projected density model for shelf leatherback turtles in the entire GOM for November 2018.

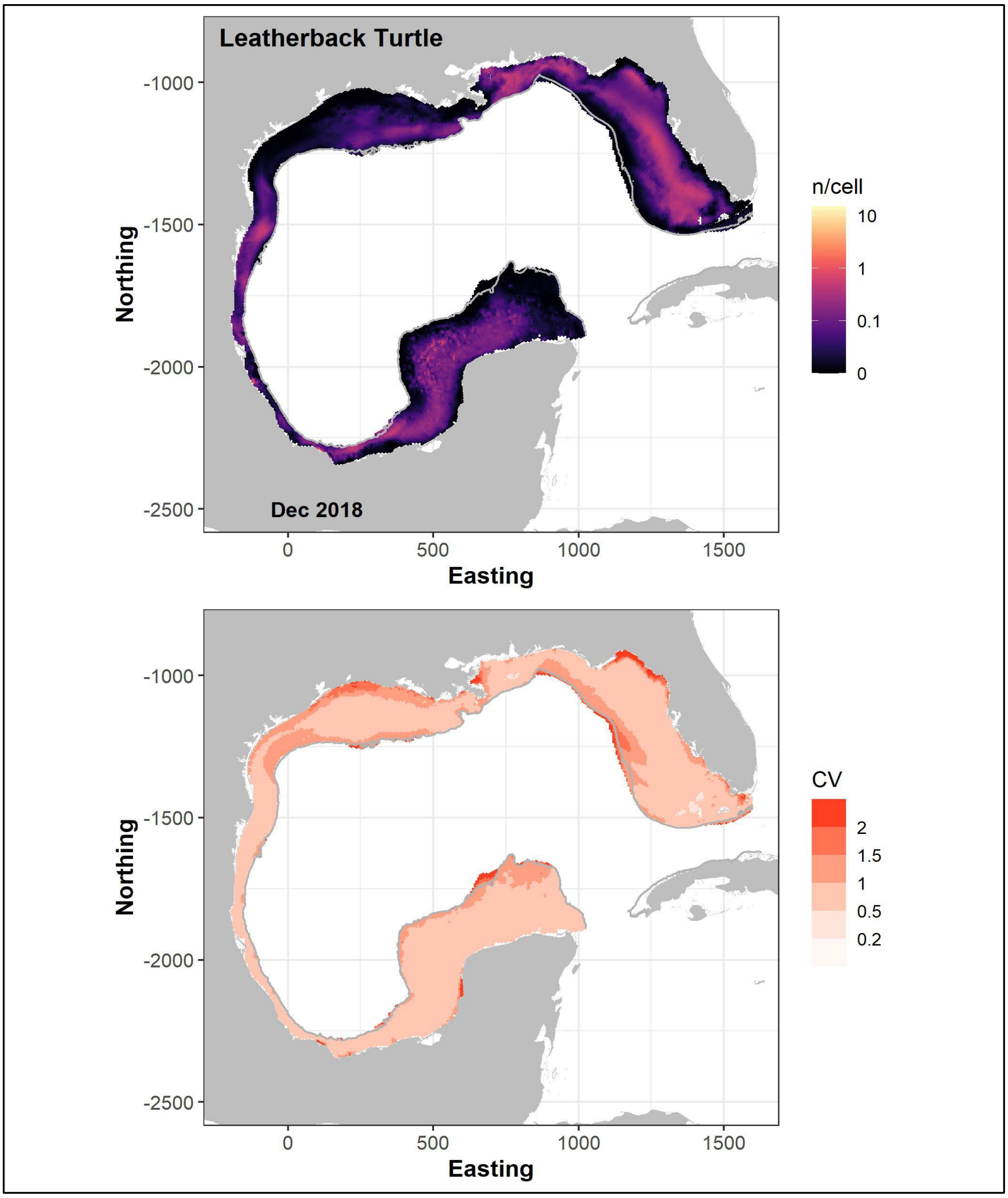

Figure D.1-36. Projected density model for shelf leatherback turtles in the entire GOM for December 2018.

D.1.5.3 Average Monthly Density: 2015–2019

Prediction maps were generated using monthly environmental parameters for the period of 2015–2019. The posterior distribution of the GAM parameters was sampled 1,000 times to generate a distribution of model coefficients that reflect the statistical uncertainty in the parameter estimation. Predictions of animal density were generated for each month in the 2015–2019 period based on each of these 1,000 parameter sets. In this way, both inter-annual variability in environmental conditions and model uncertainty were included in the resulting samples. The monthly predictions were examined to identify sampled parameters that generated extreme predicted densities, and these extreme values

were excluded from the bootstrap sample before variance estimation. These extreme values, associated with density predictions many orders of magnitude higher than the observed median, reflect projection of the model predictions into poorly sampled parameter space. It was not necessary to trim the bootstrap distribution for leatherback turtles. The resulting distribution of realizations was used to summarize predicted average densities by month and to calculate metrics of uncertainty. The average monthly abundance for leatherback turtles in US waters is shown in Table D.1-5 (Figures D.1-37–D.1-48).

Table D.1-5. Monthly average abundance of leatherback turtles in US shelf waters 2015–2019

Month	Abundance	CV
January	1,188	0.637
February	1,711	0.392
March	1,492	0.402
April	1,272	0.326
May	855	0.398
June	3,605	0.392
July	6,922	0.214
August	6,622	0.276
September	4,901	0.280
October	1,152	0.406
November	518	0.415
December	719	0.395

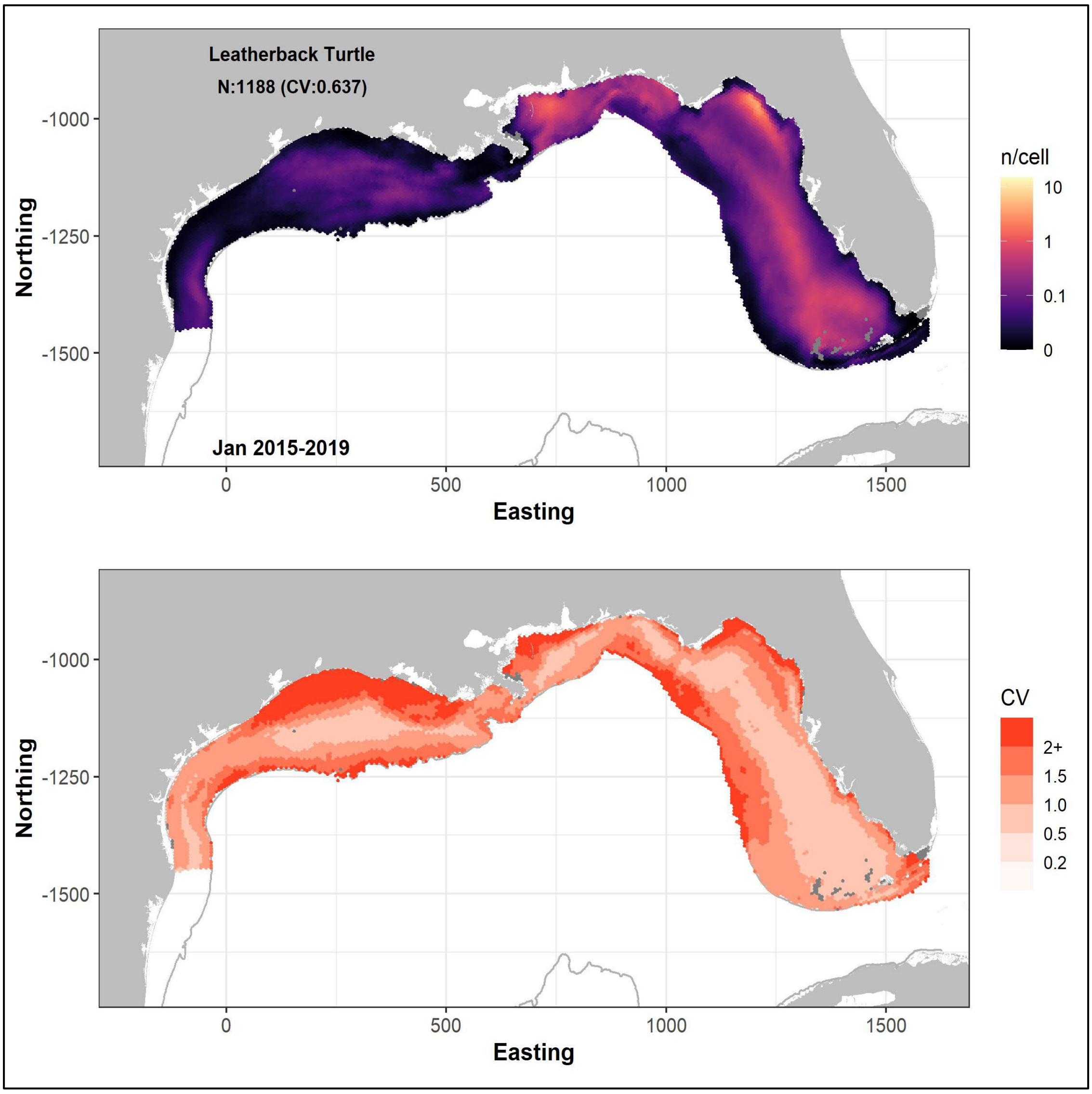

Figure D.1-37. Density model prediction for shelf leatherback turtles in the NGOM for the months of January 2015–2019.

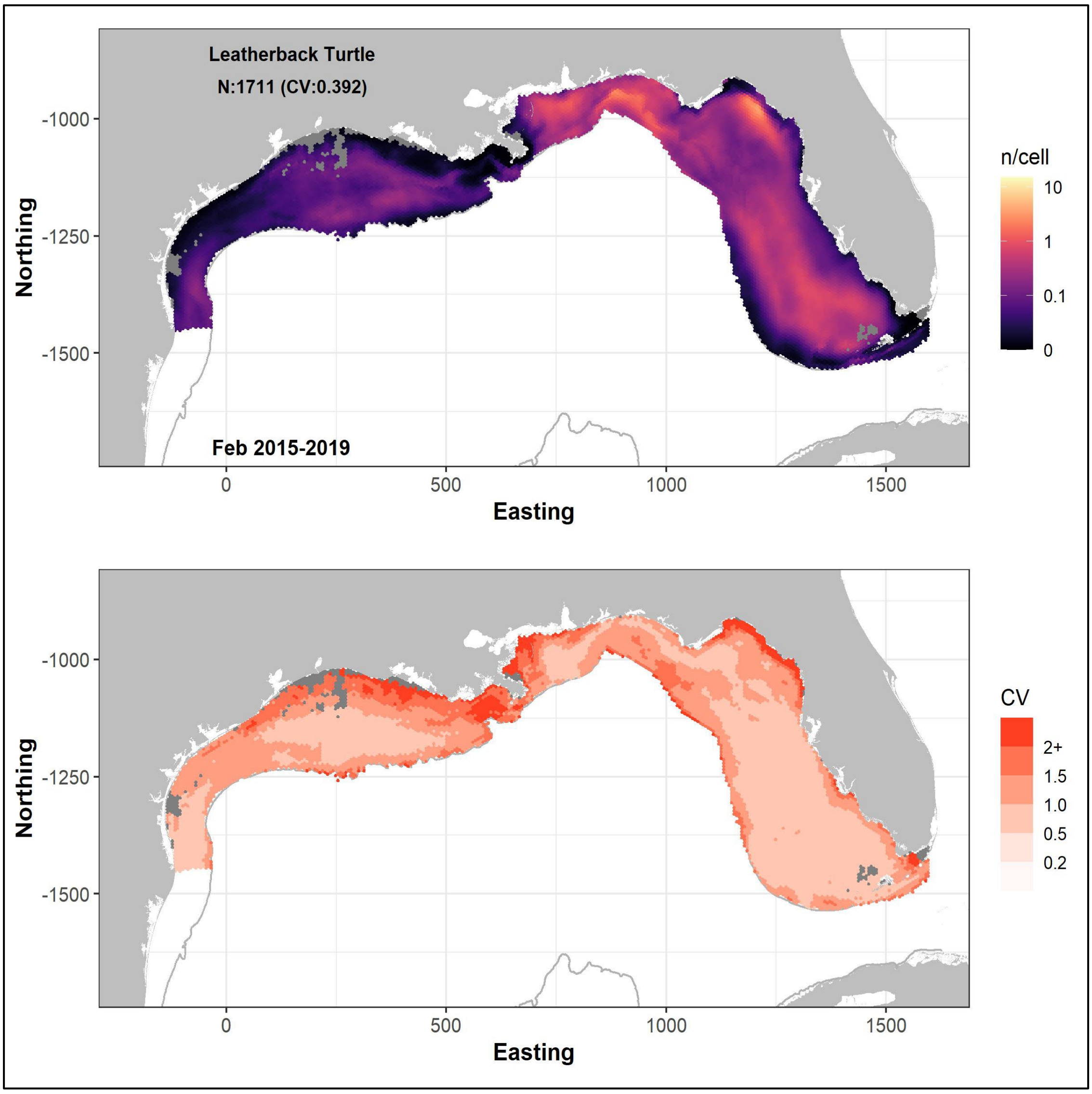

Figure D.1-38. Density model prediction for shelf leatherback turtles in the NGOM for the months of February 2015–2019.

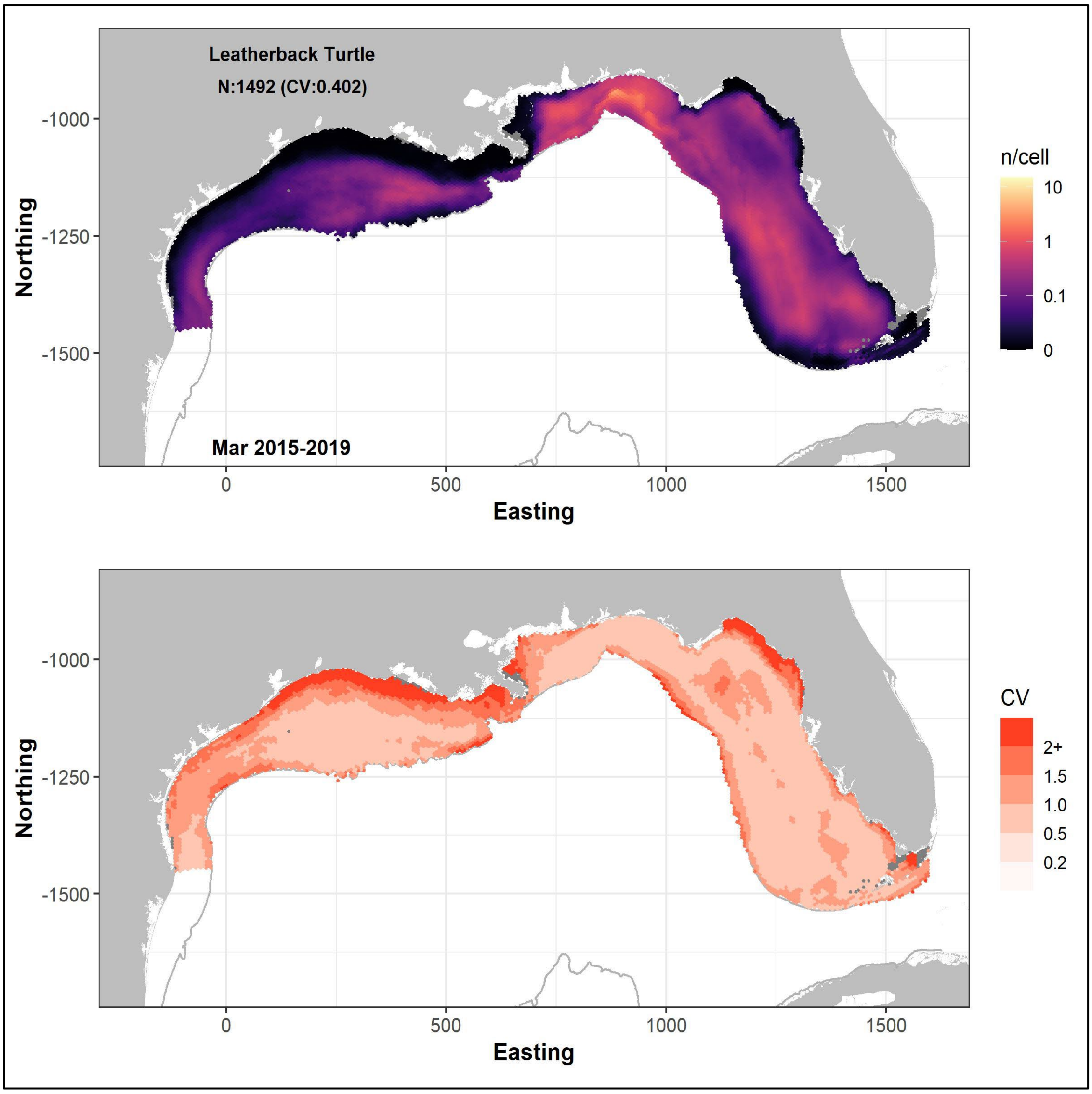

Figure D.1-39. Density model prediction for shelf leatherback turtles in the NGOM for the months of March 2015–2019.

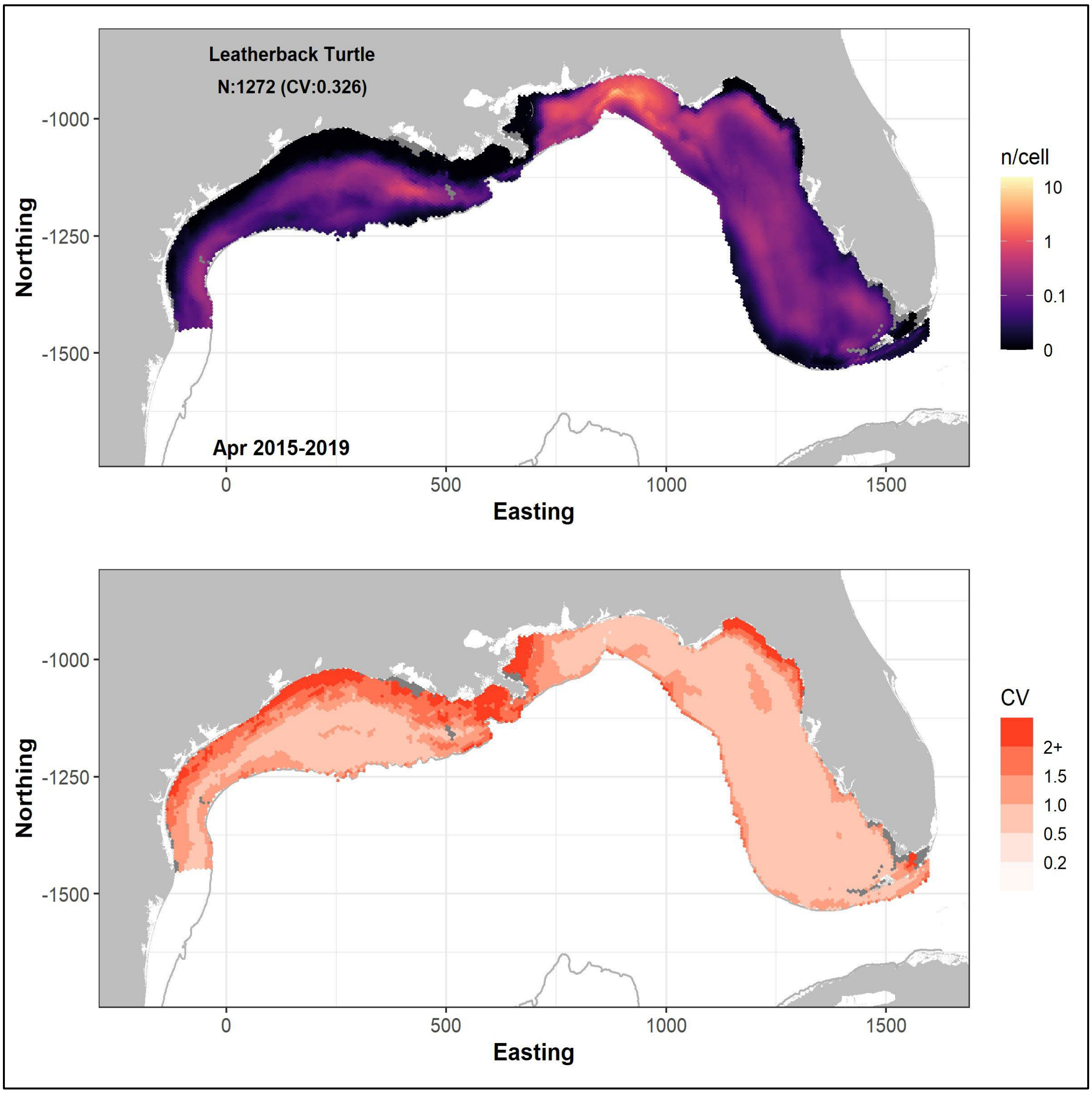

Figure D.1-40. Density model prediction for shelf leatherback turtles in the NGOM for the months of April 2015–2019.

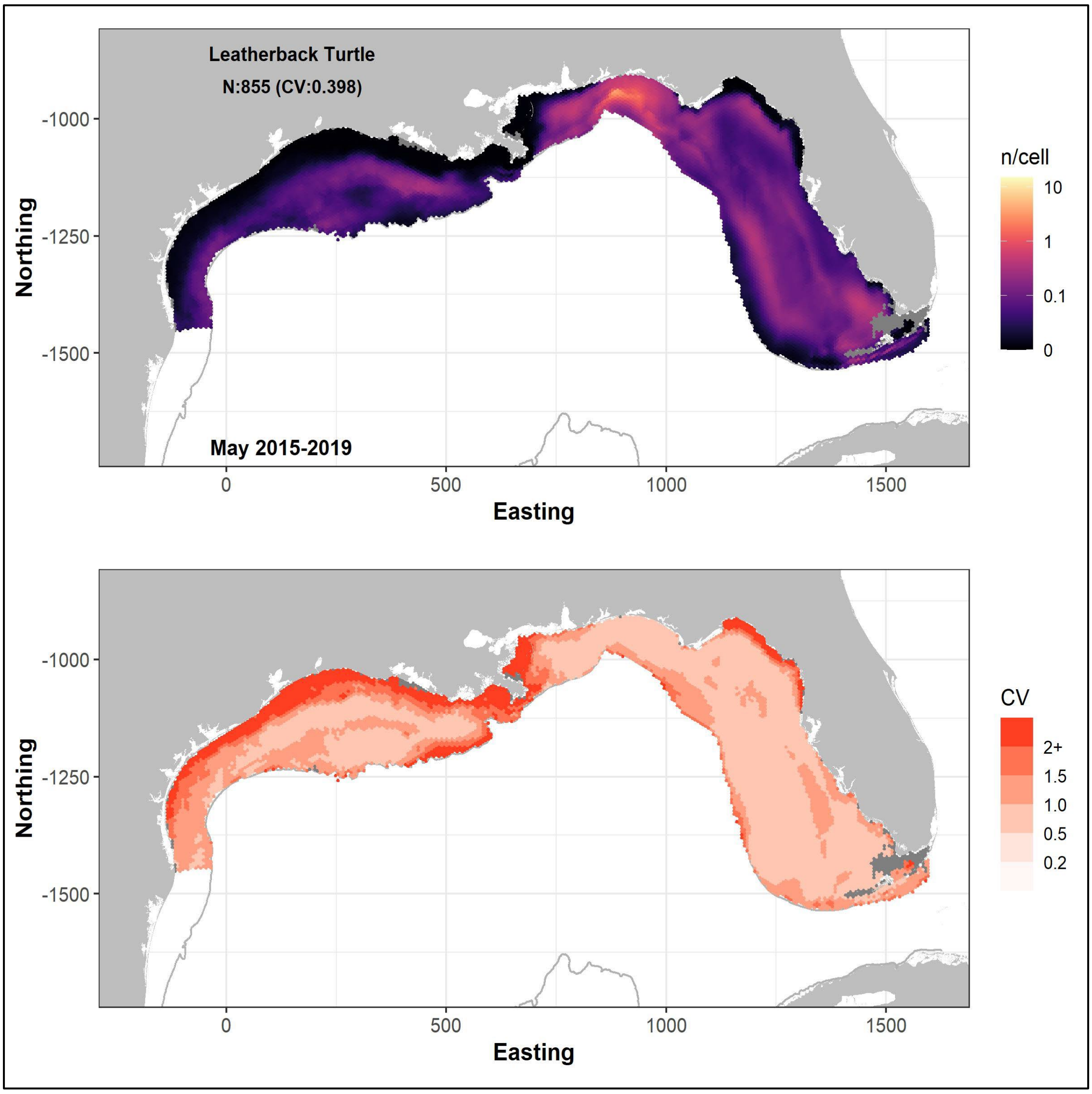

Figure D.1-41. Density model prediction for shelf leatherback turtles in the NGOM for the months of May 2015–2019.

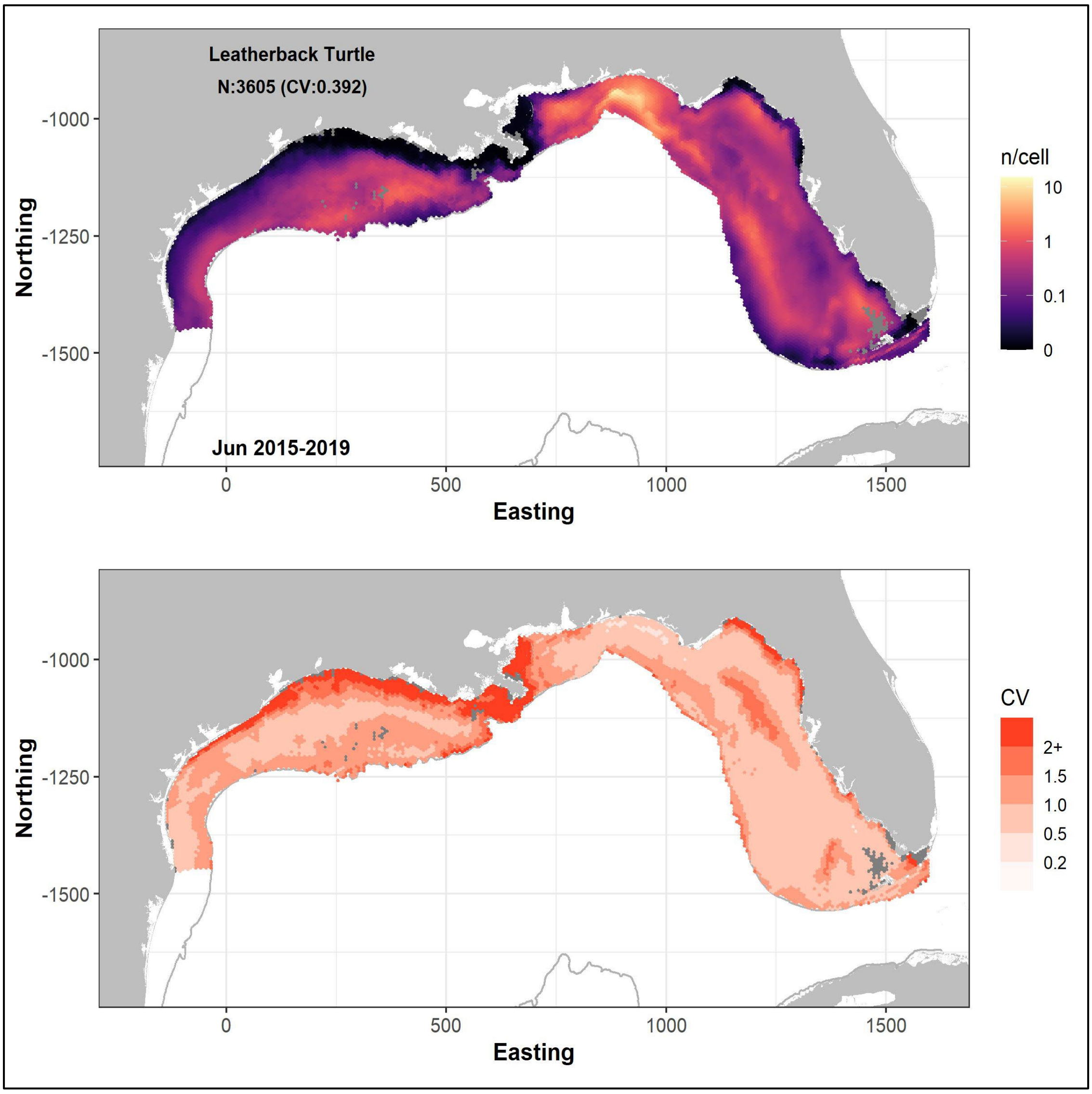

Figure D.1-42. Density model prediction for shelf leatherback turtles in the NGOM for the months of June 2015–2019.

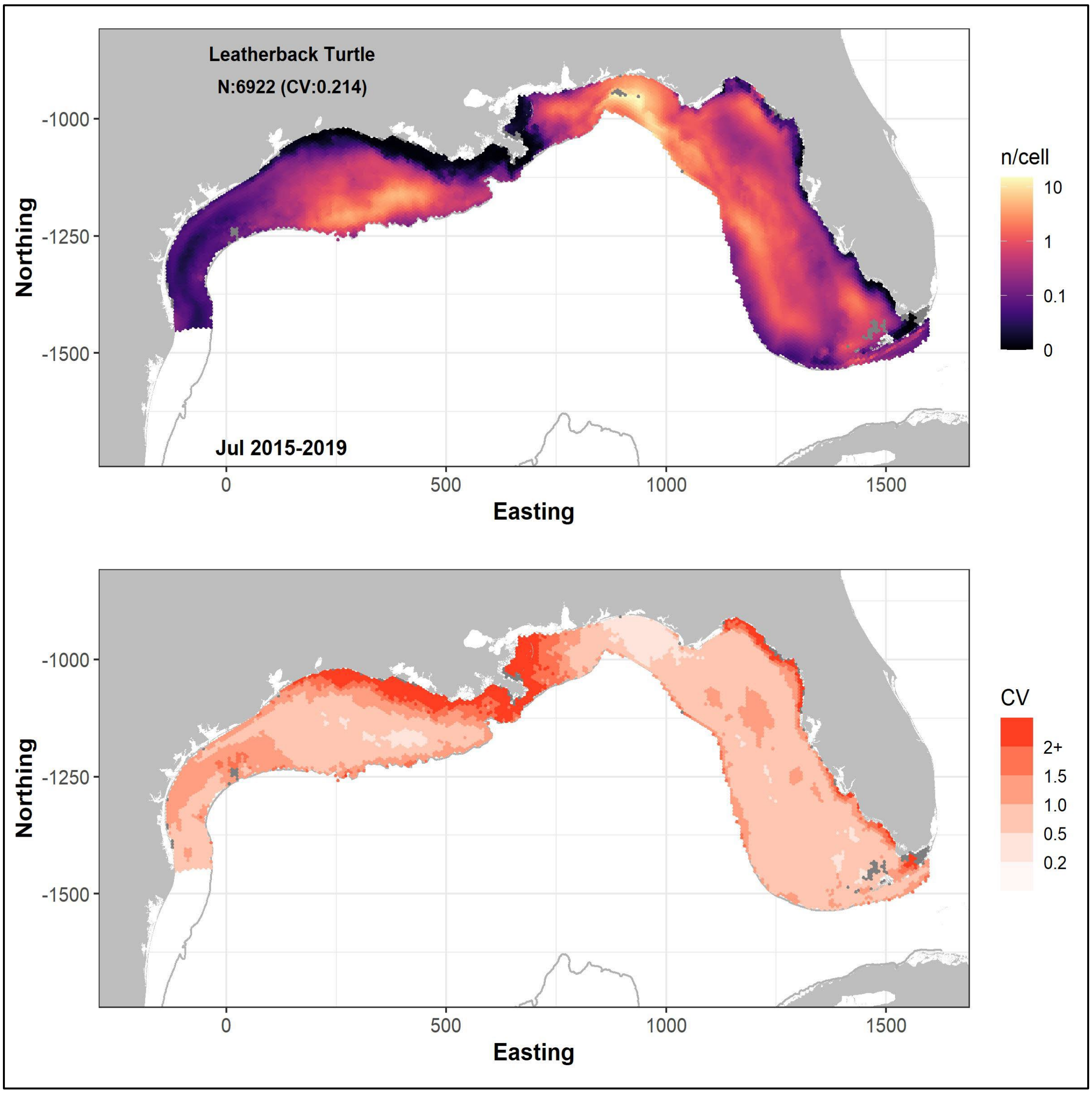

Figure D.1-43. Density model prediction for shelf leatherback turtles in the NGOM for the months of July 2015–2019.

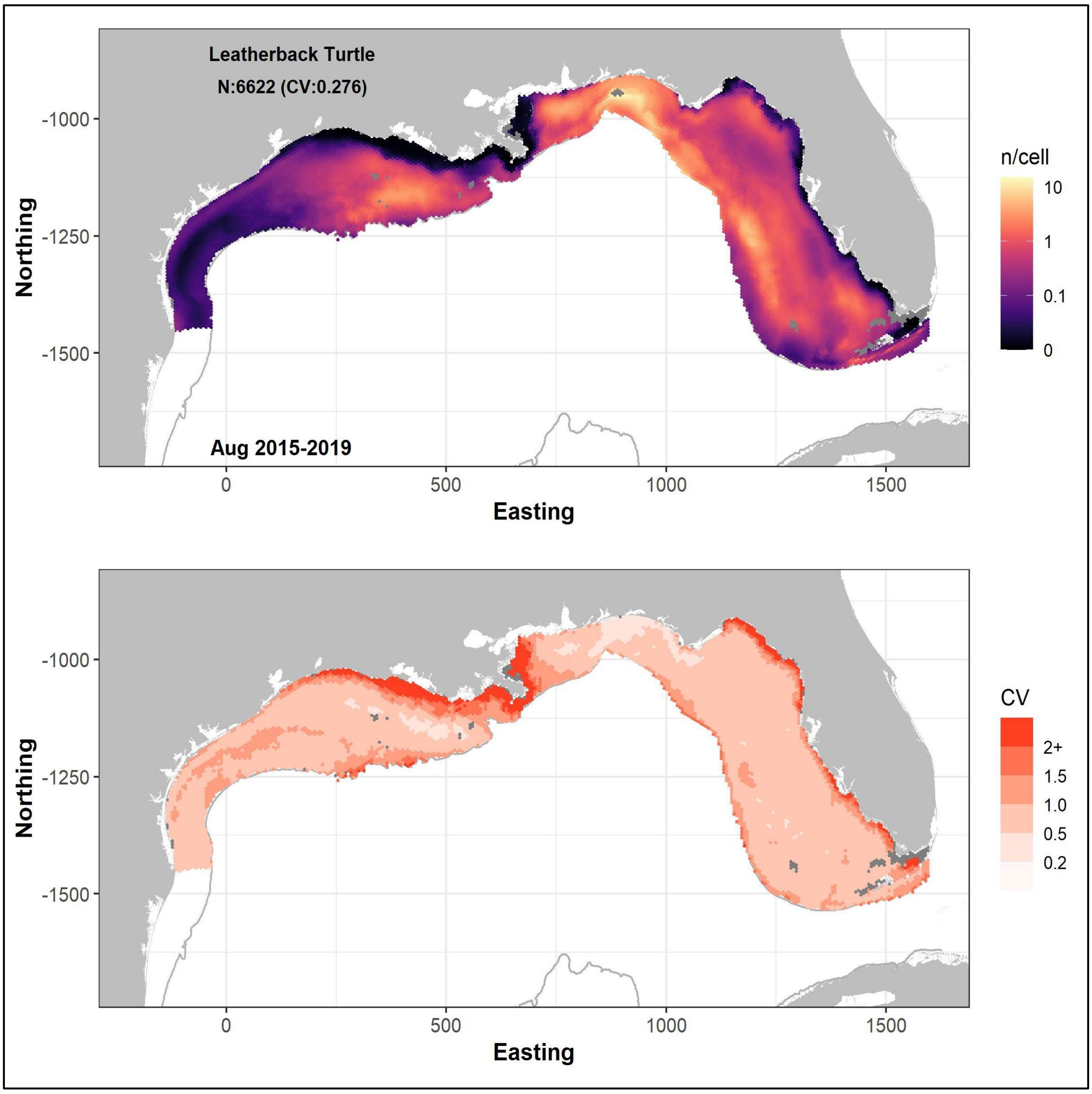

Figure D.1-44. Density model prediction for shelf leatherback turtles in the NGOM for the months of August 2015–2019.

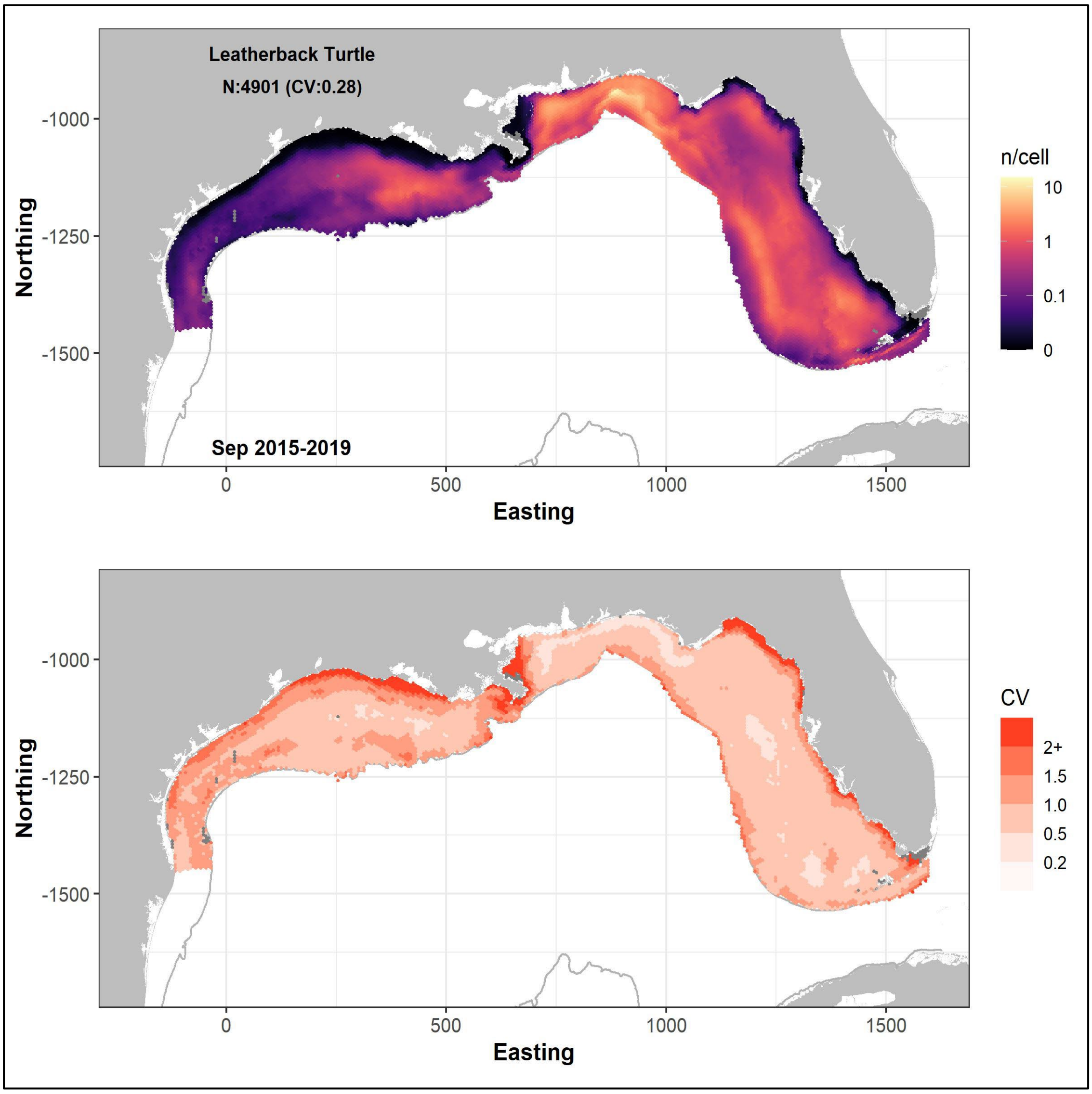

Figure D.1-45. Density model prediction for shelf leatherback turtles in the NGOM for the months of September 2015–2019.

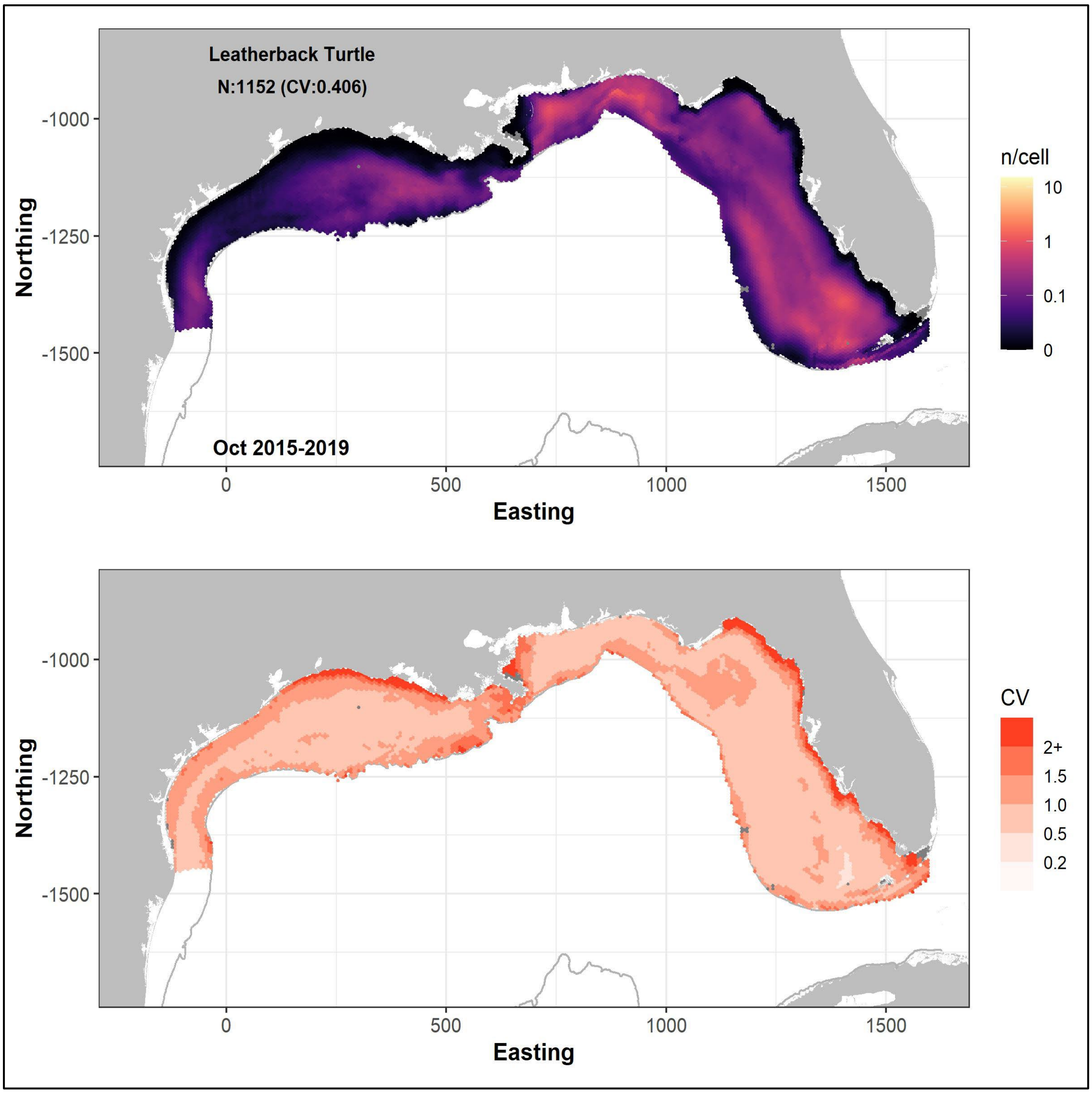

Figure D.1-46. Density model prediction for shelf leatherback turtles in the NGOM for the months of October 2015–2019.

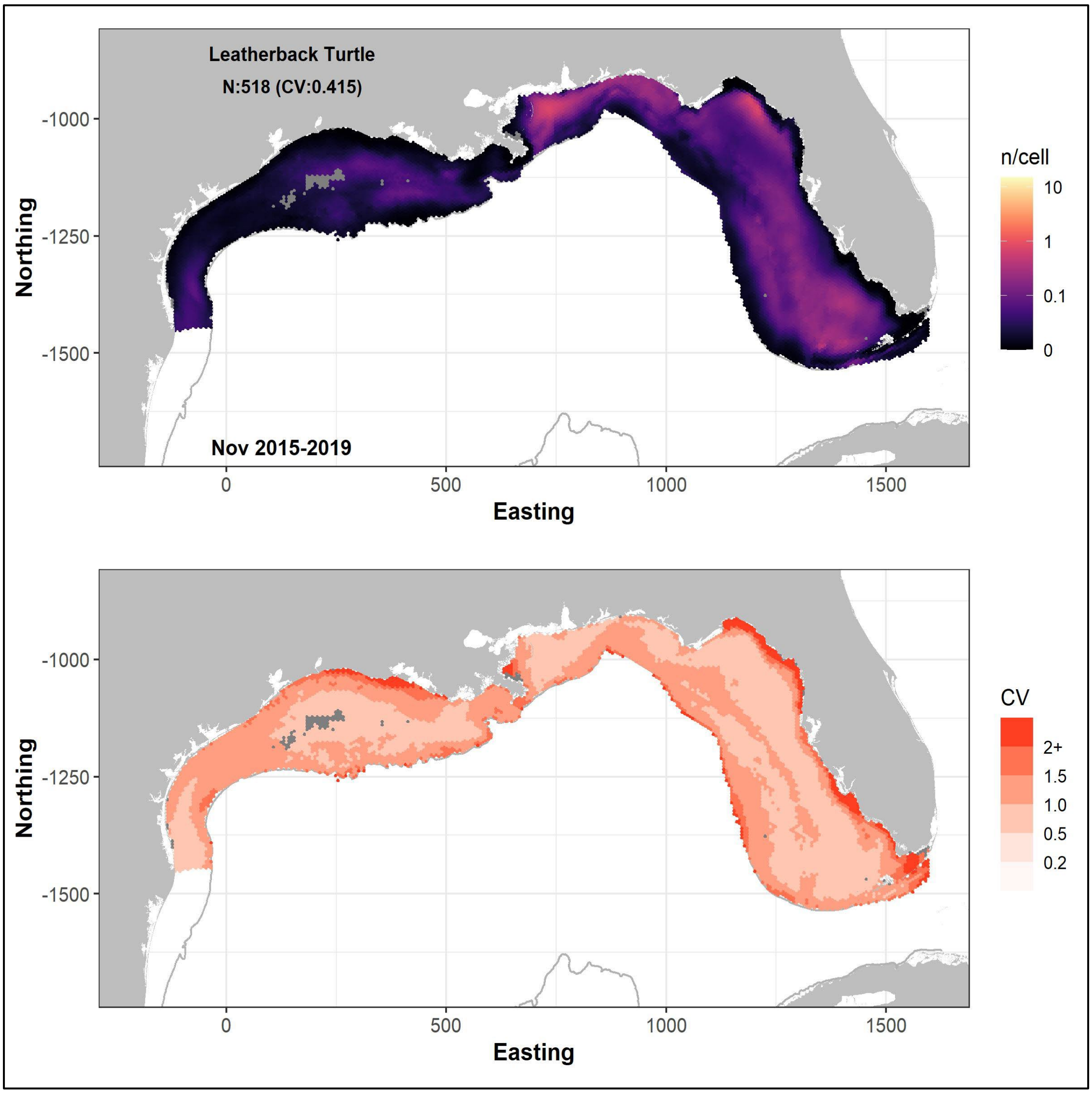

Figure D.1-47. Density model prediction for shelf leatherback turtles in the NGOM for the months of November 2015–2019.

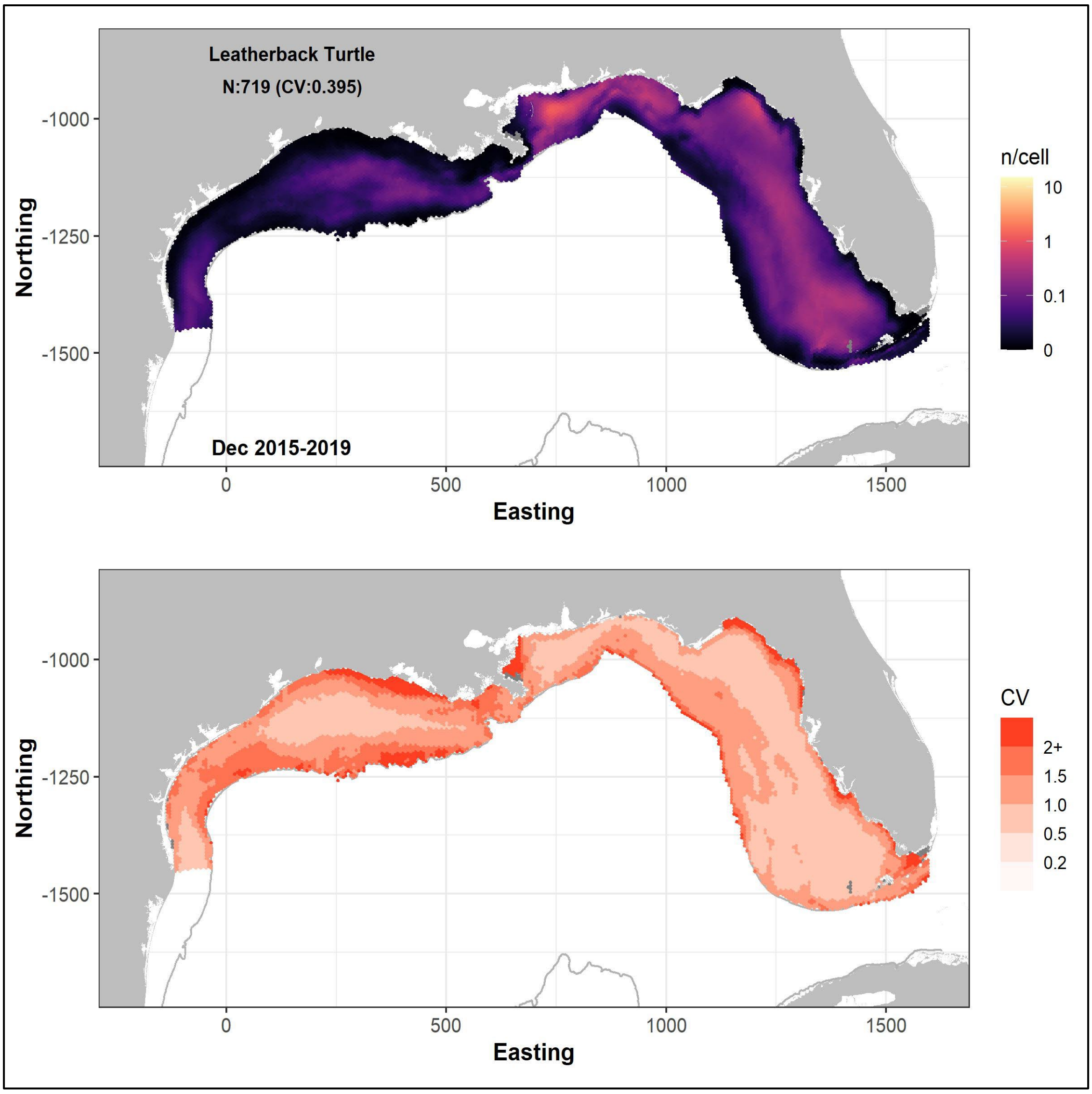

Figure D.1-48. Density model prediction for shelf leatherback turtles in the NGOM for the months of December 2015–2019.

The density models for leatherback turtles were summarized seasonally (Winter: Dec–Feb, Spring: Mar–May, Summer: Jun–Aug, Fall: Sep–Nov) and by Bureau of Ocean Energy Management (BOEM) planning area to generate abundance and CVs that reflect uncertainty in both model parameters and interannual variation in environmental conditions for each area (Table D.1-6).

Table D.1-6. Seasonal abundance (CV) of leatherback turtles in US shelf waters during 2015–2019 for BOEM planning areas

Season	Eastern	Central	Western
Winter	878 (0.646)	189 (0.723)	58 (0.732)
Spring	845 (0.492)	195 (0.532)	87 (0.665)
Summer	3,927 (0.415)	1,135 (0.504)	344 (0.724)
Fall	1,563 (0.994)	408 (1.014)	74 (0.821)

D.1.5.4 Gulf-Wide Average Monthly Density: 2015–2019

Prediction maps were generated using monthly environmental parameters for the period of 2015–2019 extrapolating the model for leatherback turtles throughout the GOM. As noted above, these extrapolations should be treated with caution given the potential for changing species-environment relationships in unsampled areas (Figures D.1-49–D.1-60).

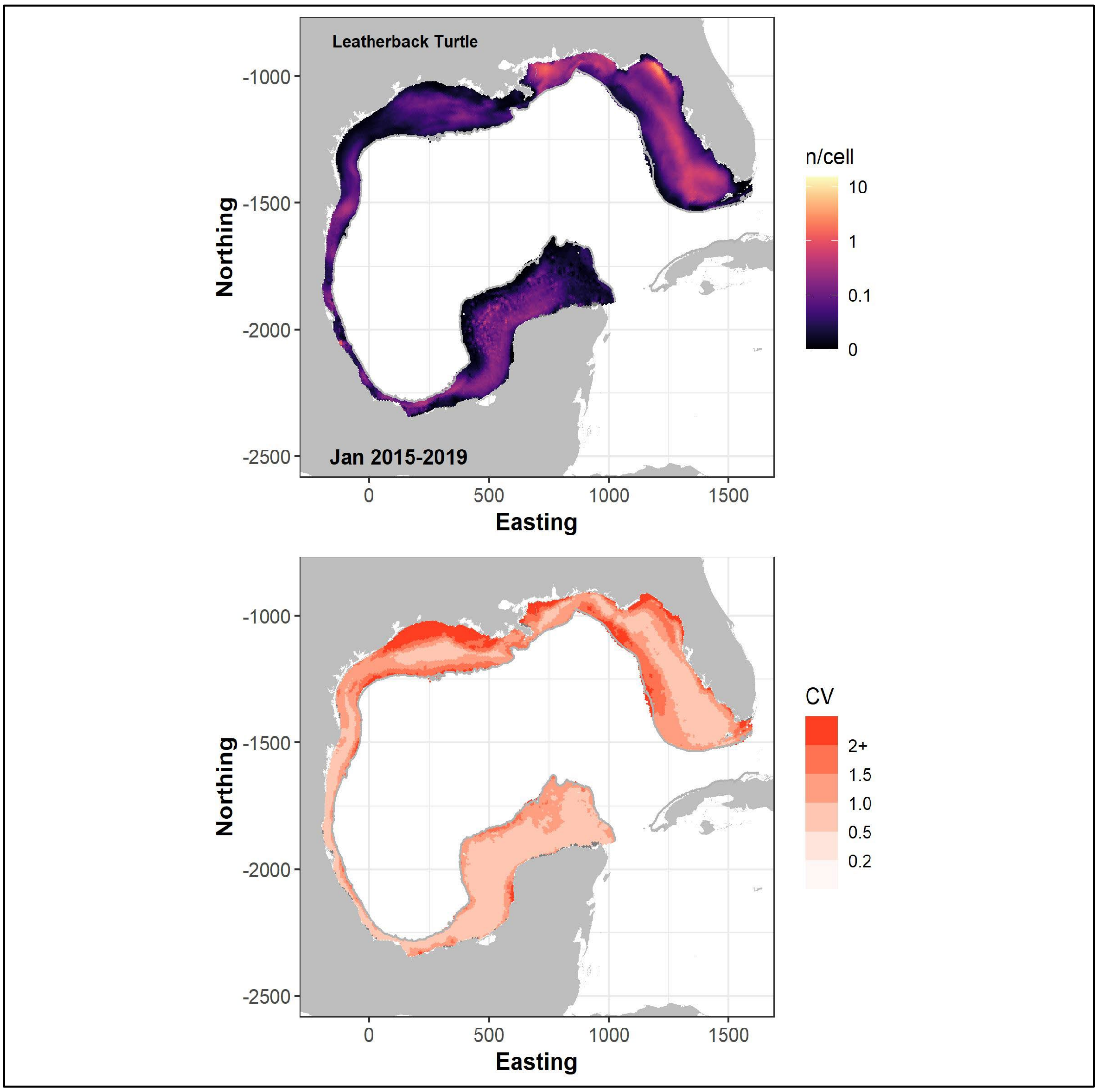

Figure D.1-49. Projected density model for shelf leatherback turtles in the entire GOM for the months of January 2015–2019.

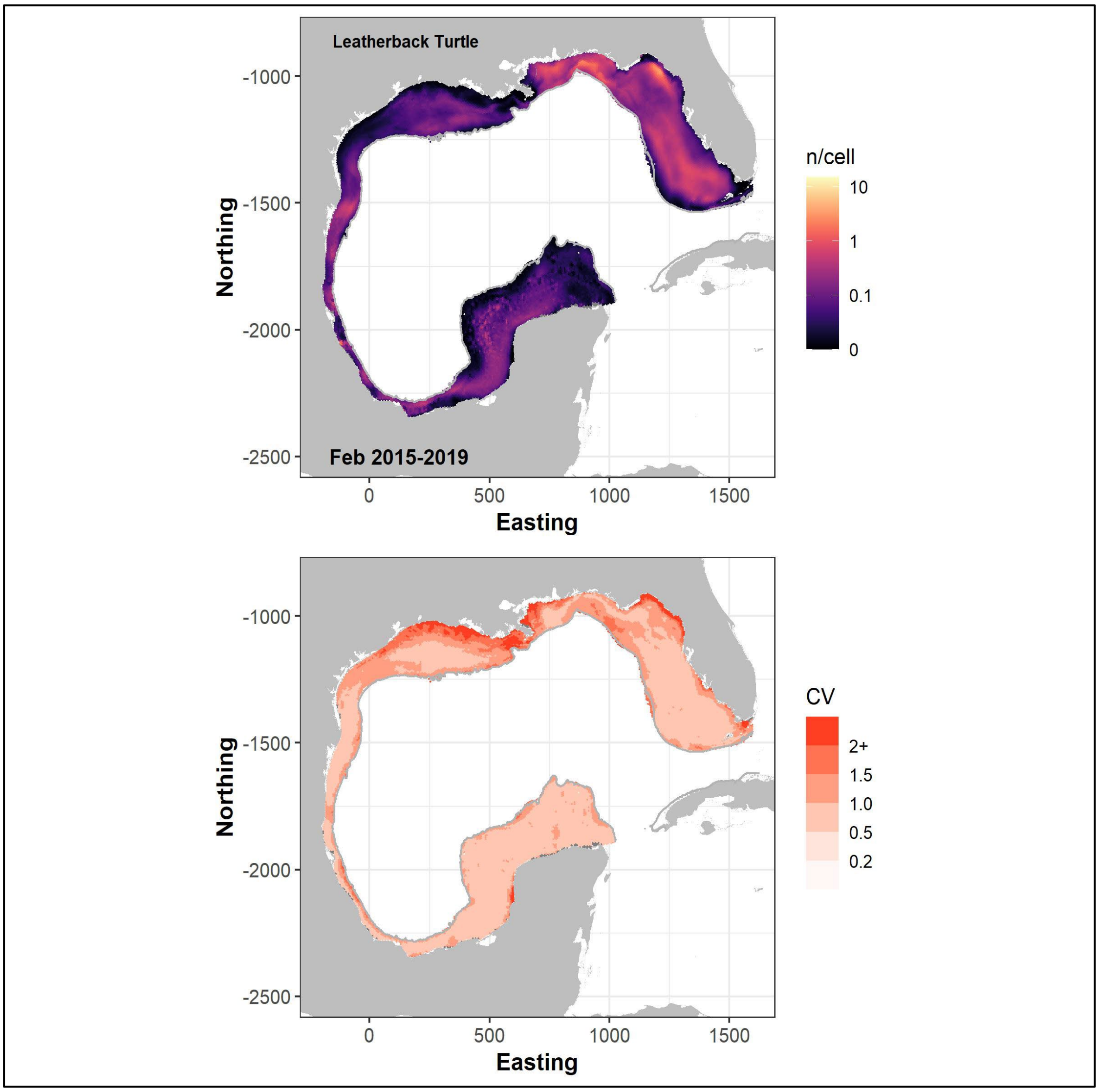

Figure D.1-50. Projected density model for shelf leatherback turtles in the entire GOM for the months of February 2015–2019.

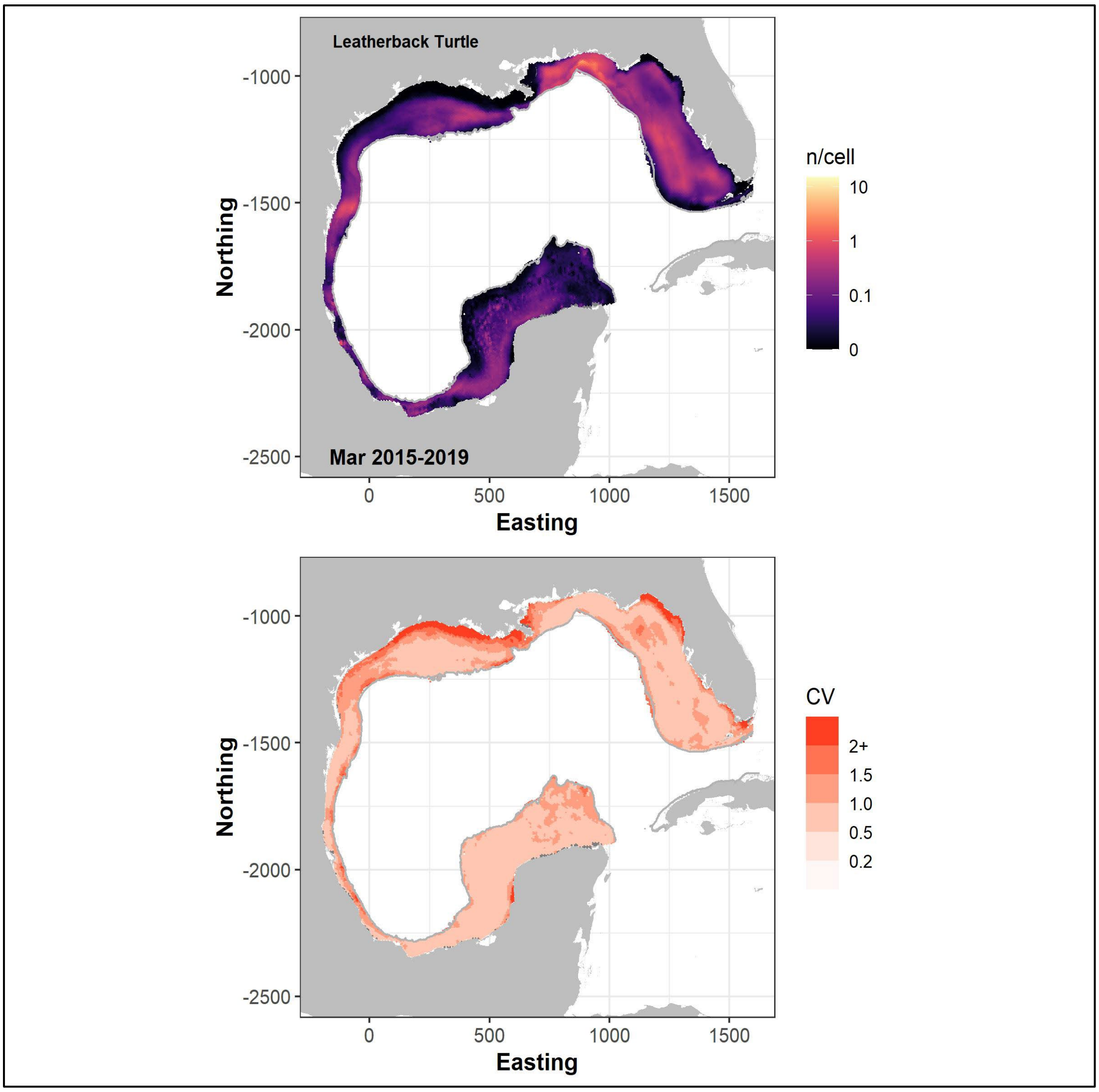

Figure D.1-51. Projected density model for shelf leatherback turtles in the entire GOM for the months of March 2015–2019.

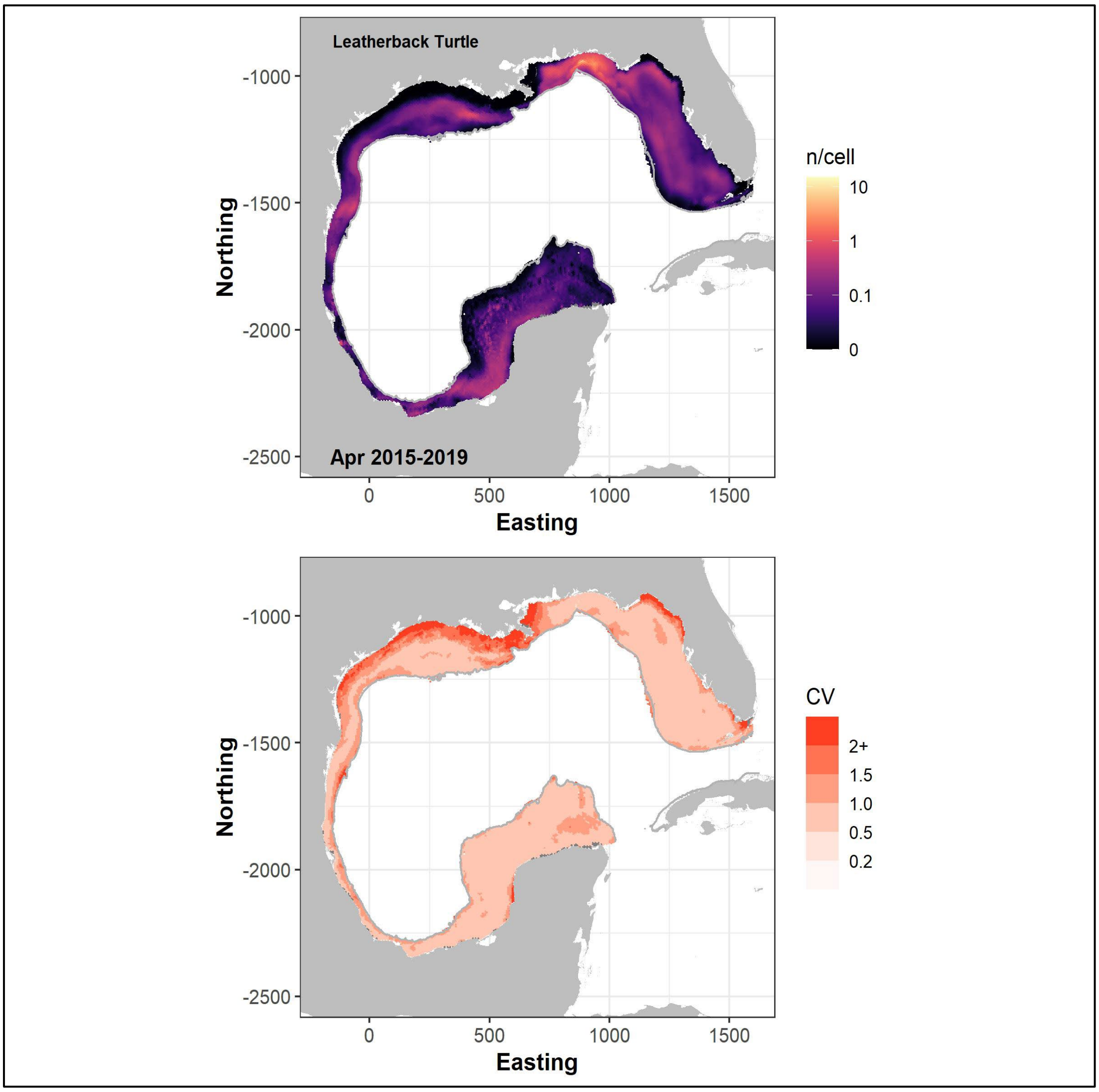

Figure D.1-52. Projected density model for shelf leatherback turtles in the entire GOM for the months of April 2015–2019.

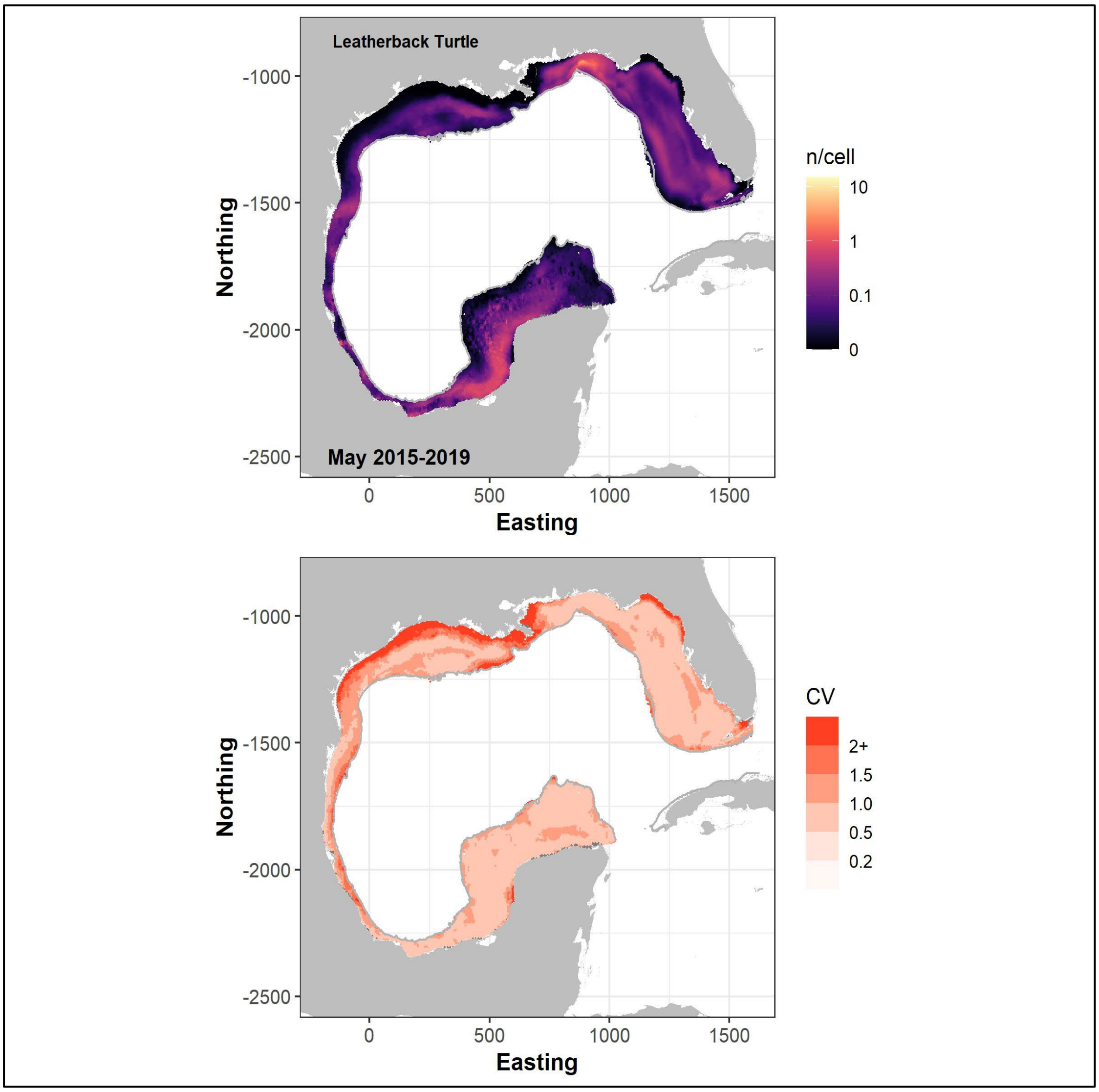

Figure D.1-53. Projected density model for shelf leatherback turtles in the entire GOM for the months of May 2015–2019.

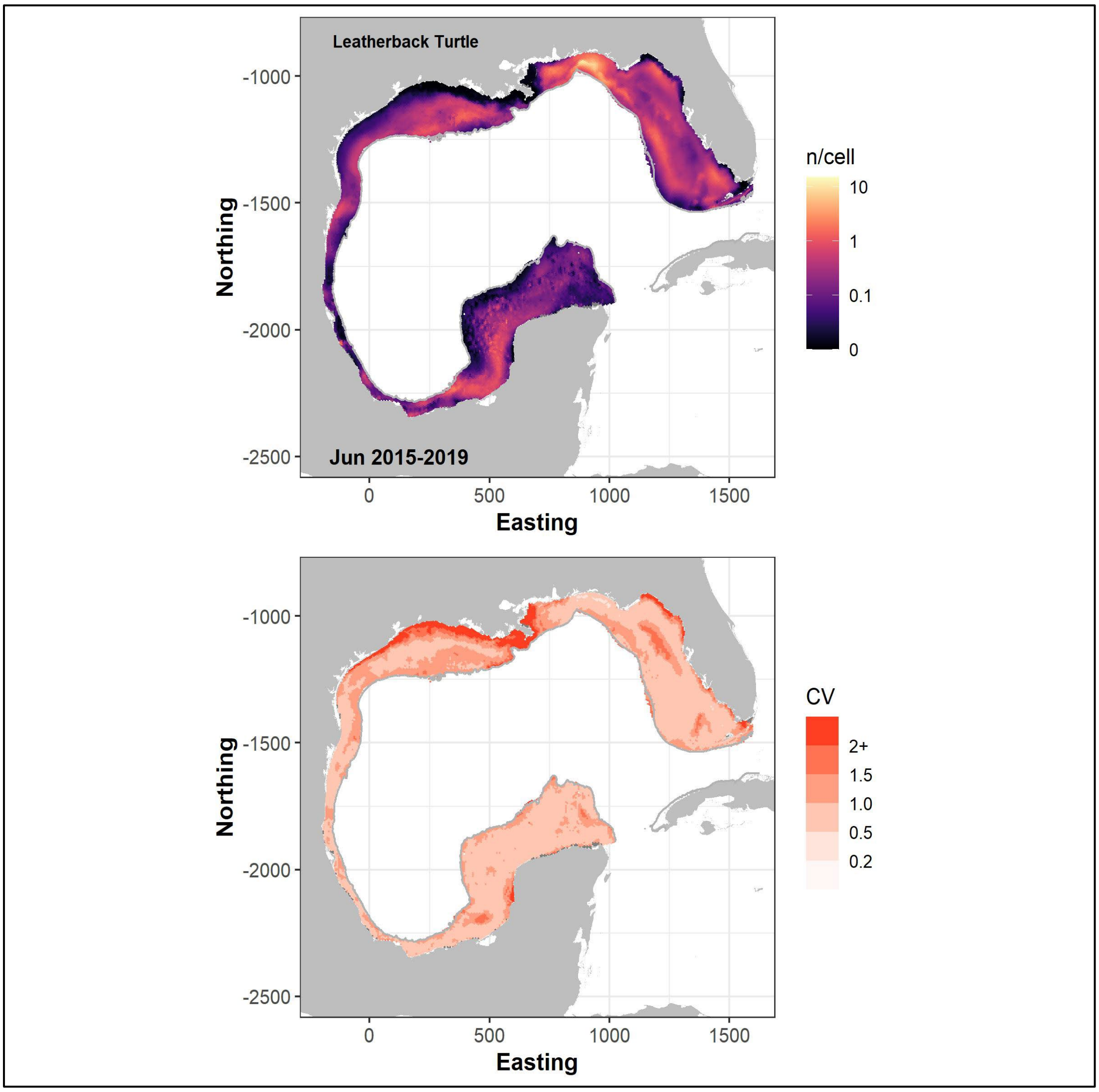

Figure D.1-54. Projected density model for shelf leatherback turtles in the entire GOM for the months of June 2015–2019.

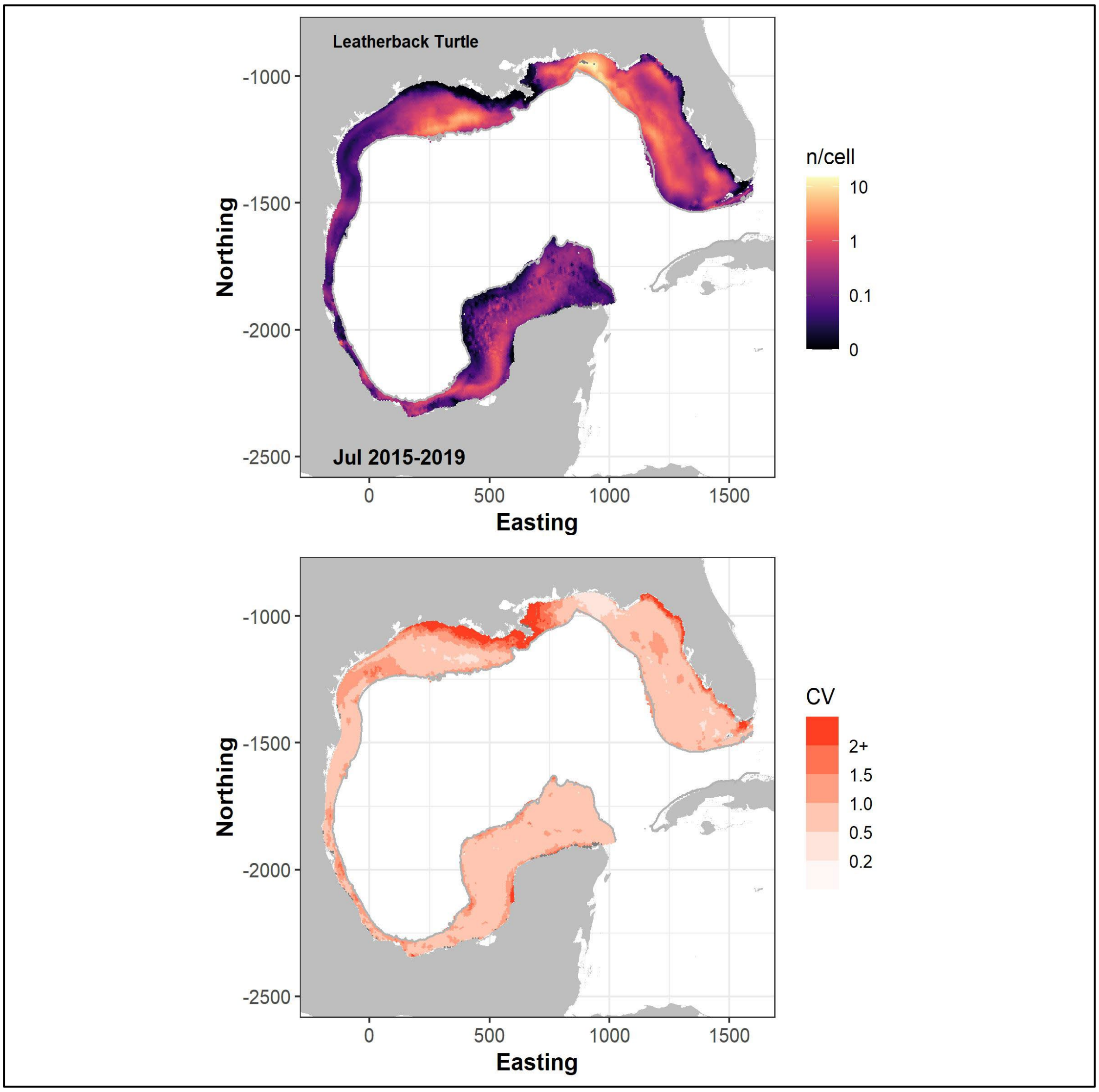

Figure D.1-55. Projected density model for shelf leatherback turtles in the entire GOM for the months of July 2015–2019.

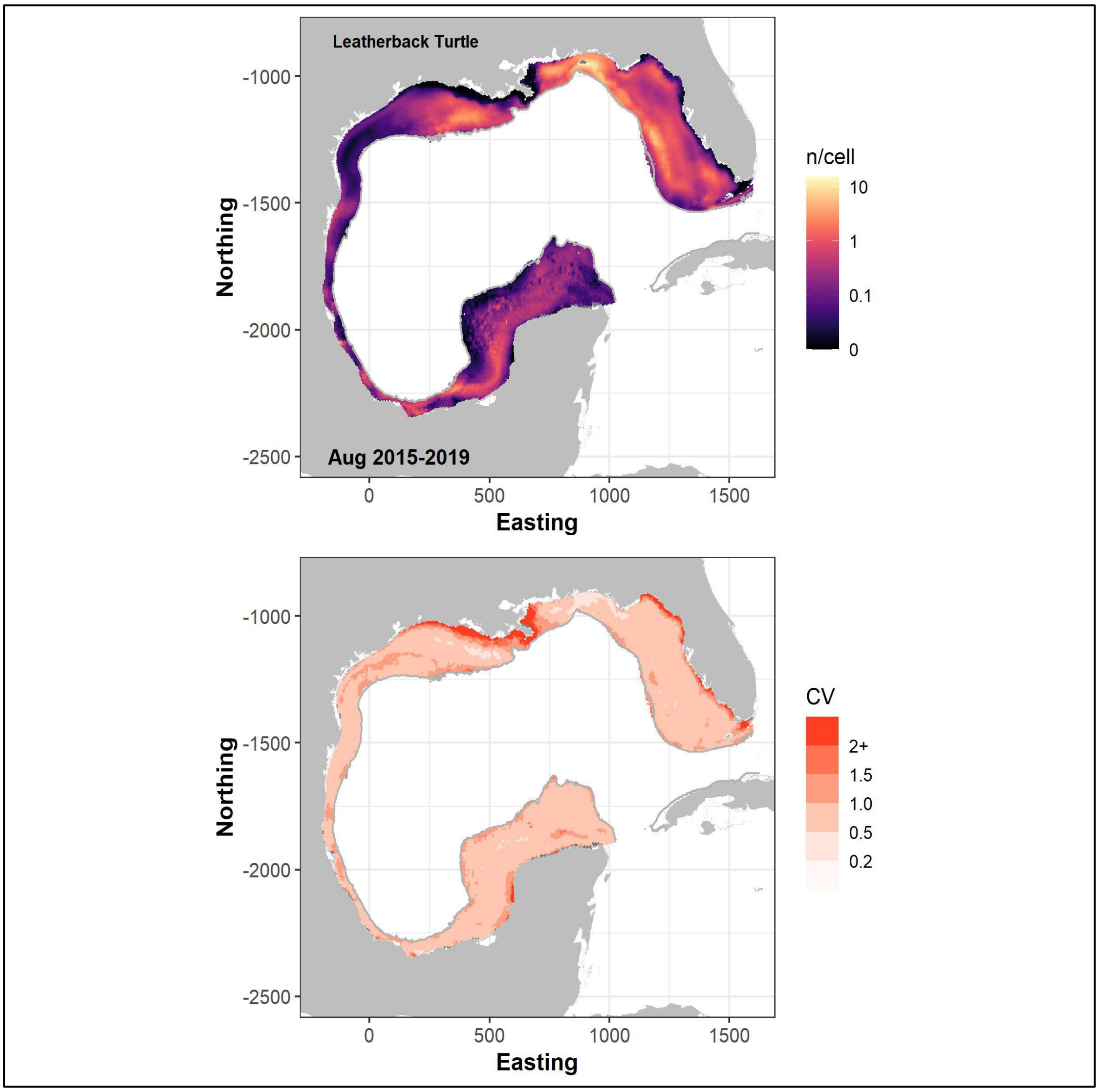

Figure D.1-56. Projected density model for shelf leatherback turtles in the entire GOM for the months of August 2015–2019.

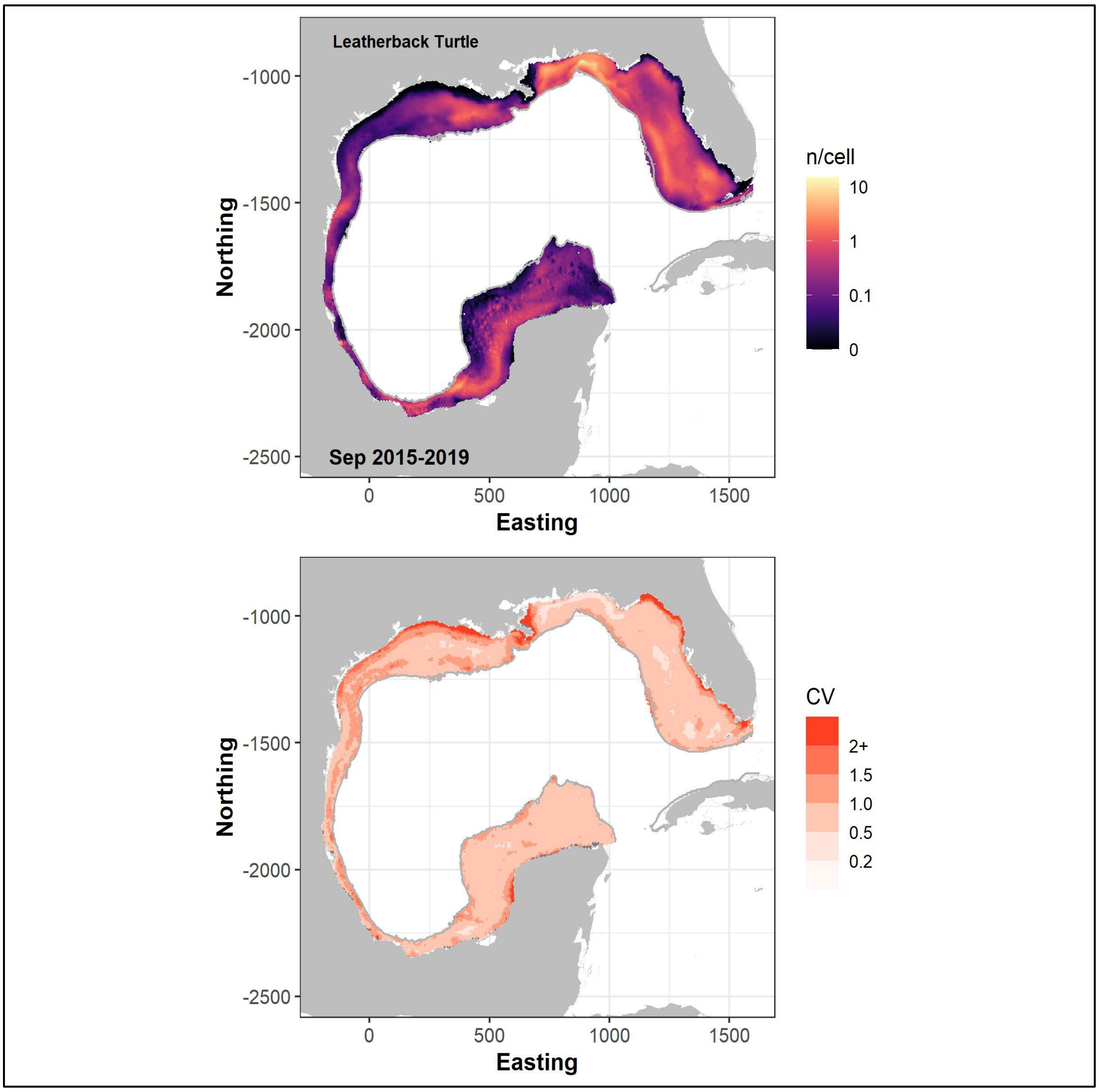

Figure D.1-57. Projected density model for shelf leatherback turtles in the entire GOM for the months of September 2015–2019.

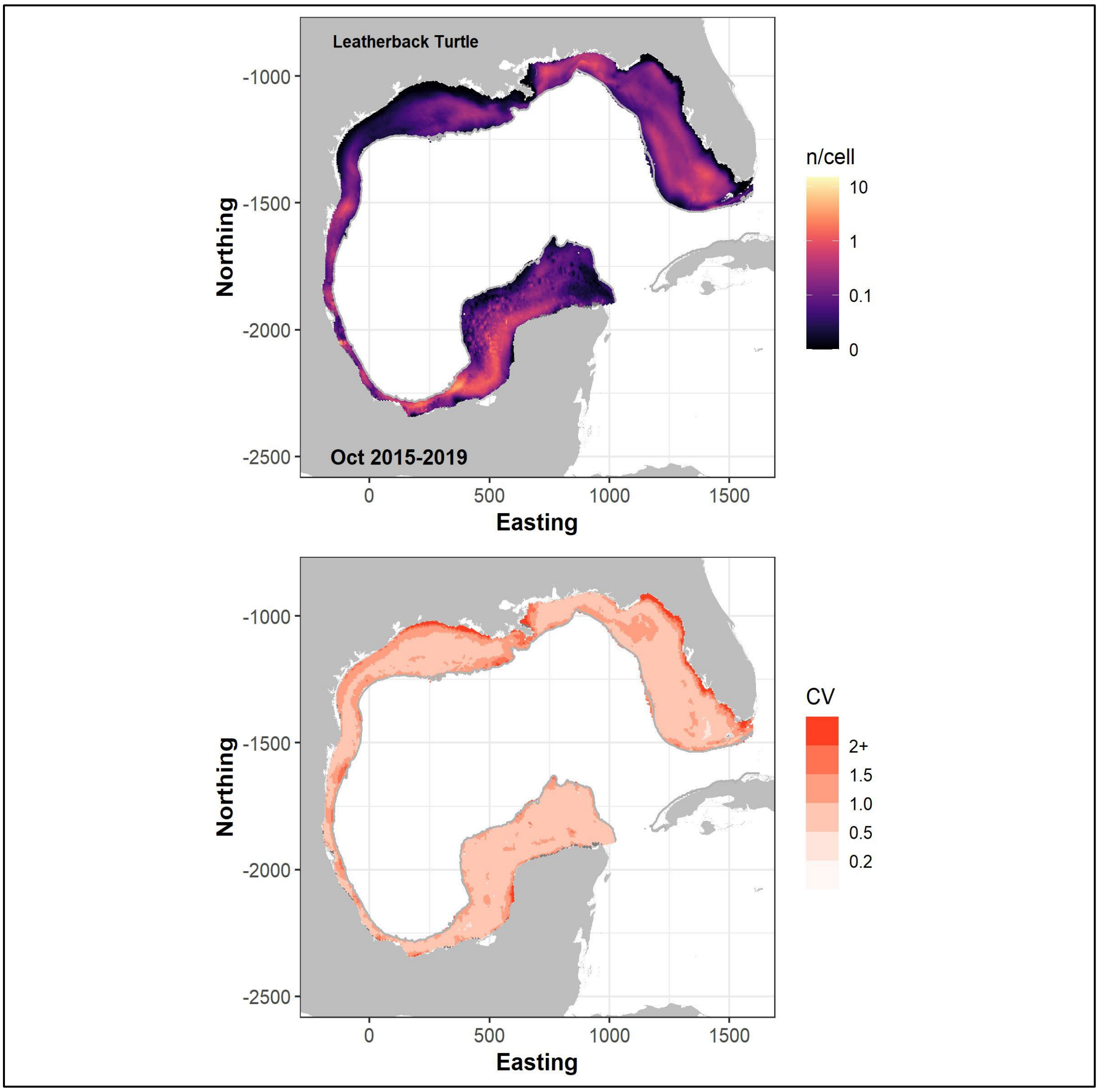

Figure D.1-58. Projected density model for shelf leatherback turtles in the entire GOM for the months of October 2015–2019.

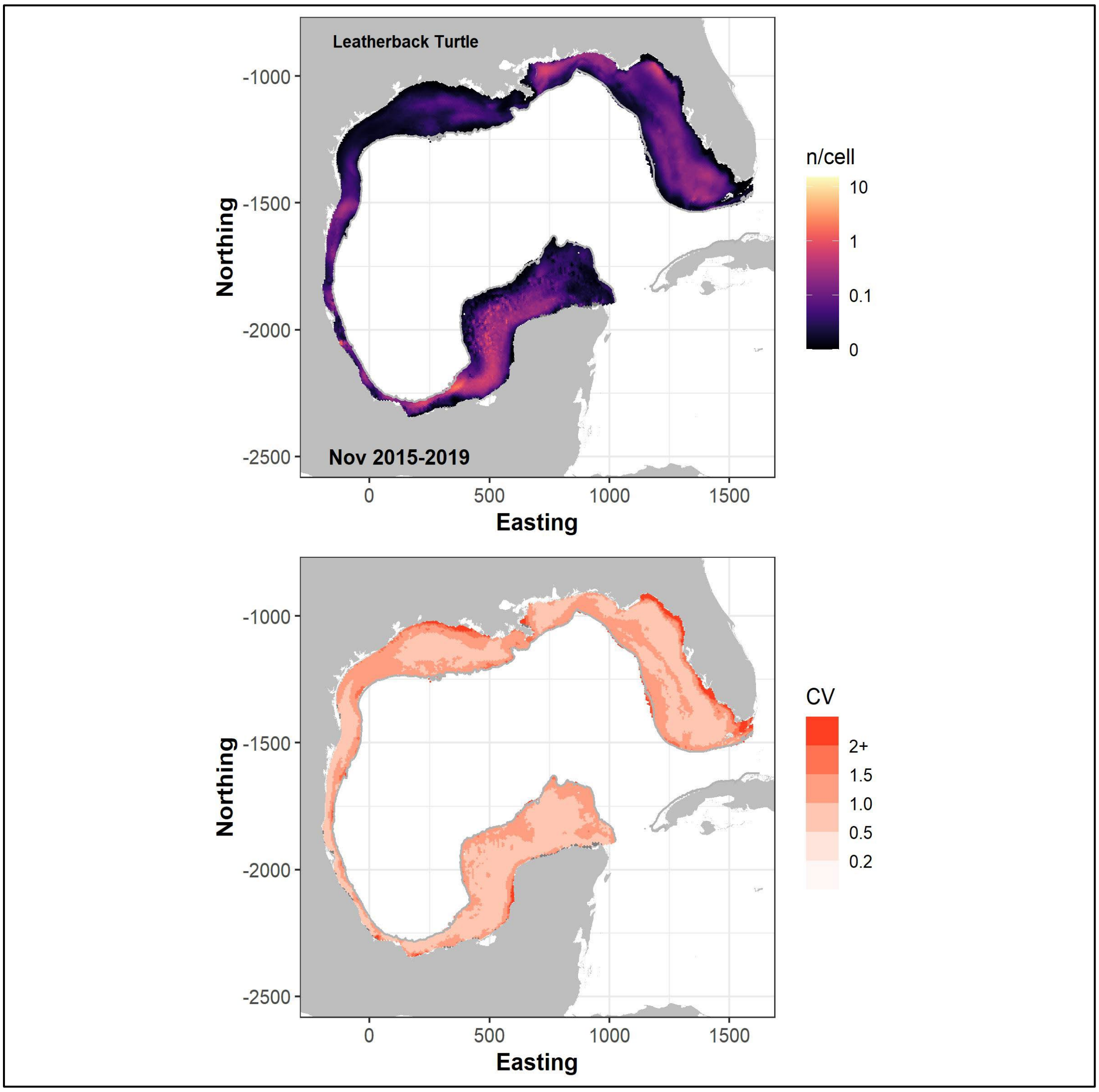

Figure D.1-59. Projected density model for shelf leatherback turtles in the entire GOM for the months of November 2015–2019.

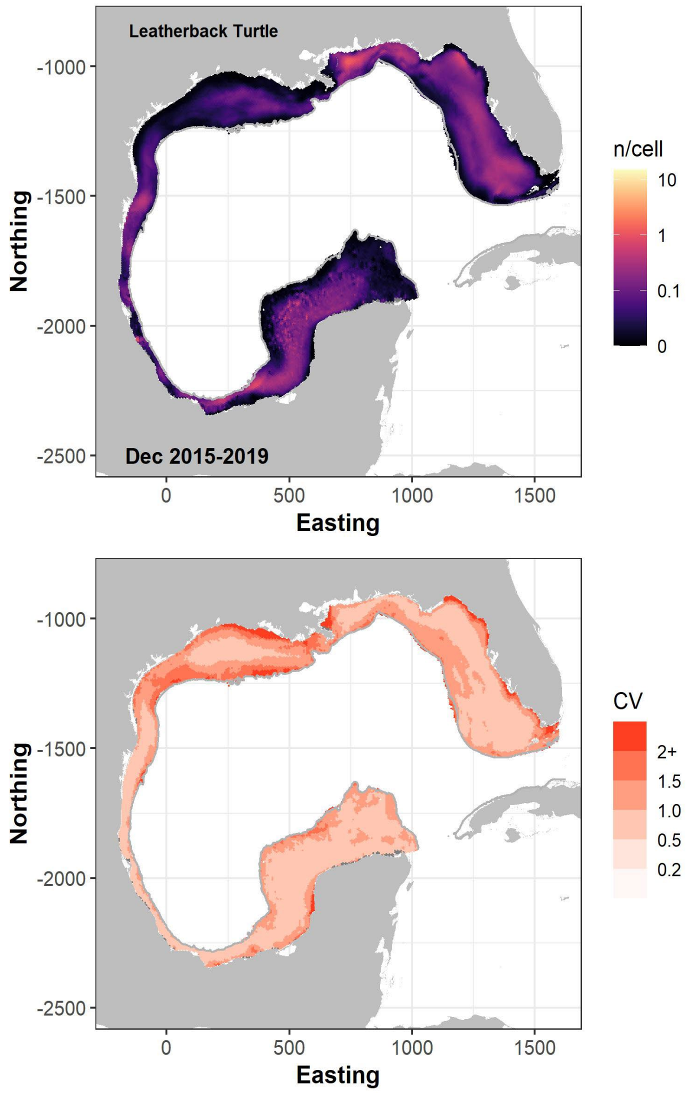

Figure D.1-60. Projected density model for shelf leatherback turtles in the entire GOM for the months of December 2015–2019.

D.2 Gulf of Mexico Green Turtle Density Models

Photo credit: NOAA Fisheries/Lesley Stokes

This section describes the development of spatial density models (SDMs) for green turtles (*Chelonia mydas*) occurring over the continental shelf based upon seasonal aerial surveys conducted in 2011–2012 and 2017–2018, including average abundance prediction maps generated using monthly environmental parameters for the period of 2015–2019. This section also includes projected density prediction maps for shelf waters of the entire Gulf of Mexico (GOM).

D.2.1 Survey Data and Sightings

Aerial line-transect surveys were conducted over the continental shelf of the northern Gulf of Mexico (NGOM) in a survey region extending from the shoreline to the shelf break (approximately the 200 m isobath) between Key West, Florida and the US/Mexico border near Brownsville, Texas. Each survey was conducted in a NOAA Twin Otter flying at a survey altitude of 183 m (600 ft) and an approximate speed of 100 knots. Survey tracklines were spaced approximately 20 km apart and were oriented so as to be perpendicular to the shoreline. The aircraft was equipped with two large bubble windows in the forward portion of the aircraft (left and right sides) and one right bubble window and a belly window in the aft portion of the aircraft to allow effective visualization of the trackline (see Figure 2 in the GoMMAPPS project final report). Surveys were conducted using two independent teams to allow estimation of detection probability in within the surveyed strip and on the trackline using Mark Recapture Distance Sampling (MRDS) approaches. Aerial surveys were conducted in spring 2011, summer 2011, fall 2011, and winter 2012 as part of the Natural Resource Damage Assessment (NRDA) associated with the *Deepwater Horizon* oil spill. Additional surveys were conducted in the summer of 2017, winter 2018, and fall 2018 as part of the Gulf of Mexico Marine Assessment Program for Protected Species (GoMMAPPS). Additional details about the survey design and execution are contained in Garrison et al. (2022). The total number of green turtle groups sighted is shown in Table D.2-1.

Table D.2-1. Green turtles observed for each survey included in this analysis

Survey	Groups	Individuals
TOSE11F	88	99
TOSE11Sp	54	70
TOSE11Su	46	52
TOSE12W	29	29
TOSE17Su	21	21
TOSE18F	1	1
TOSE18W	2	2

Green turtles were observed through the survey range in all seasons with higher densities of animals typically occurring in the eastern portion of the NGOM and in particular in the southeastern NGOM near the Florida Keys (Figure D.2-1).

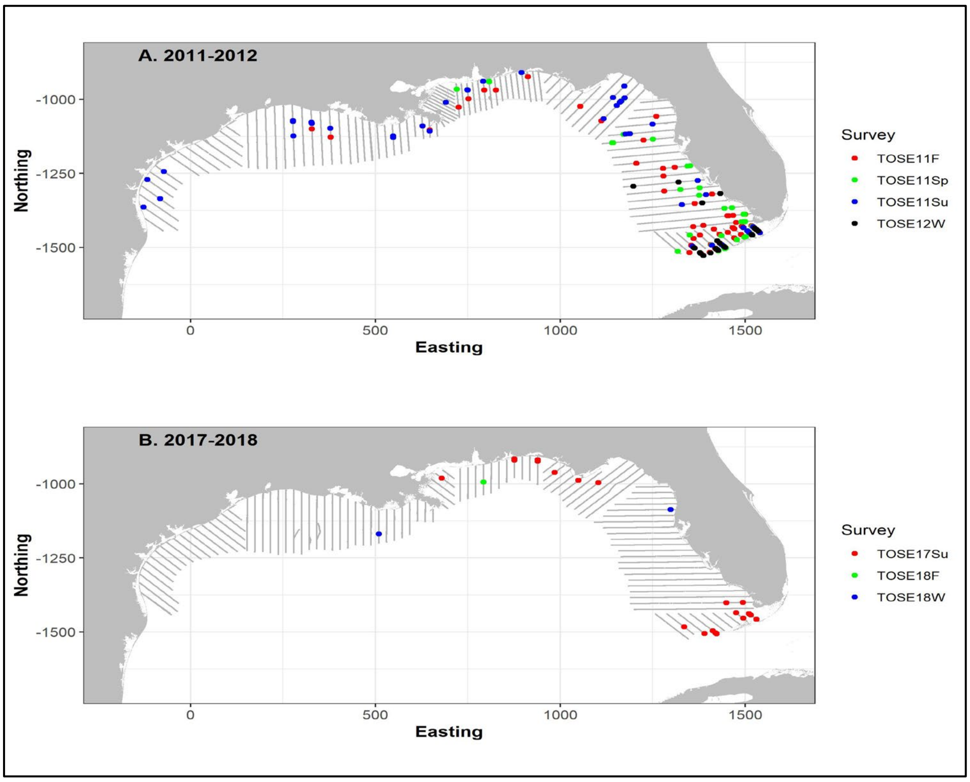

Figure D.2-1. Survey effort and green turtle sightings during (A) 2011–2012 and (B) 2017–2018.

D.2.2 Distribution of Sightings and Physical Oceanography during Each Survey

Green turtles were observed primarily in the eastern and southeastern NGOM in all seasons. There is some seasonal variation in spatial distribution with animals occurring in the northwestern GOM during summer surveys. The spatial pattern in the winter 2018 survey reflects incomplete survey effort where tracklines in the northeastern GOM were not completed due to poor weather conditions. The distribution of sightings and surface temperature and chlorophyll-a concentrations are shown in Figures D.2-2–D.2-8.

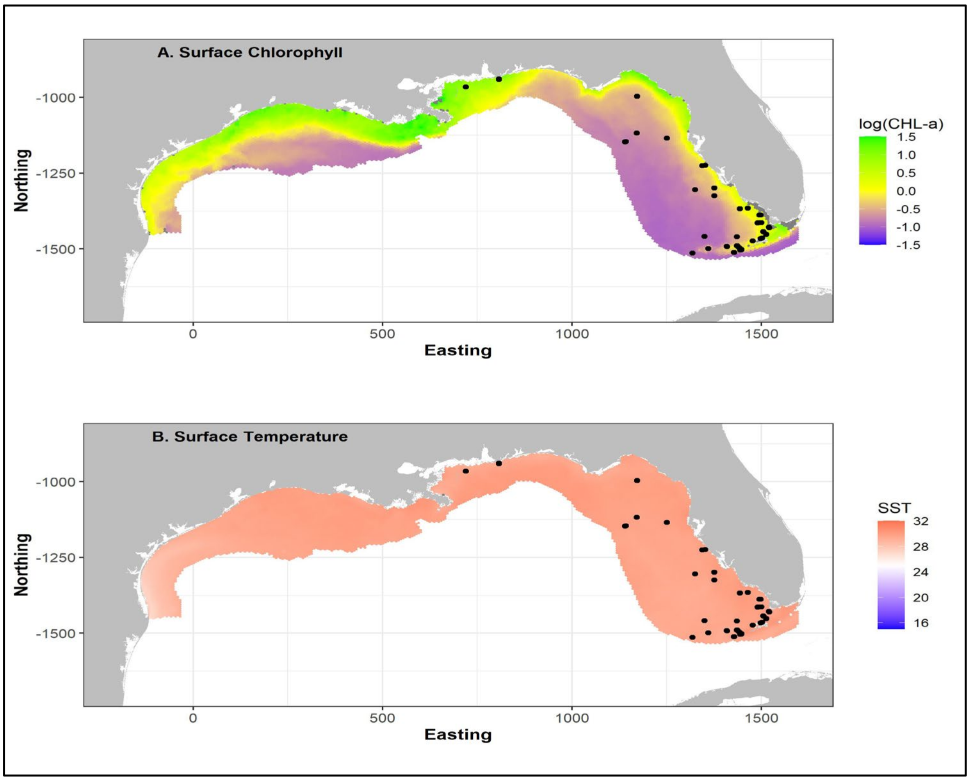

Figure D.2-2. Green turtle sightings during spring 2011.

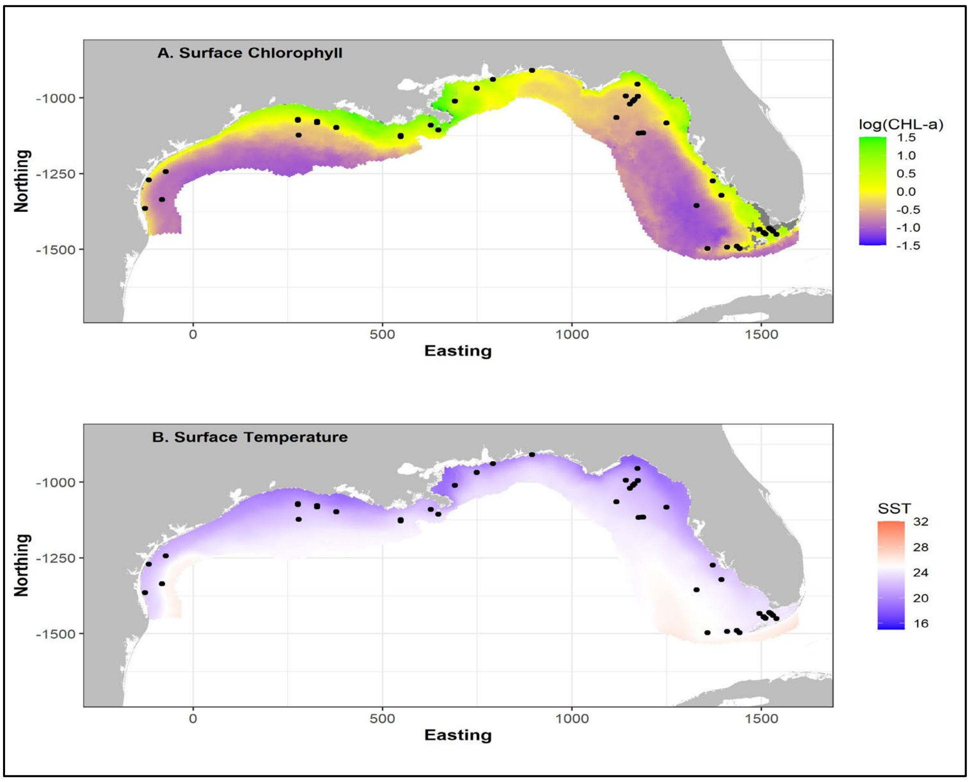

Figure D.2-3. Green turtle sightings during summer 2011.

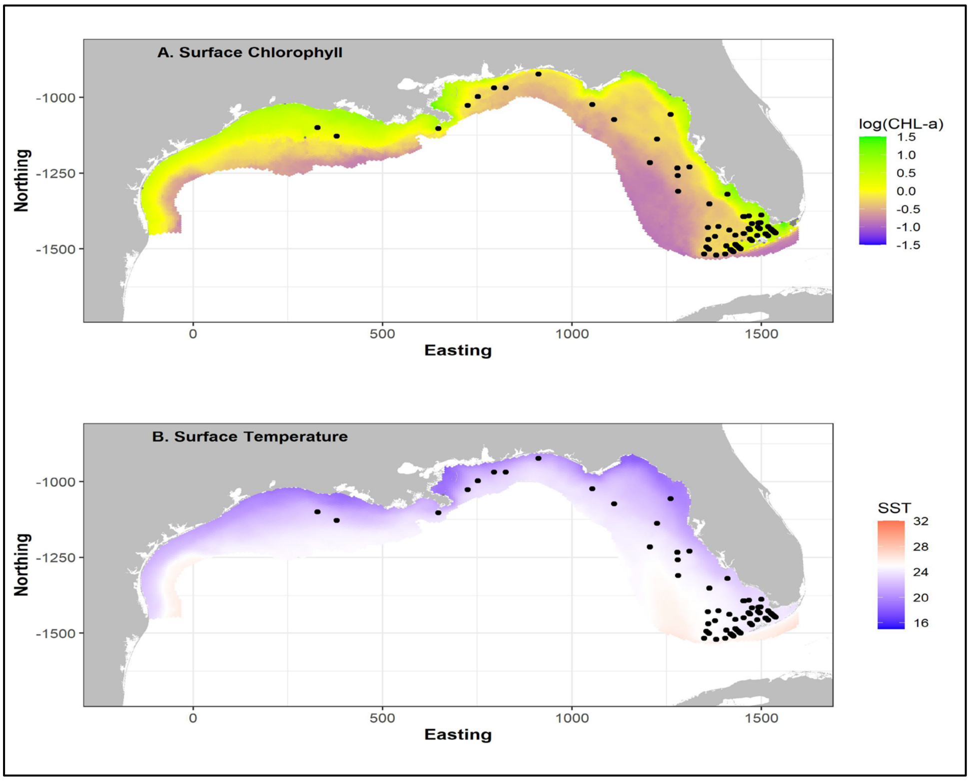

Figure D.2-4. Green turtle sightings during fall 2011.

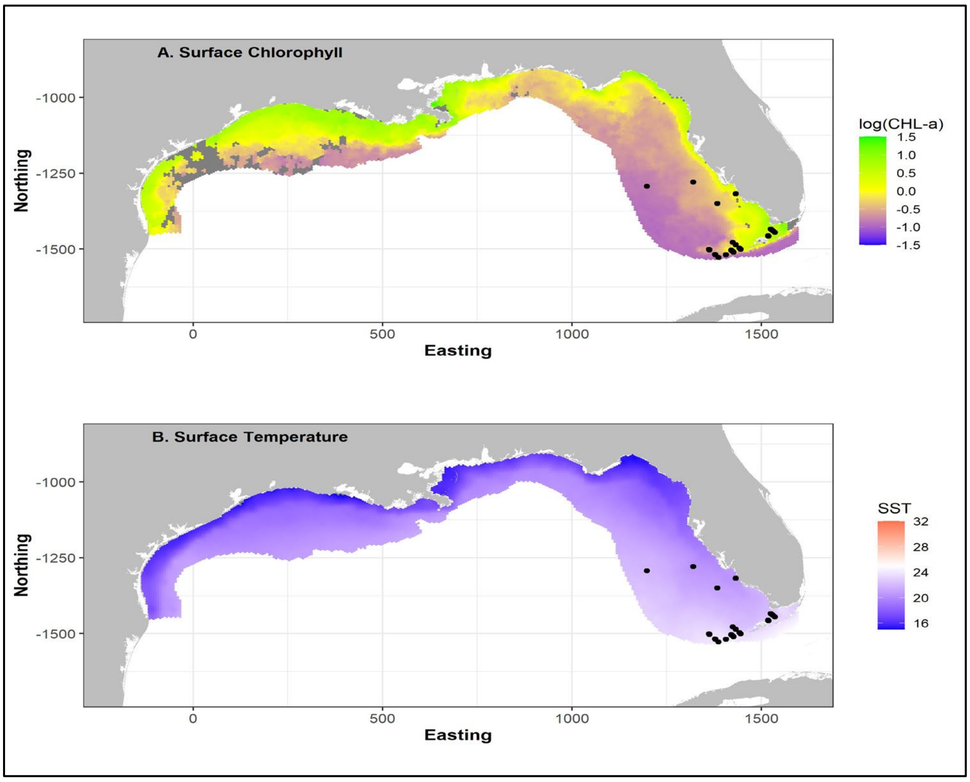

Figure D.2-5. Green turtle sightings during winter 2012.

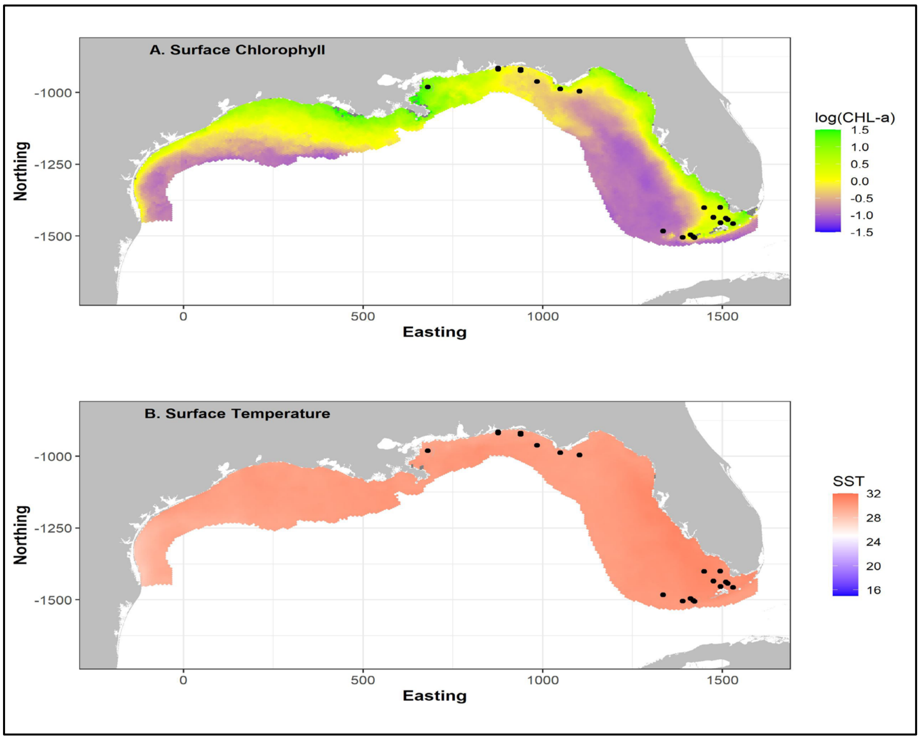

Figure D.2-6. Green turtle sightings during summer 2017.

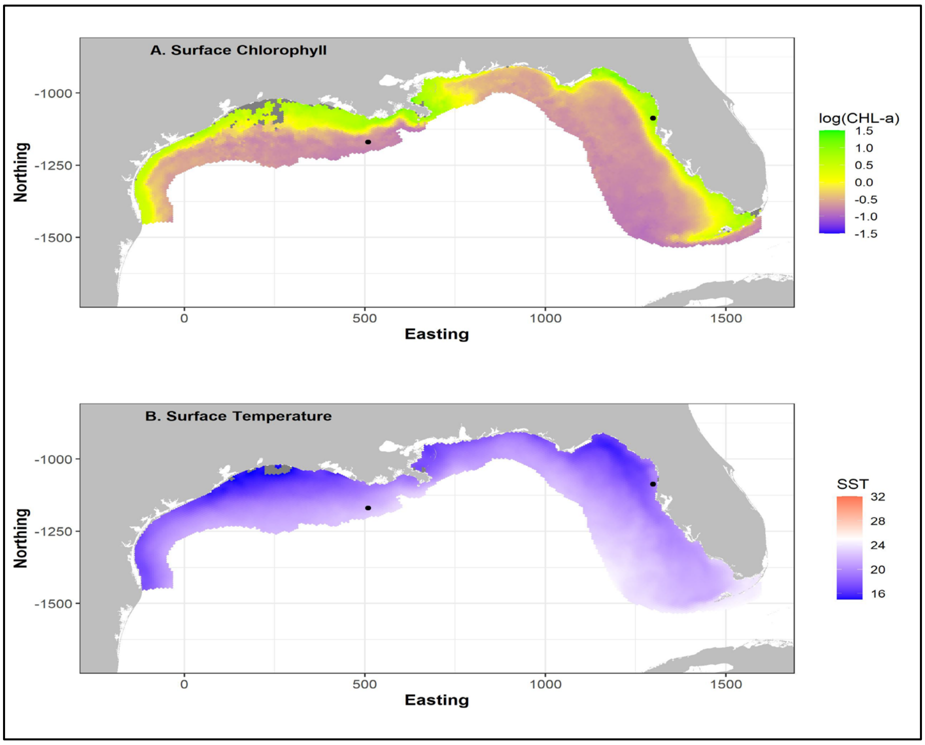

Figure D.2-7. Green turtle sightings during winter 2018.

Note that survey effort was incomplete in the northeastern GOM during this survey.

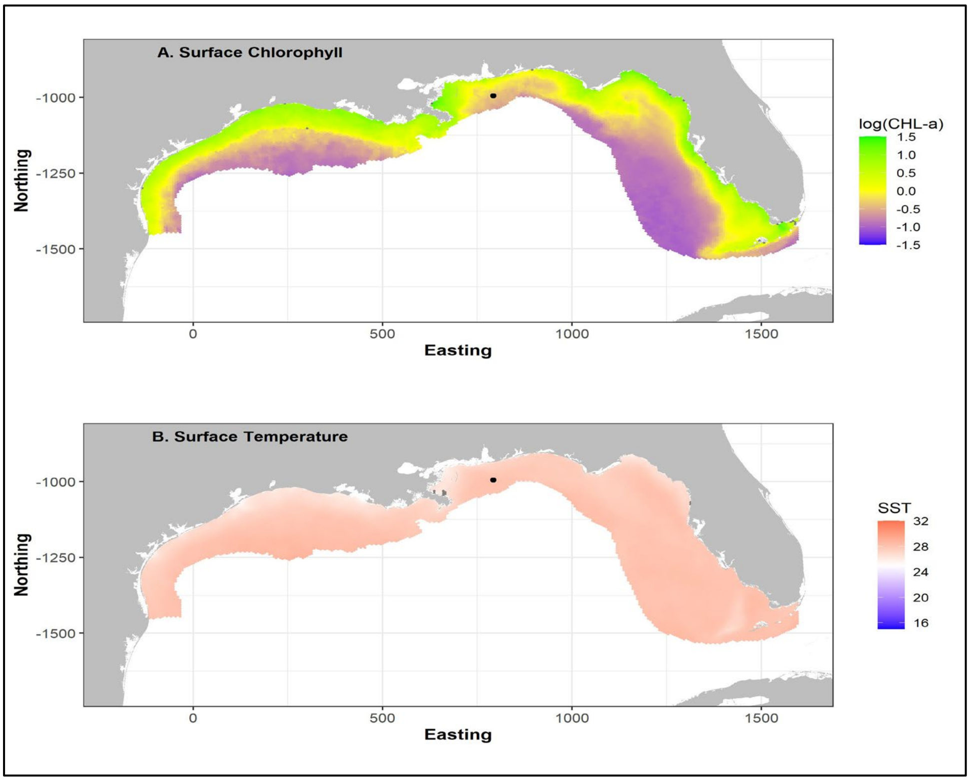

Figure D.2-8. Green turtle sightings during fall 2018.

D.2.3 Distance Analysis and Detection Probability

Detection probability within the surveyed strip was estimated using MRDS approaches. Covariates considered for inclusion in the detection function included sea state, cloud cover, water turbidity, and sun penetration. In addition, the correlation between ln(group size) and perpendicular sighting distance (PSD) was examined, but there was no relationship between group size and detection distances, so group size was not considered for inclusion in the model.

The best model was selected by first examining the distribution of PSD and selecting an appropriate right truncation distance and key function. Then, all combinations of detection covariates were considered for both the detection function and mark-recapture portion of the model, and the model with the lowest Akaike's Information Criterion (AIC) was selected. The best model used a hazard-rate key function with a right truncation distance of 200 m. Sun Penetration was included as a covariate in the distance component of the model. Sea state, Turbidity, and an interaction term with observer position were included in the mark-recapture component of the model (Table D.2-2).

Table D.2-2. Parameters included in the detection probability function

(MCDS = Multiple covariate distance sampling)

Model	Parameter	Estimate	SE
MCDS	MCDS Intercept	4.185	0.320
MCDS	Sun Penetration	0.254	0.181
MRDS	MRDS Intercept	-0.343	1.054
MRDS	Distance	0.004	0.007
MRDS	Observer	-0.156	0.280
MRDS	Sea State	-0.722	0.263
MRDS	Turbidity	0.818	0.449
MRDS	Distance x Observer	-0.007	0.003

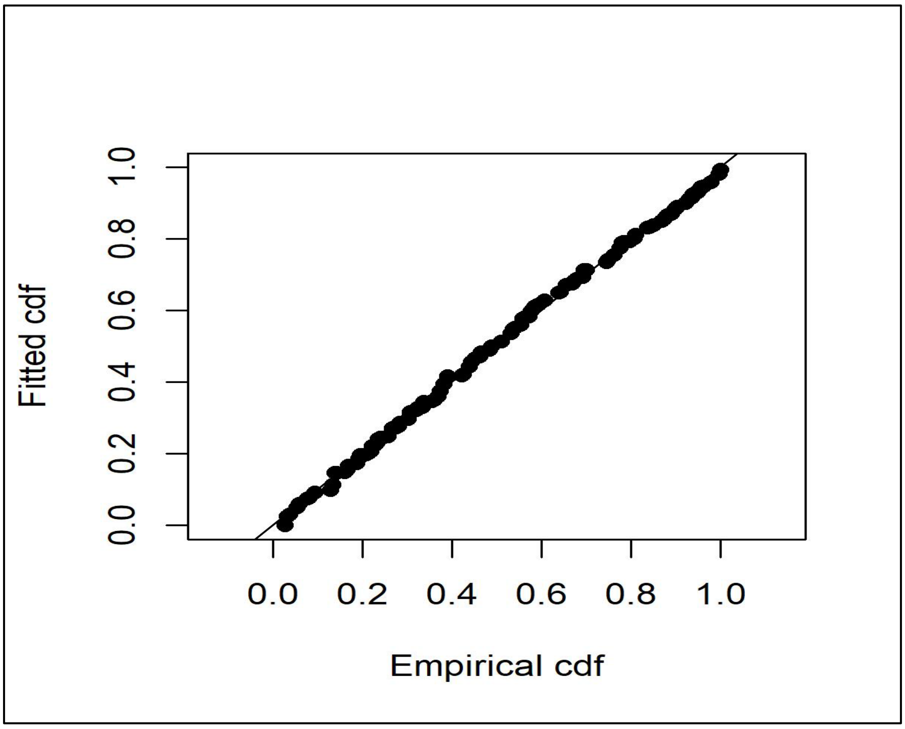

Figure D.2-9. MRDS detection function Q-Q plot.

(cdf = cumulative distribution function)

The resulting detection probability function had a good overall fit as indicated by the linear Quantile-Quantile (Q-Q) plot (Figure D.2-9). The Chi-square goodness of fit test p-value was 0.001 (Chi-square = 15.71, df = 3) indicating some deviation from the expected model especially in the mark-recapture component at high PSDs. However, the Cramer-von Mises test p-value was 0.884 (test statistic = 0.049) suggesting an adequate model fit overall.

The estimated detection probability on the trackline is shown in Table D.2-3, and the detection probability function is shown in Figure D.2-10.

Table D.2-3. Estimated detection probability and number of detections in the surveyed area from Multiple Covariate Distance function

Parameter	Estimate	SE	CV
Detection probability	0.610	0.037	0.061
Team 1 p(0)	0.348	0.095	0.273
Team 2 p(0)	0.317	0.086	0.271
Combined p(0)	0.530	0.119	0.225
Overall Avg. Detection Prob.	0.323	0.075	0.232

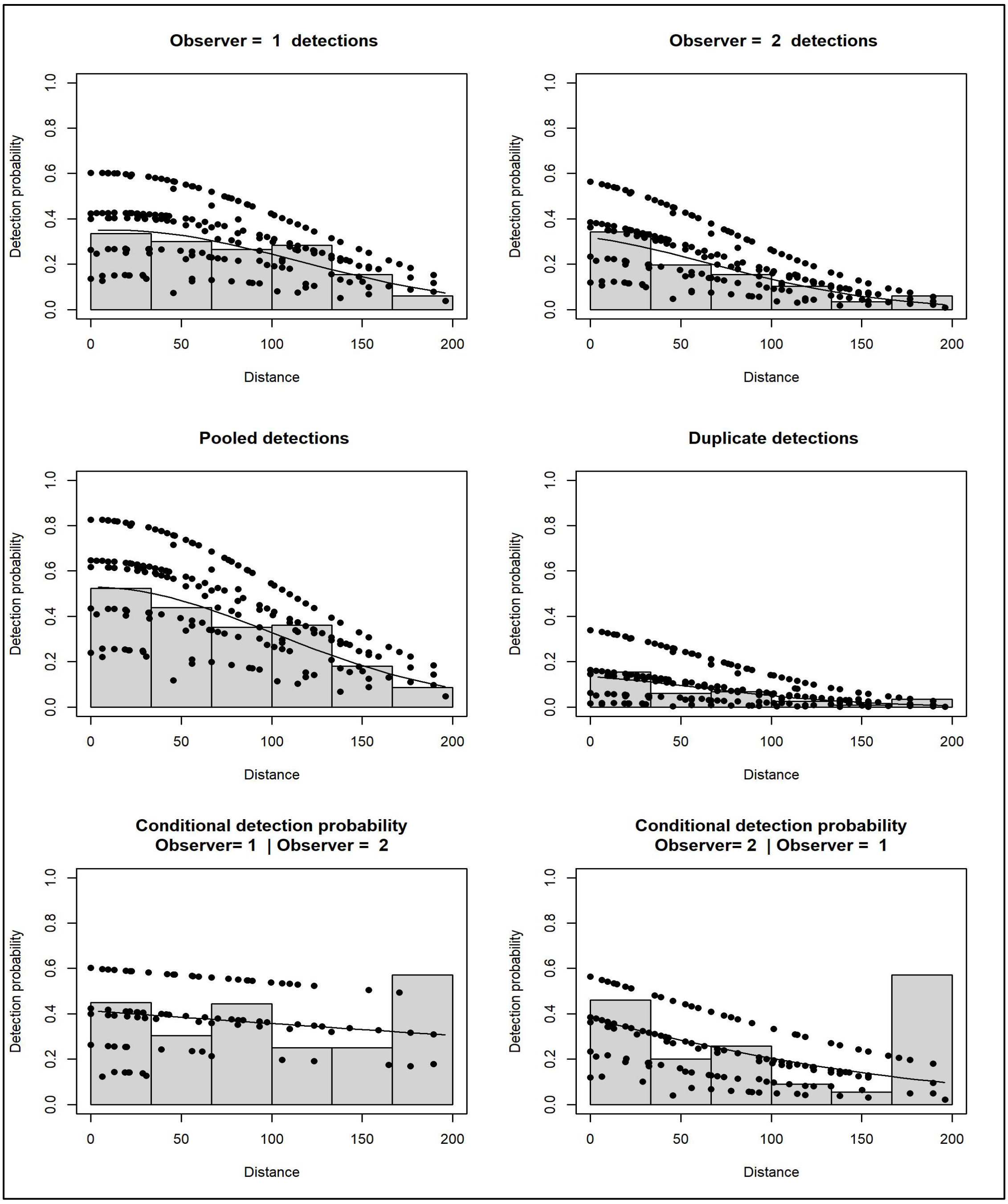

Figure D.2-10. Mark-recapture distance sampling detection probability.

D.2.3.1 Estimating Availability Bias

Green turtles spend a significant amount of time underwater where they are not available to be counted by aerial observers. The amount of time below the surface varies both spatially and temporally as a function of the behavioral state of the turtles (e.g., feeding compared to traveling) and in response to environmental conditions. To account for availability bias, we applied a generalized additive model (GAM) of green turtle occurrence in the upper 2 m of the water column based upon an extensive database of telemetry tag data (Roberts et al. 2022). This GAM used environmental variables to predict the probability that green turtles would be near the surface and available to the aerial survey team. For green turtles, significant environmental predictors of availability included season, sea surface temperature anomaly, water depth, the occurrence of fronts, and spatial location. The sample size for the green turtle availability model was relatively small and did not include some spatial areas where large numbers of turtles were observed in the aerial survey. As a result, extrapolation outside of the spatial range of the model resulted in extremely low predicted availability values. To avoid biases associated with extrapolation, a lower bound of 0.15 was applied. The probability that each turtle observed in the aerial survey was near the surface was predicted based upon the environmental conditions at the time of observation (Figure D.2-11). The median probability that a green turtle was at the surface was 0.744 (Inter-quartile range: 0.609–0.818). The number of turtles observed at the location was divided by the estimated probability to account for availability to the survey team. This corrected number was the response variable in the SDM.

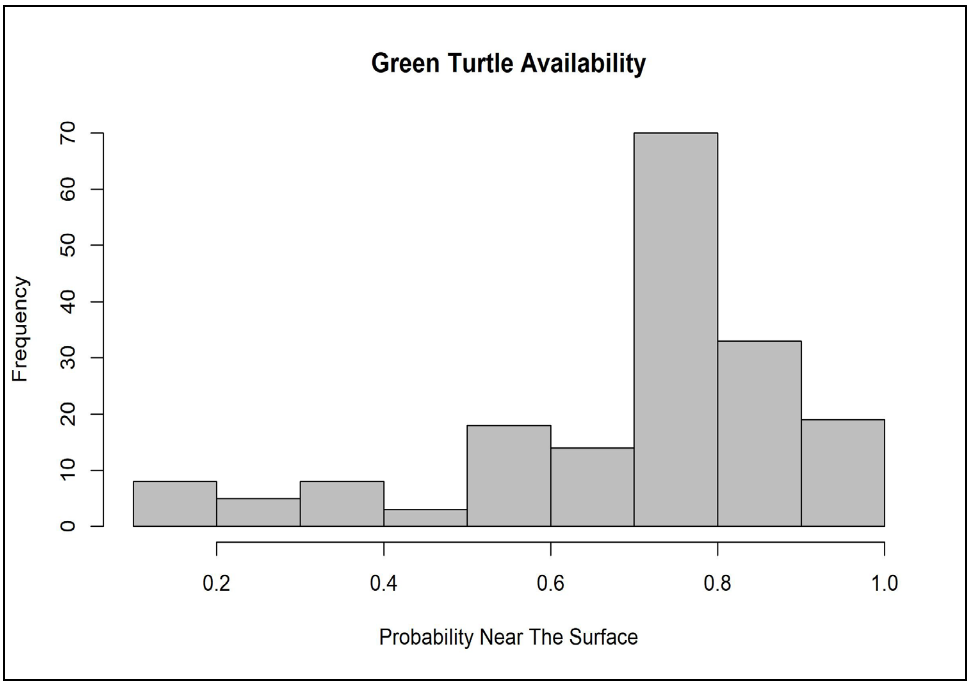

Figure D.2-11. Probability that green turtles observed during the aerial surveys were near the surface based upon a generalized additive model accounting for spatial and temporal variability in turtle dive behavior.

(Roberts et al. 2022).

D.2.4 Spatial Density Model Selection

A GAM was used to develop a spatial density model to describe the effect of habitat variables on the density and abundance of green turtles in the NGOM. Survey effort (kilometers of survey trackline) was partitioned into segments within a grid of hexagonal cells of 40 km^2 area and matched to physical oceanographic parameter values within each cell. Each resulting segment was considered a sampling unit within the GAM, and the number of animals observed on the segments was the response variable in a log count model assuming a Tweedie error distribution to account for overdispersed count data. An offset term (ln[strip area]) was included in the model to account for the effective area surveyed within each spatial cell based upon the detection probability function described above and covariates during the survey.

An initial GAM model was fit using all available oceanographic and physiographic variables. A reduced model was the selected including only model terms with p-value < 0.2. This reduced model was compared to the full model using AIC to ensure selection of the best fitting, most parsimonious model. Model fit was assessed through the examination of randomized quantile residuals and the associated Q-Q plot for deviance residuals.

For green turtles, the selected model included Average Depth (AvgDepth), Sea Surface Temperature (Avg_SST), log(chlorophyll-a concentration) (lAvg_Chl), Mixed Layer Depth (Avg_CMEMS_MLD), and the East-West coordinate (Easting) (Table D.2-4). In addition, a factor variable was included in the model to reflect the overall higher density of green turtles in the northeastern GOM compared to the northwestern GOM and a year class factor was included to reflect the lower overall density of green turtles observed in recent surveys. The model fit to the data was good with a generally linear Q-Q plot and few outlier residual values (Figure D.2-12).

Table D.2-4. Parameter estimates for the selected Generalized Additive Model

(EDF = effective degrees of freedom)

Term	EDF	Max..EDF	F.Statistic	P.value
s(AvgDepth)	0.979	9	1.822	< 0.001
s(lAvg_Chl)	2.681	9	2.379	< 0.001
s(Avg_SST)	1.005	9	2.04	< 0.001
s(Easting)	0.995	9	0.942	0.002
s(Avg_CMEMS_MLD)	0.926	9	1.295	< 0.001

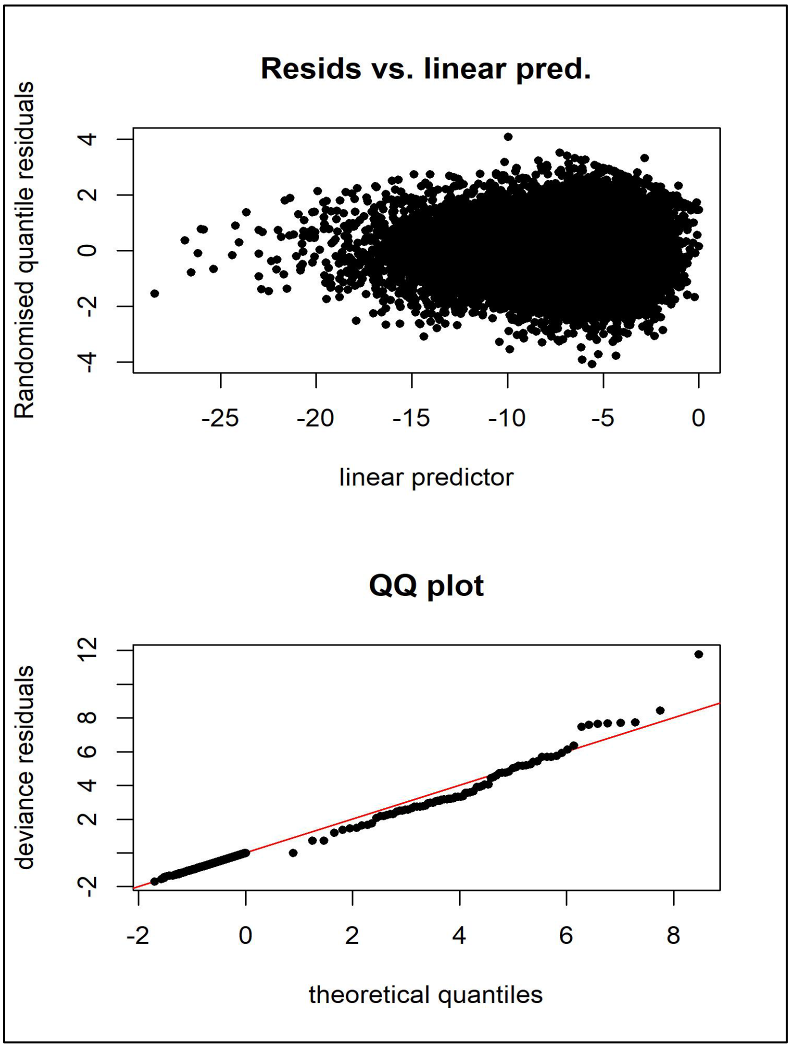

Figure D.2-12. GAM residual plots.

The selected model indicated that green turtle density was highest in waters close to shore and in warm water temperatures in the eastern GOM. The year class parameter was significant consistent with the relatively low number of identified green turtle sightings in the 2017–2018 aerial surveys (Figure D.2-13).

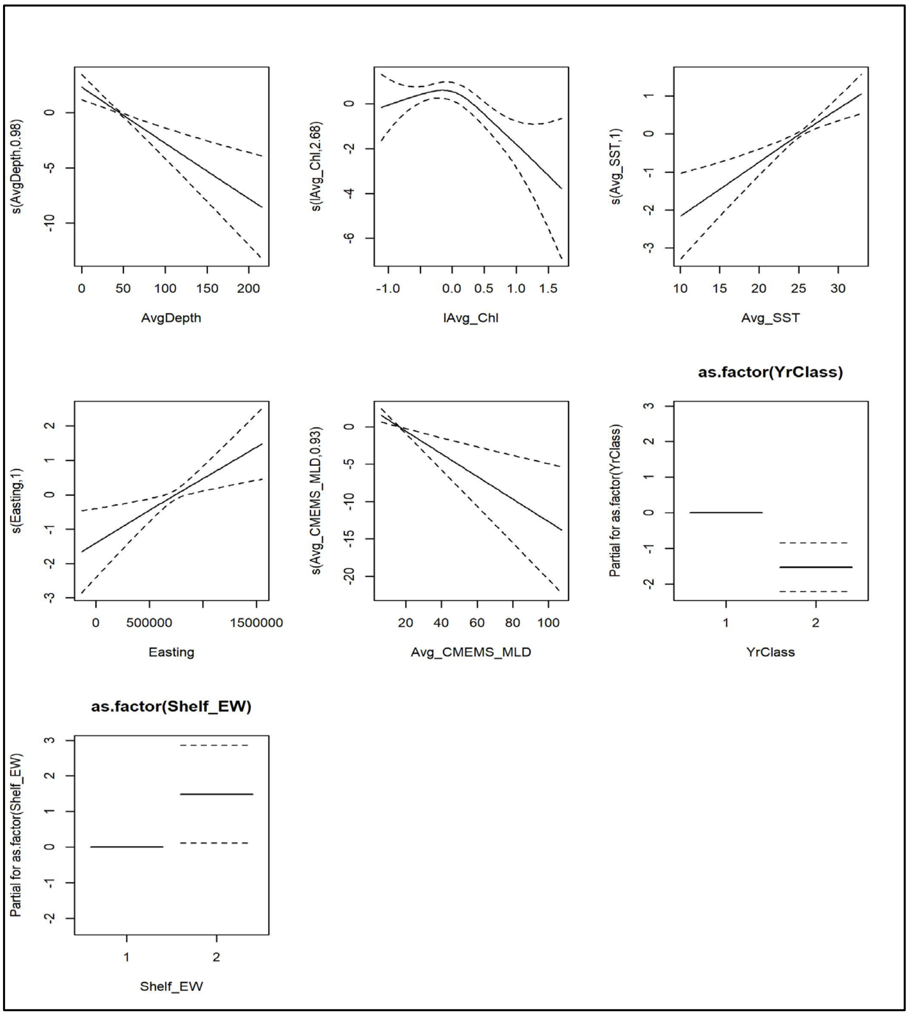

Figure D.2-13. GAM partial plots.

D.2.5 Spatial Density Model Prediction Maps and Model Output

Based upon the selected model, prediction maps were developed based upon monthly average oceanographic variable values for 2018. The estimated uncertainty (coefficient of variation [CV]) reflects only uncertainty in the GAM model fit and does not account for uncertainty in the detection probability function.

D.2.5.1 Northern Gulf of Mexico

Monthly prediction maps demonstrate variability in animal density resulting from variability in the underlying physical oceanography (Figures D.2-14–D.2-25).

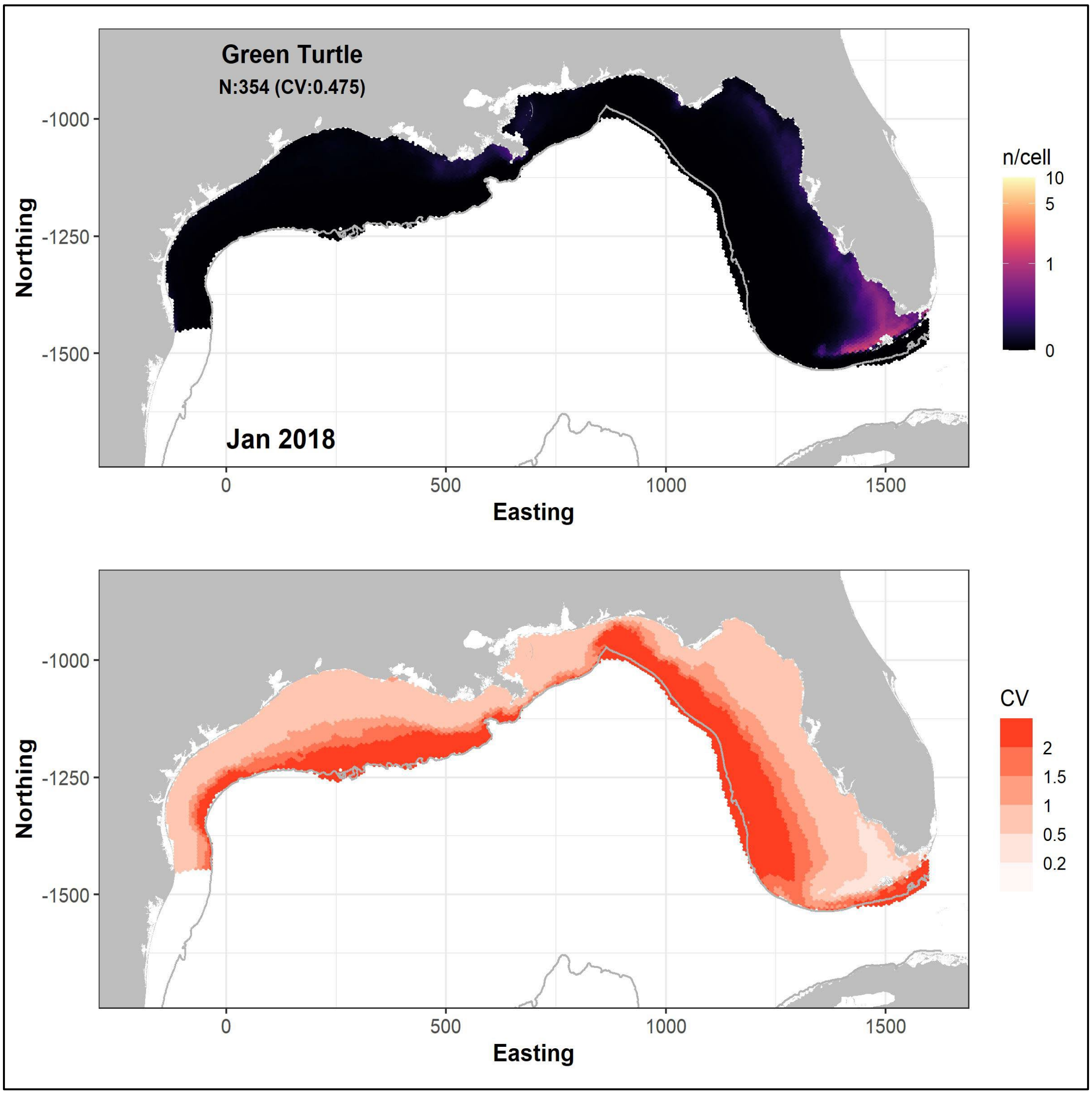

Figure D.2-14. Density model prediction for shelf green turtles in the NGOM in January 2018.

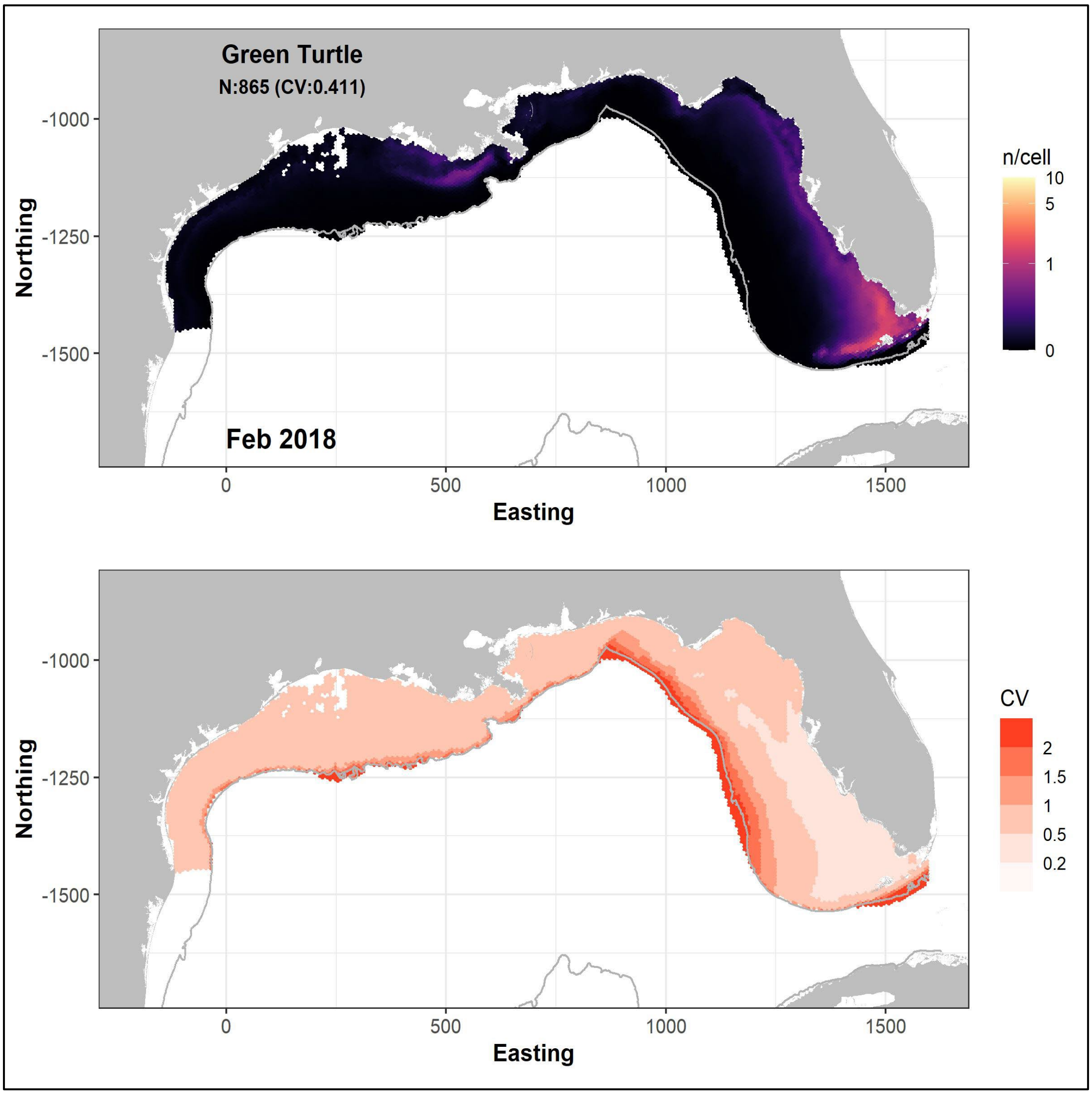

Figure D.2-15. Density model prediction for shelf green turtles in the NGOM in February 2018.

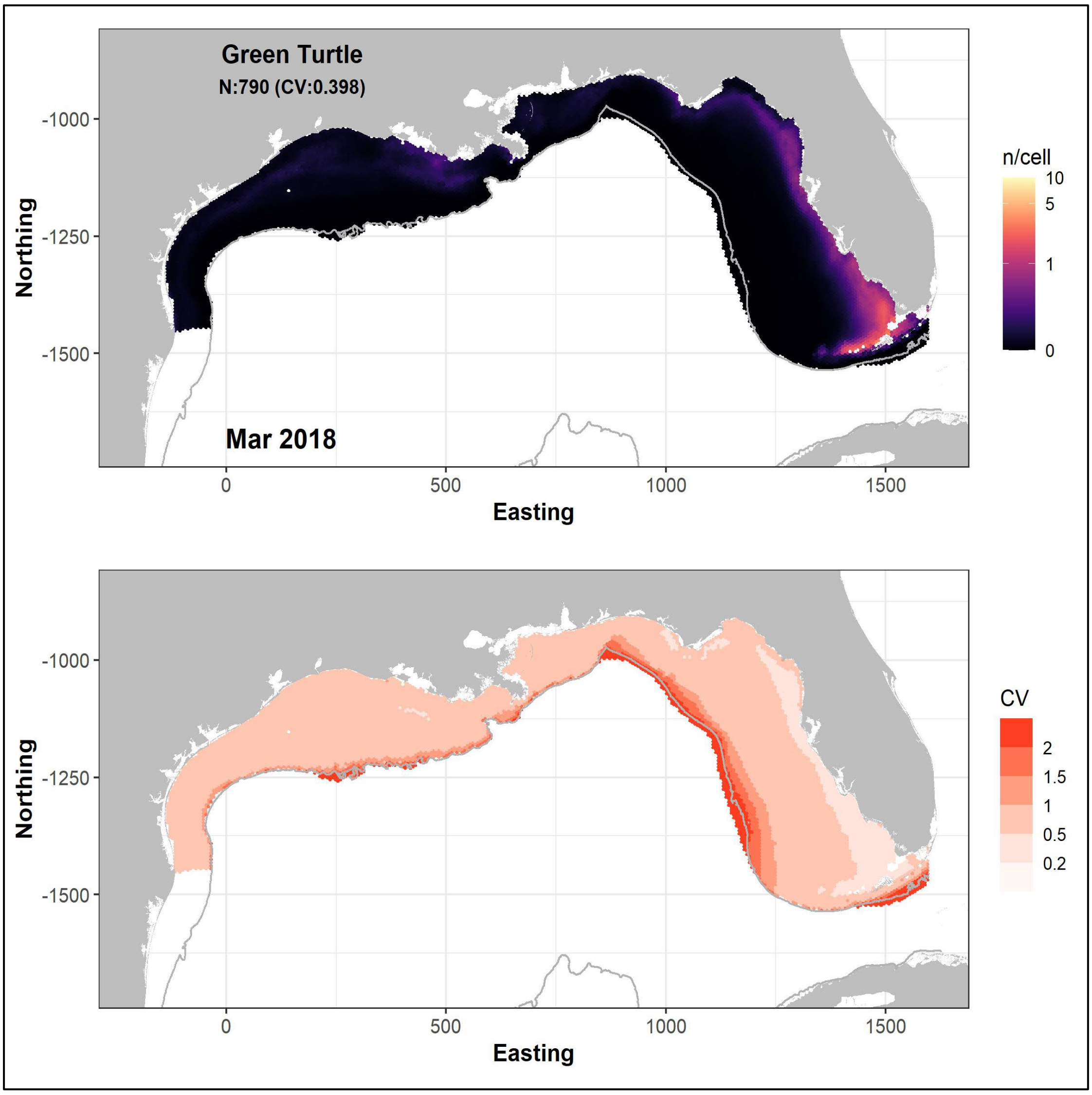

Figure D.2-16. Density model prediction for shelf green turtles in the NGOM in March 2018.

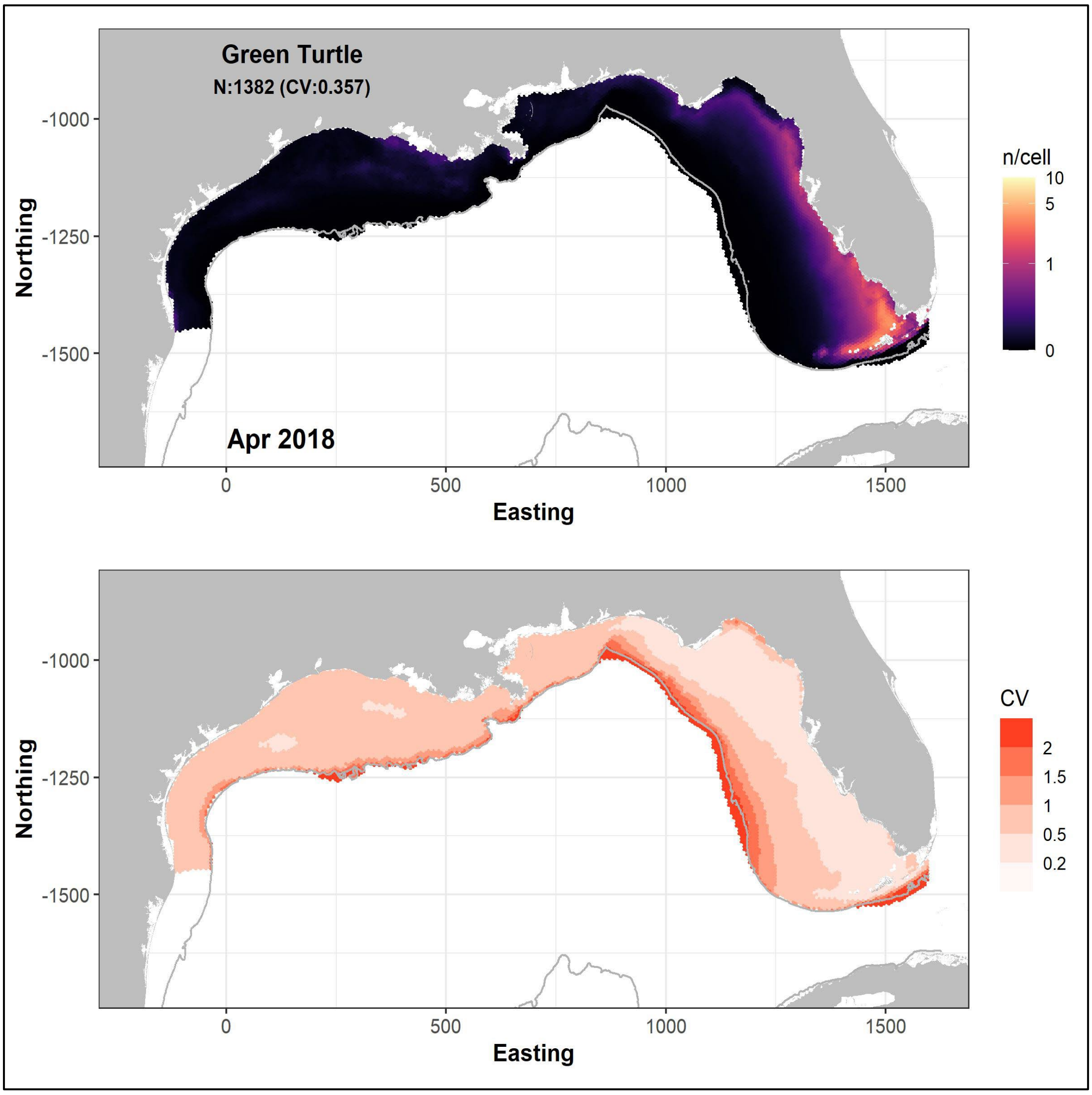

Figure D.2-17. Density model prediction for shelf green turtles in the NGOM in April 2018.

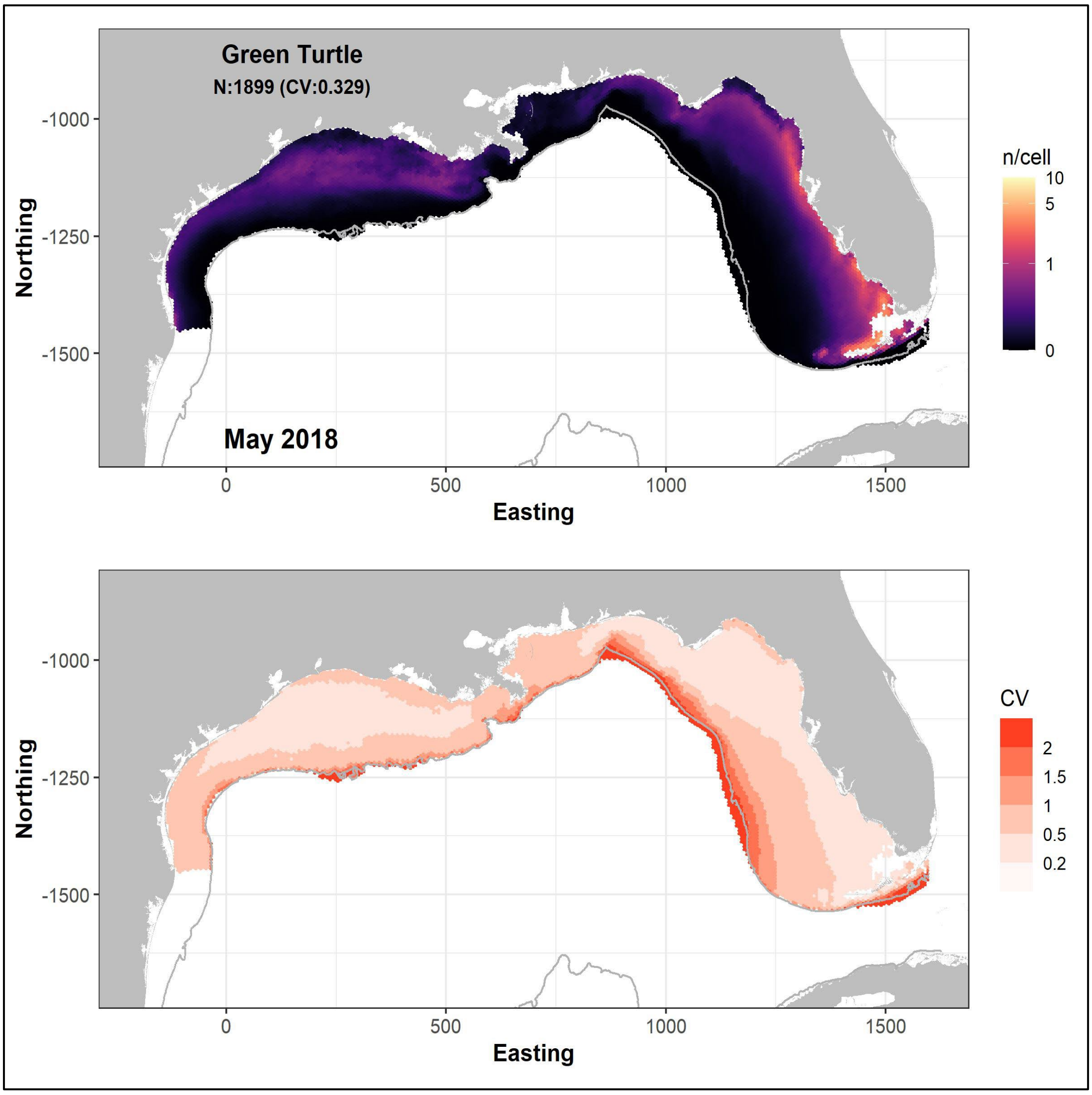

Figure D.2-18. Density model prediction for shelf green turtles in the NGOM in May 2018.

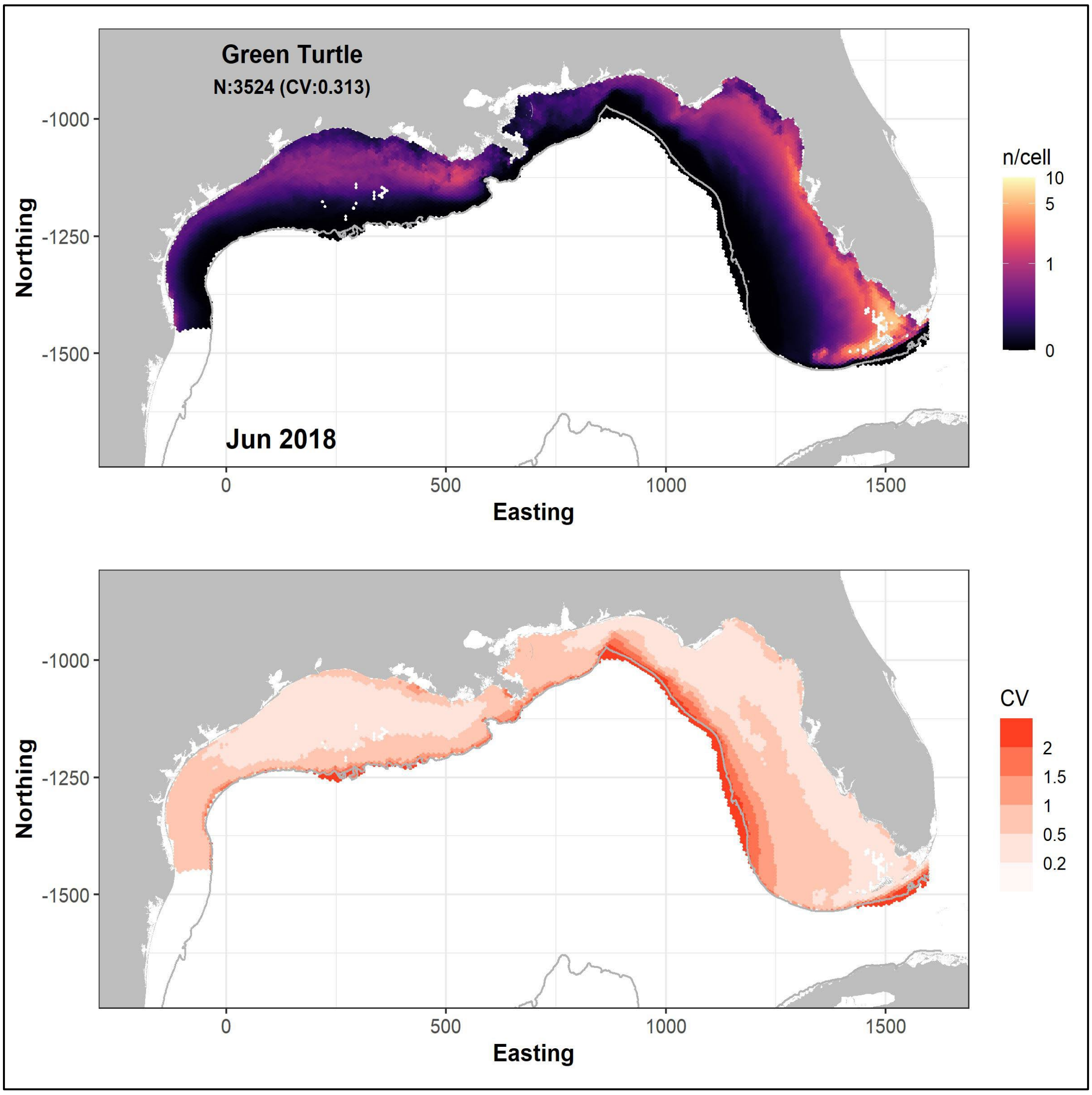

Figure D.2-19. Density model prediction for shelf green turtles in the NGOM in June 2018.

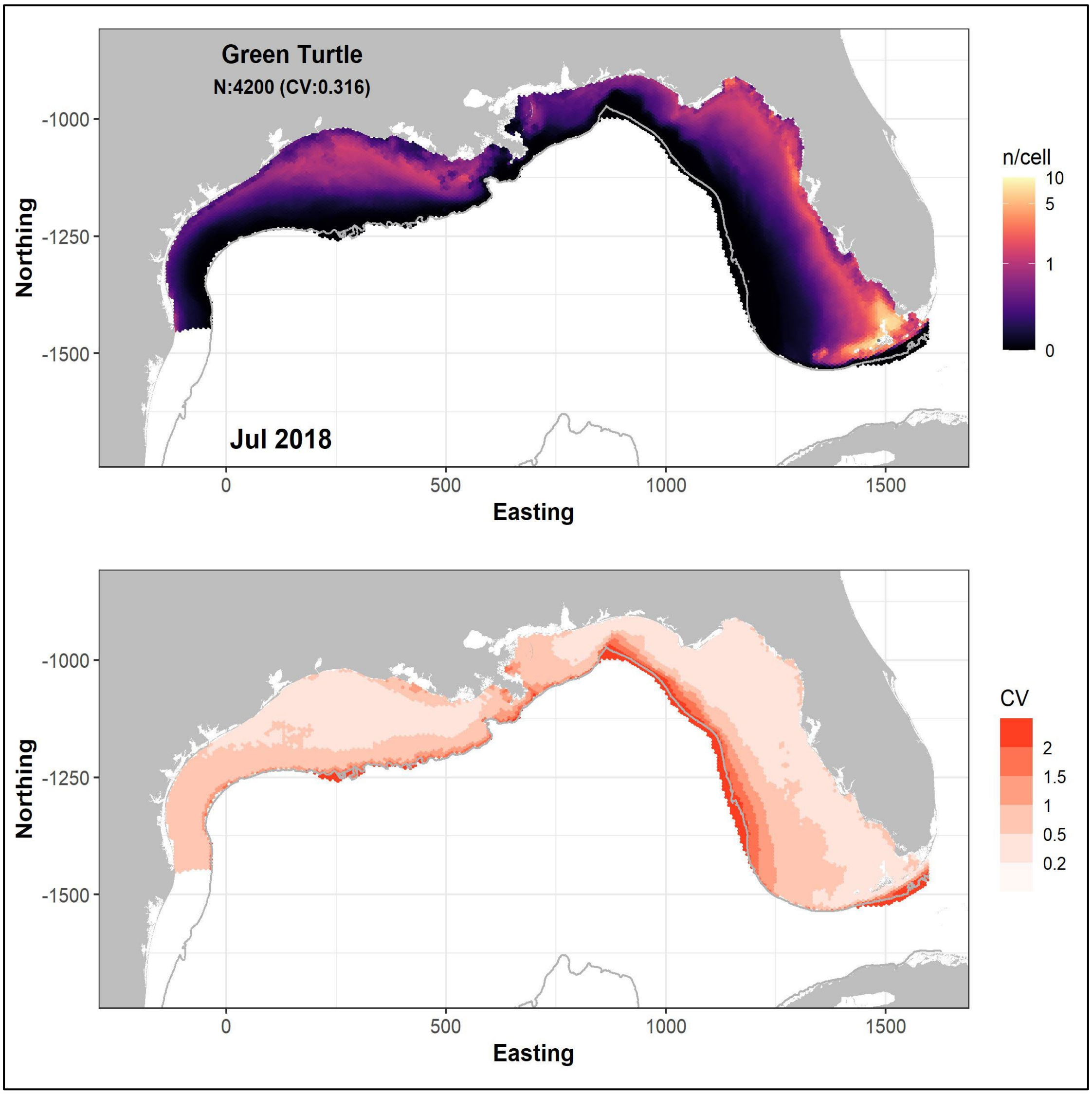

Figure D.2-20. Density model prediction for shelf green turtles in the NGOM in July 2018.

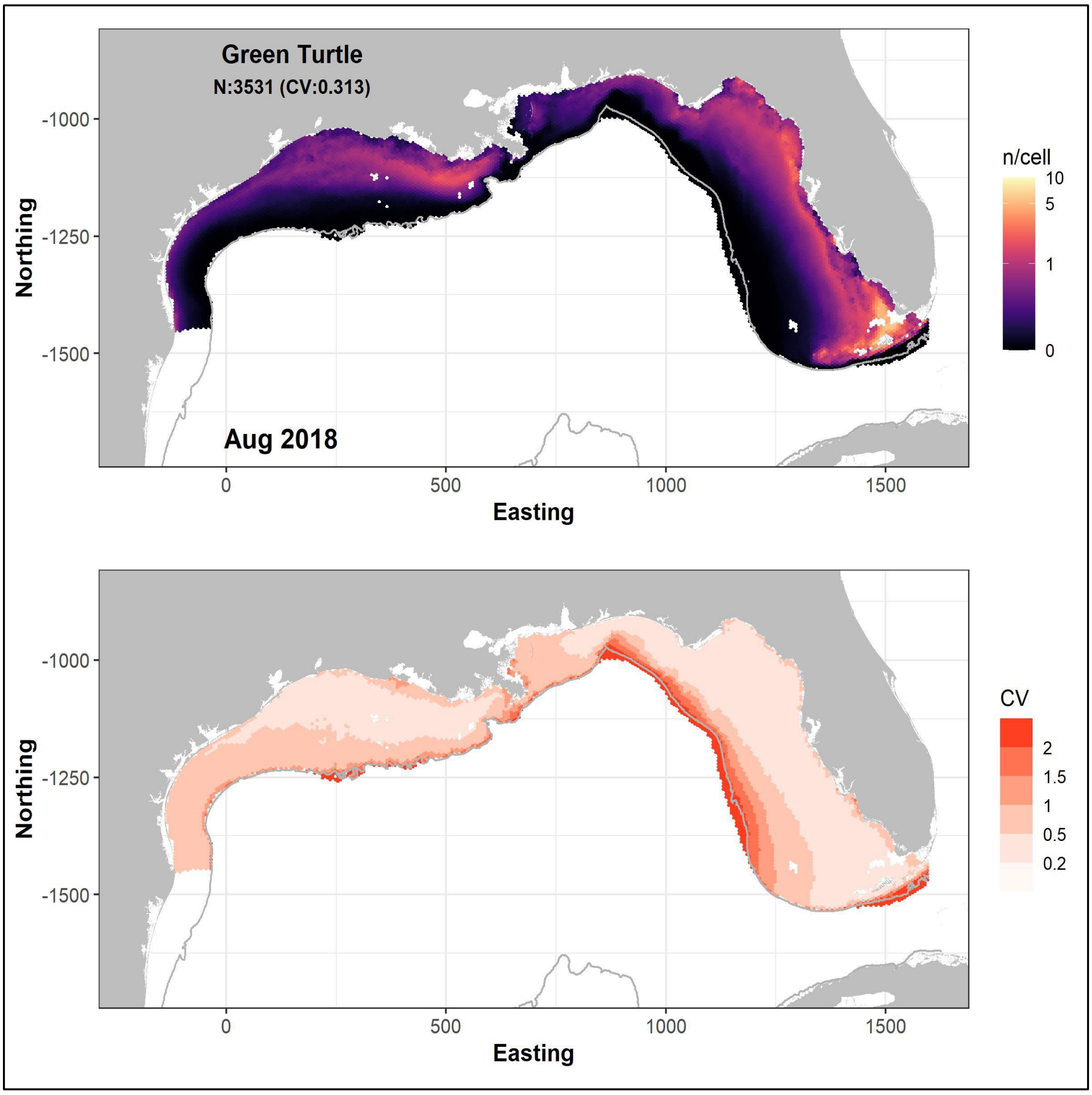

Figure D.2-21. Density model prediction for shelf green turtles in the NGOM in August 2018.

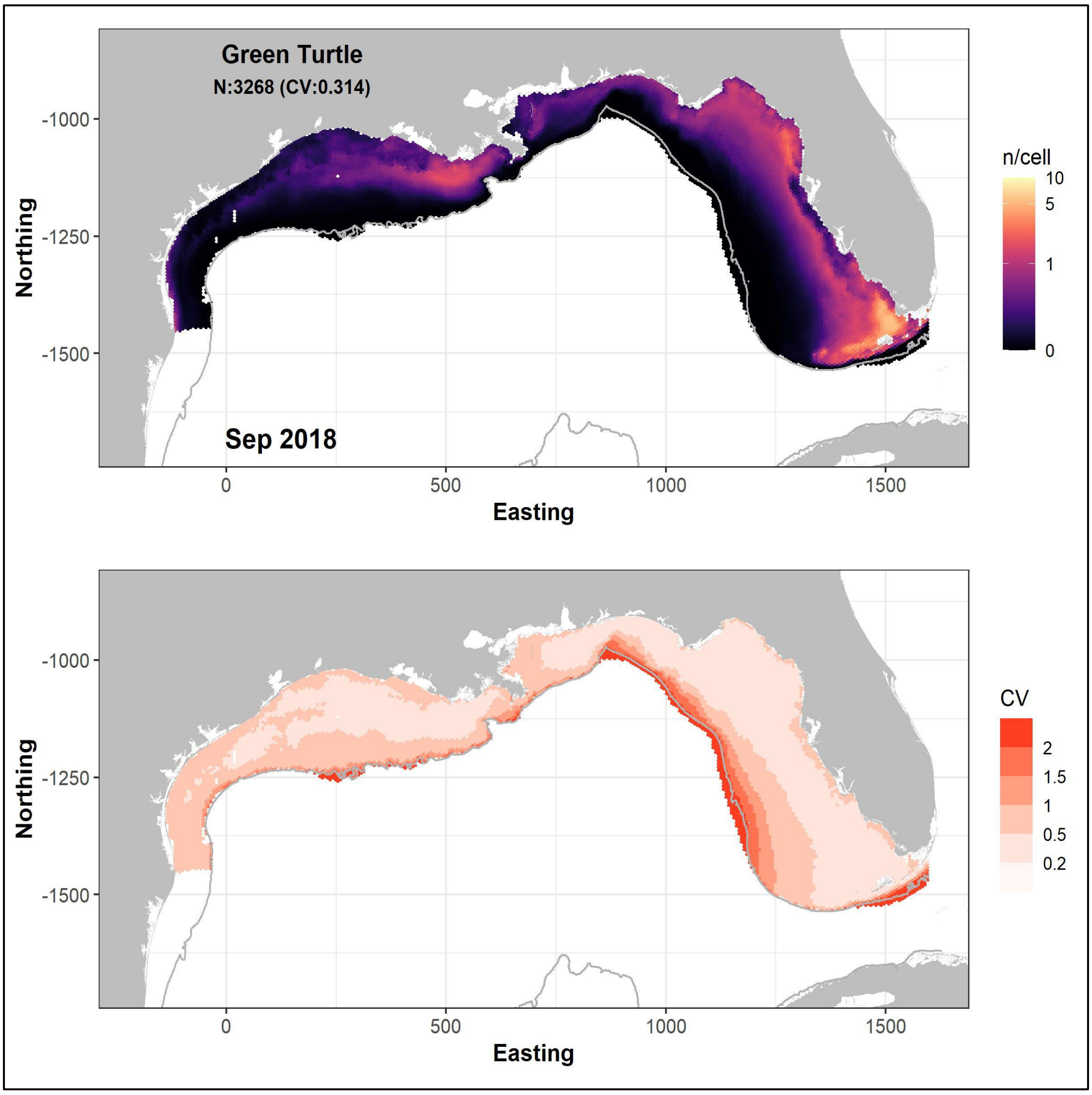

Figure D.2-22. Density model prediction for shelf green turtles in the NGOM in September 2018.

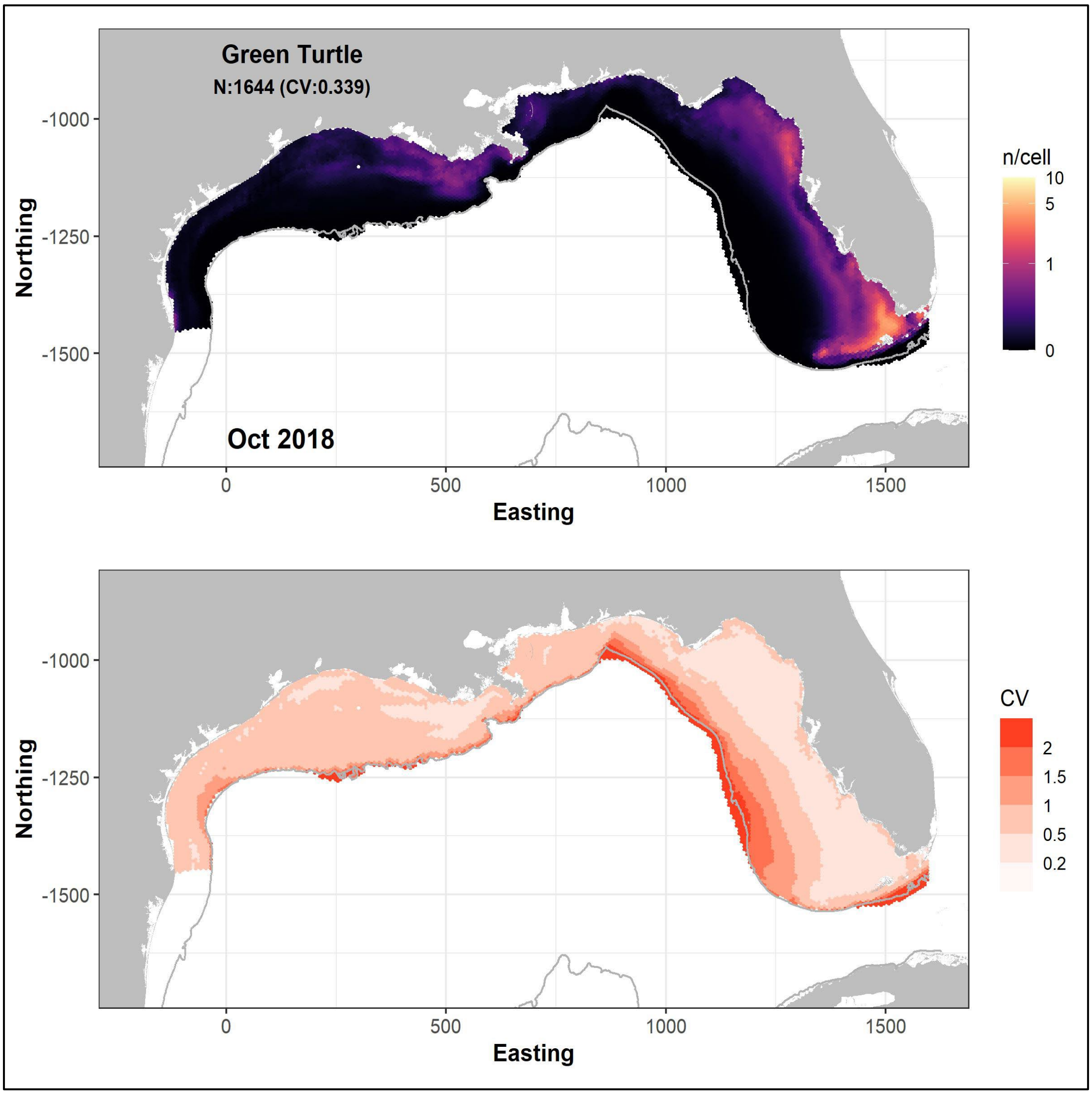

Figure D.2-23. Density model prediction for shelf green turtles in the NGOM in October 2018.

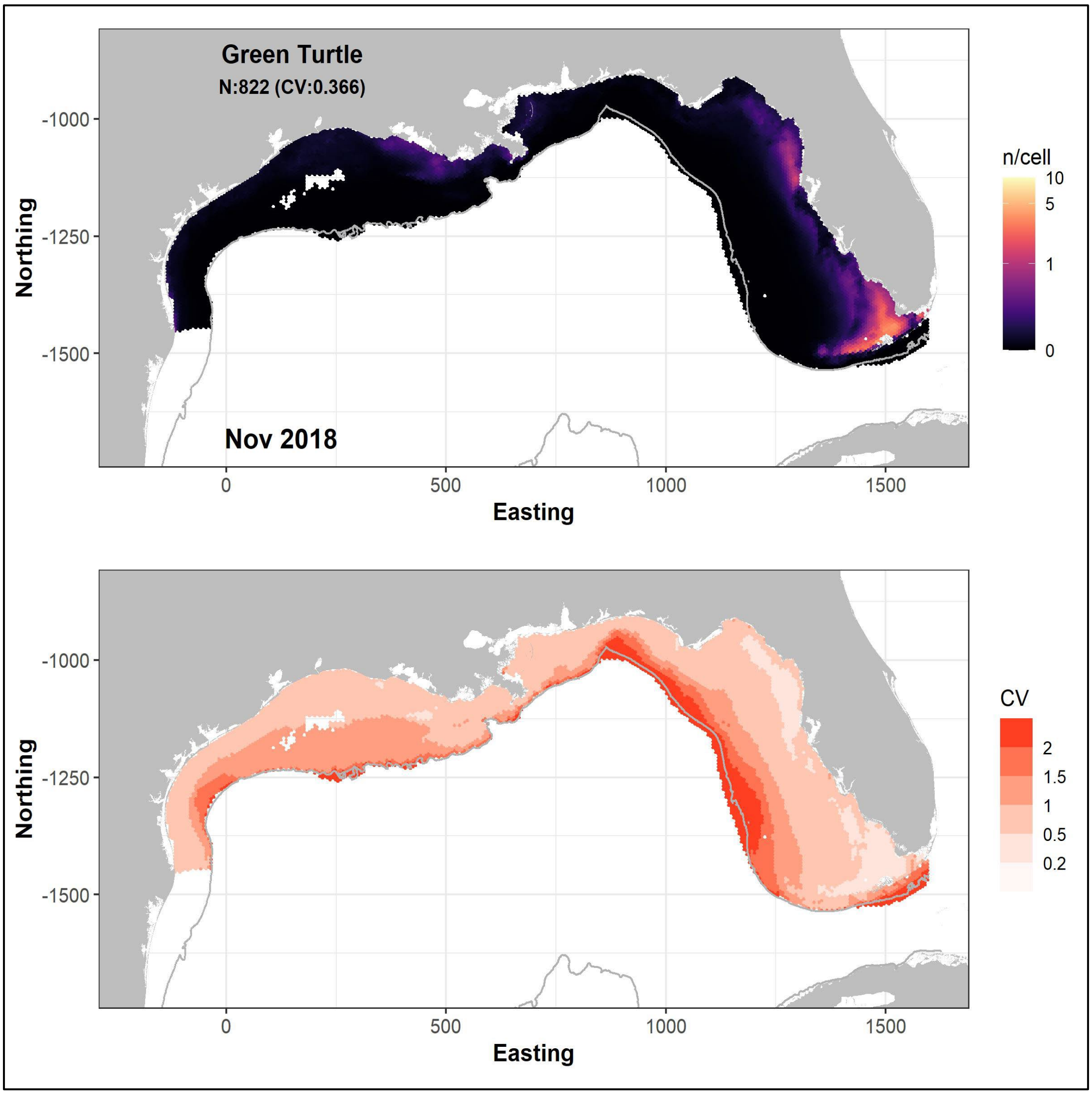

Figure D.2-24. Density model prediction for shelf green turtles in the NGOM in November 2018.

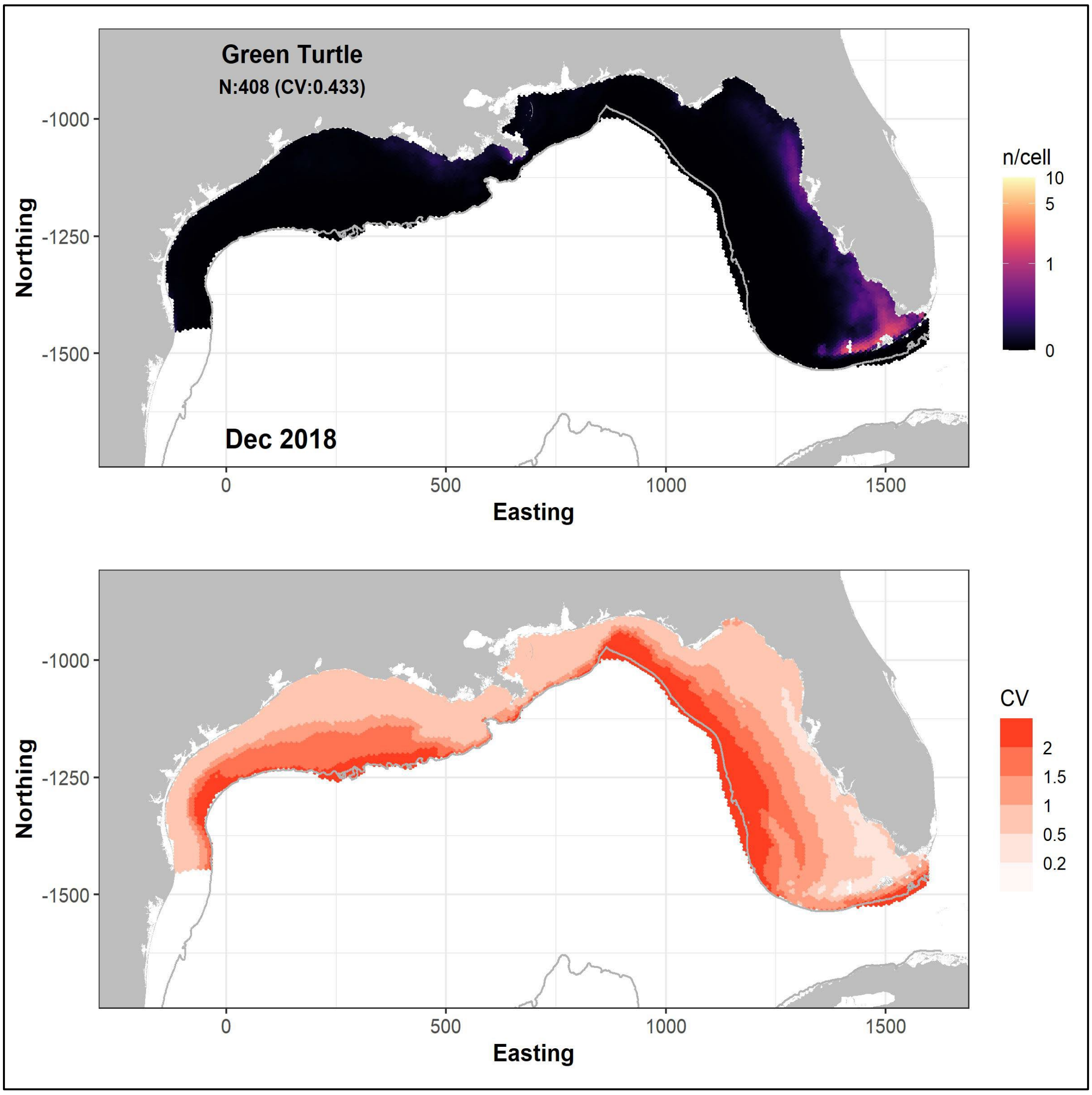

Figure D.2-25. Density model prediction for shelf green turtles in the NGOM in December 2018.

D.2.5.2 Inclusion of Unidentified Turtles

Aside from leatherbacks, sea turtles are difficult to identify reliably from the air, and observers are trained to make positive identification to species only when they feel confident in their identification. In particular, distinguishing between green turtles and loggerhead turtles requires careful observation. In addition, turtles are often observed just below the water surface or diving, making reliable identification more challenging. As a result, many of the observed turtles during the aerial surveys were identified only as "hardshell turtles". Incorporating these unidentified observations into density estimates is essential to developing unbiased estimates. To properly apportion unidentified turtles among species, a SDM model was developed for hardshell turtles. The resulting density of hardshell turtles were partitioned among the identified species based upon the relative predicted density of each species in each spatial cell. Monthly density maps for green turtles including both identified turtles and the proportion of unidentified turtles were generated (Figures D.2-26–D.2-37).

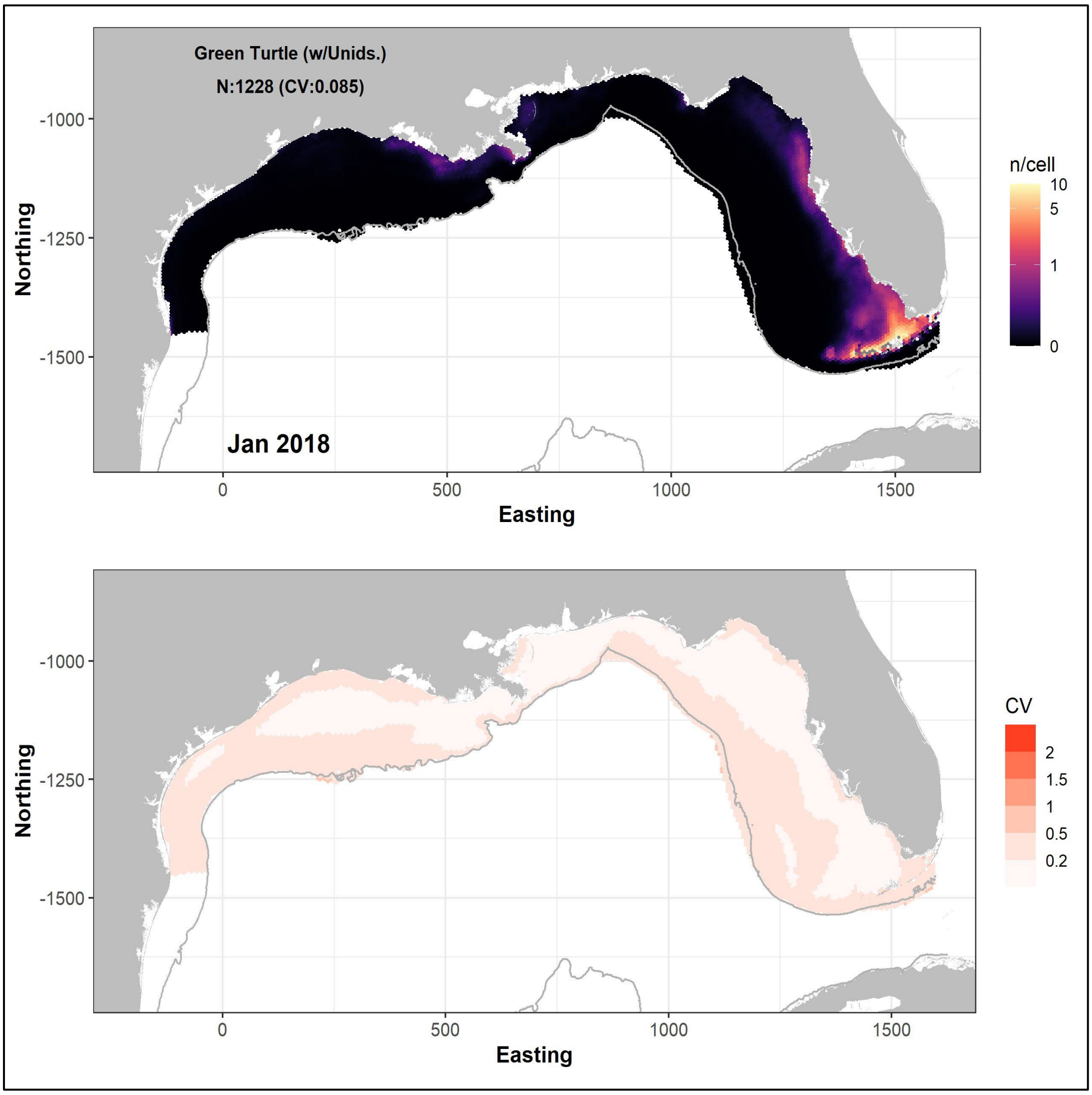

Figure D.2-26. Density model prediction for green turtles including apportioned unidentified turtles in the NGOM in January 2018.

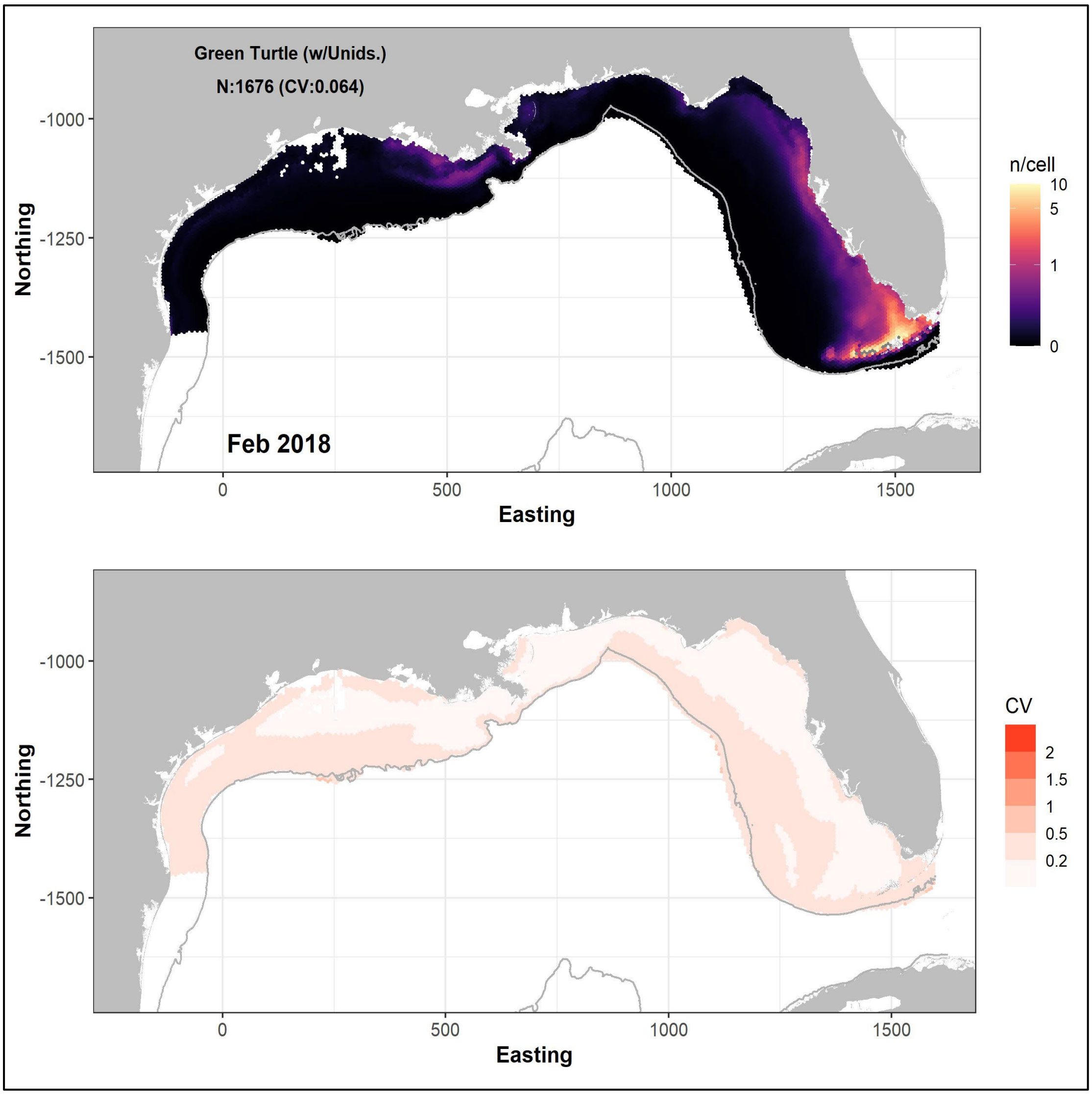

Figure D.2-27. Density model prediction for green turtles including apportioned unidentified turtles in the NGOM in February 2018.

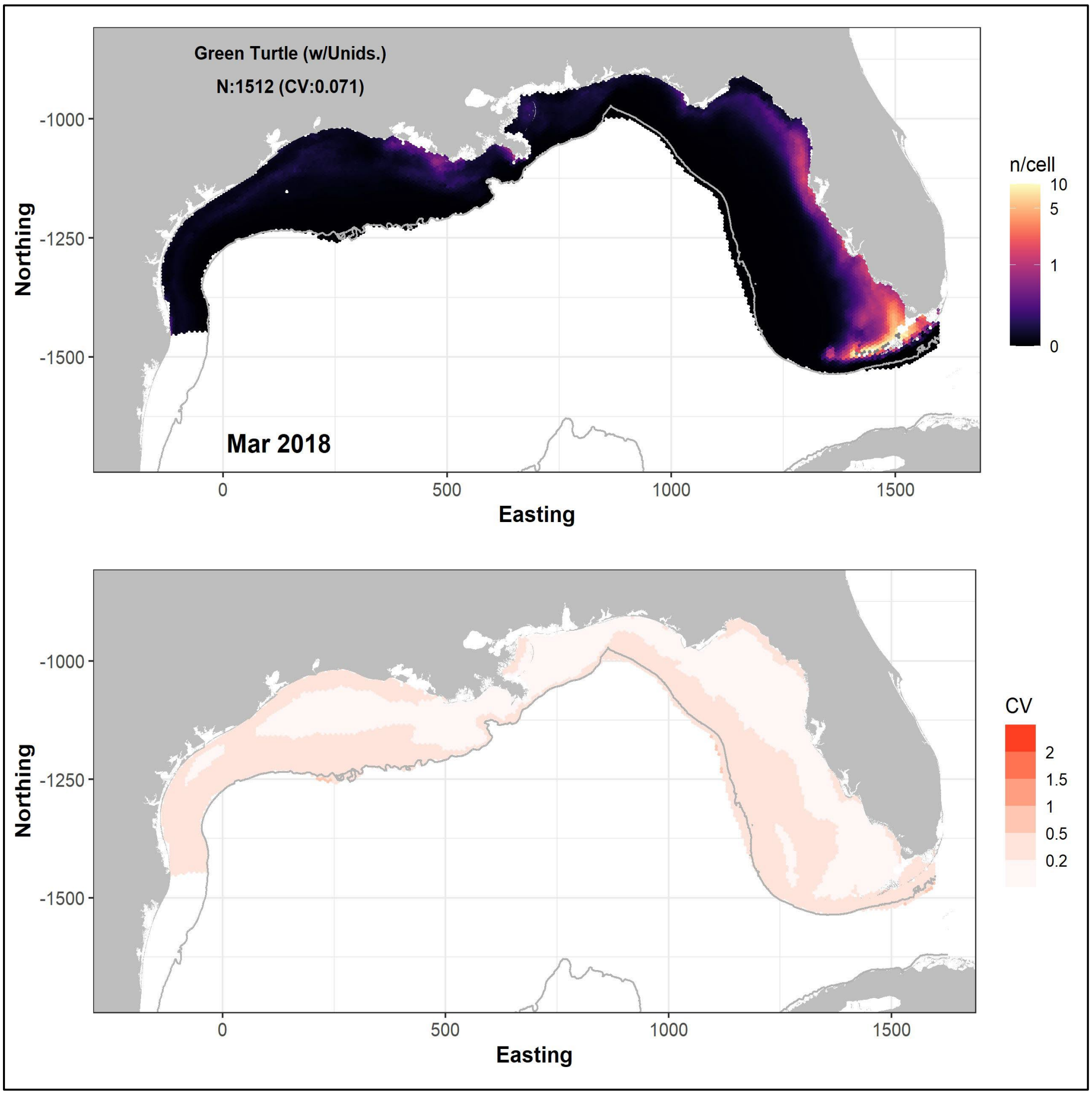

Figure D.2-28. Density model prediction for green turtles including apportioned unidentified turtles in the NGOM in March 2018.

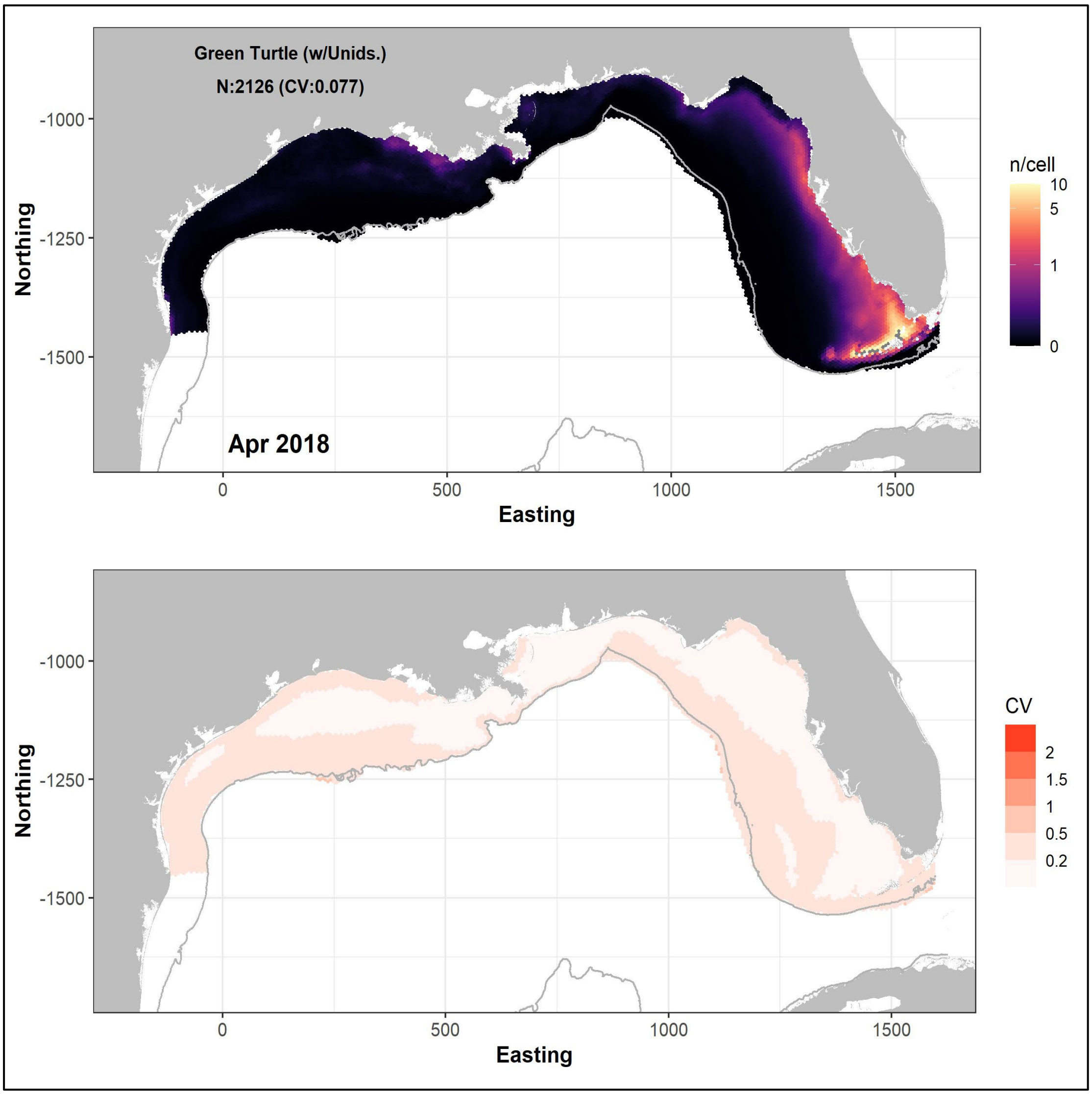

Figure D.2-29. Density model prediction for green turtles including apportioned unidentified turtles in the NGOM in April 2018.

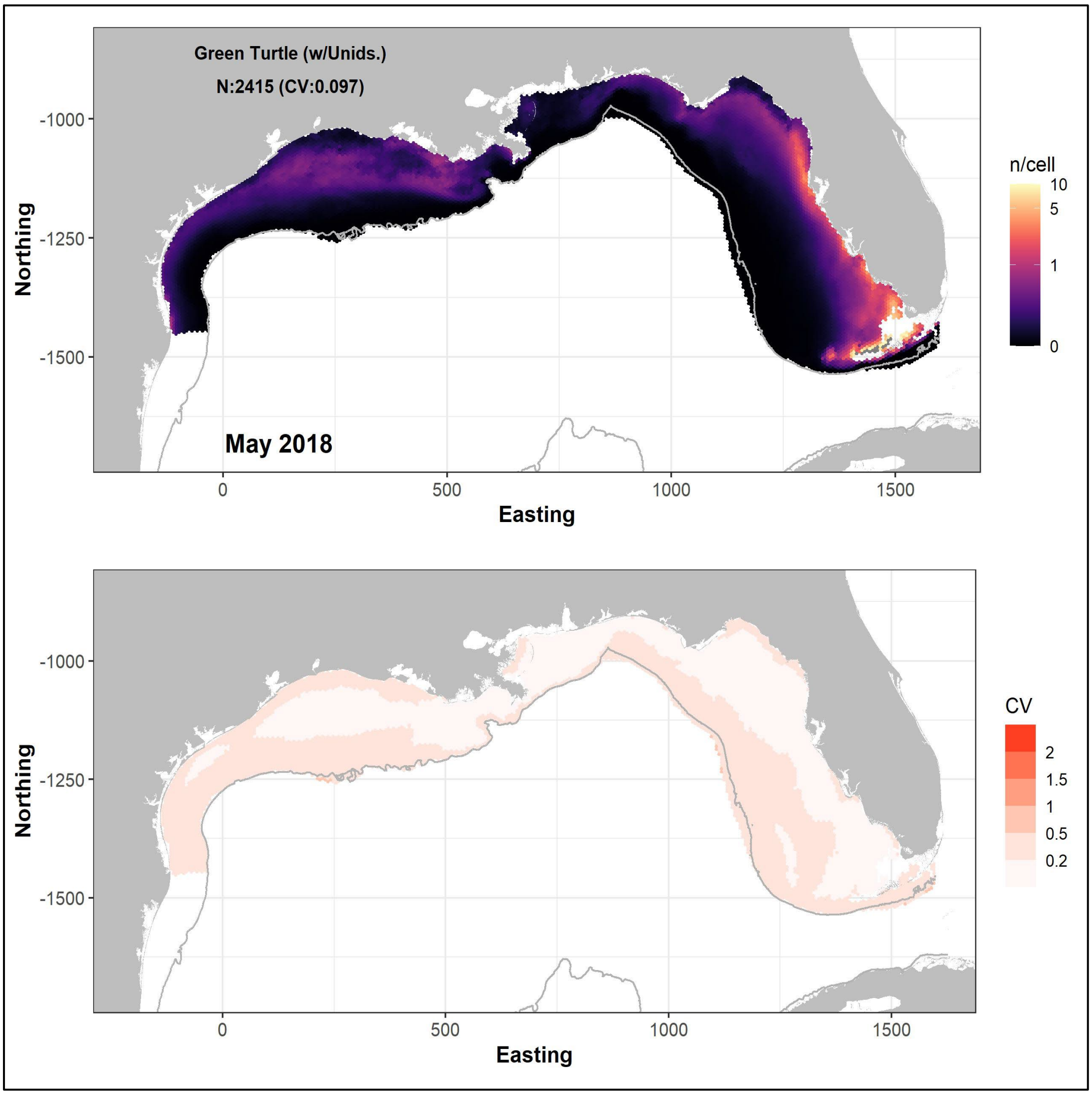

Figure D.2-30. Density model prediction for green turtles including apportioned unidentified turtles in the NGOM in May 2018.

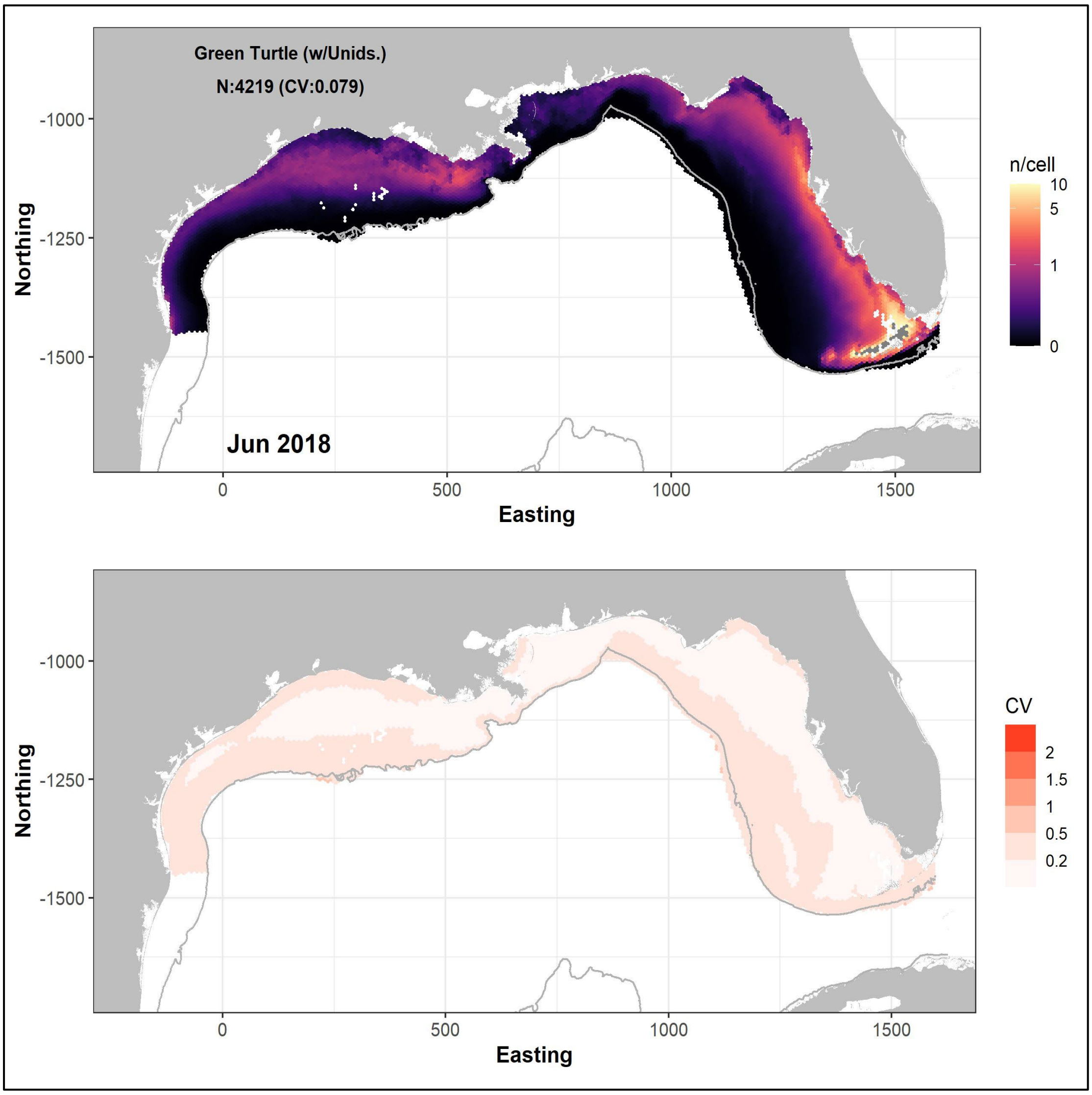

Figure D.2-31. Density model prediction for green turtles including apportioned unidentified turtles in the NGOM in June 2018.

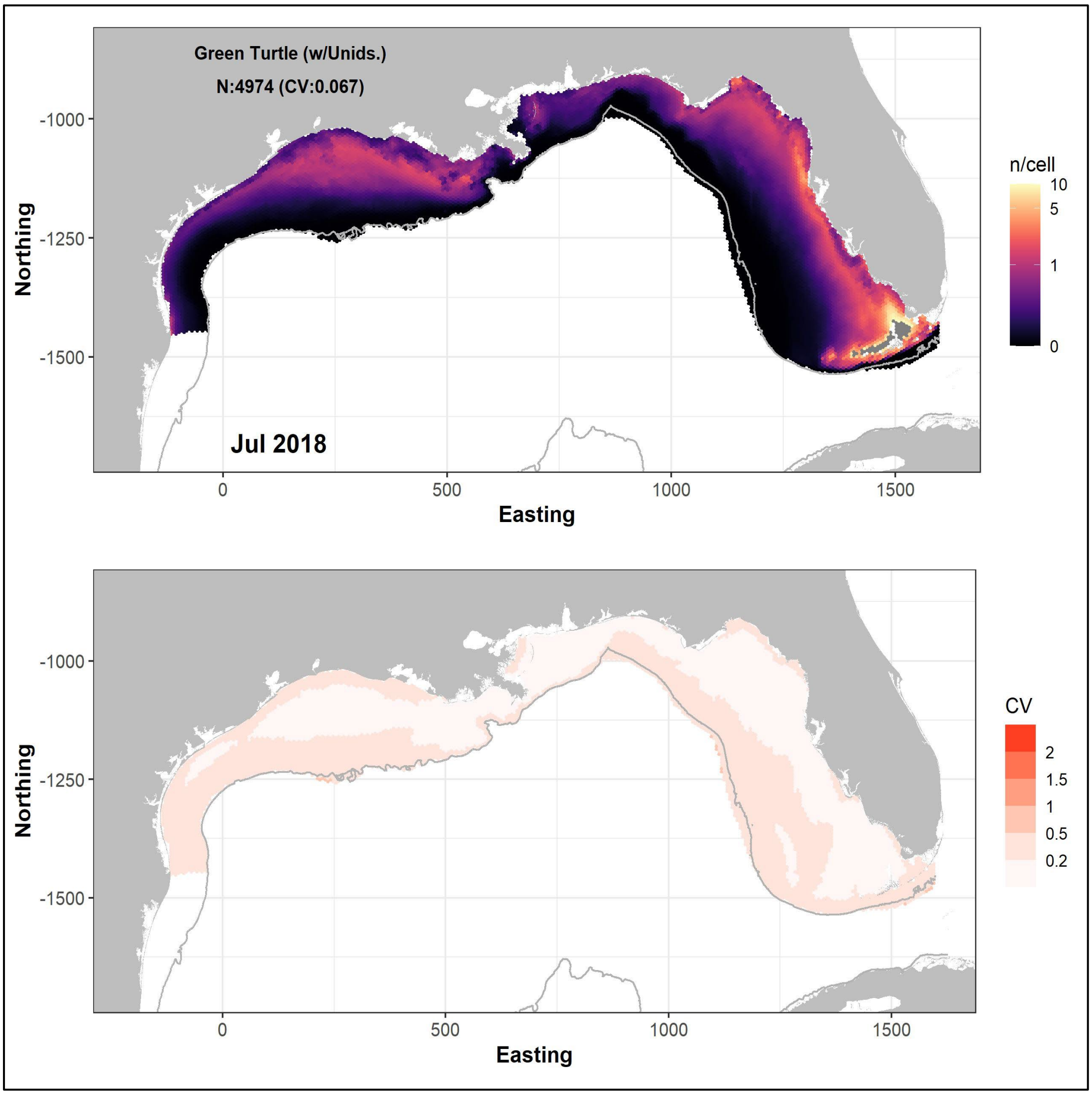

Figure D.2-32. Density model prediction for green turtles including apportioned unidentified turtles in the NGOM in July 2018.

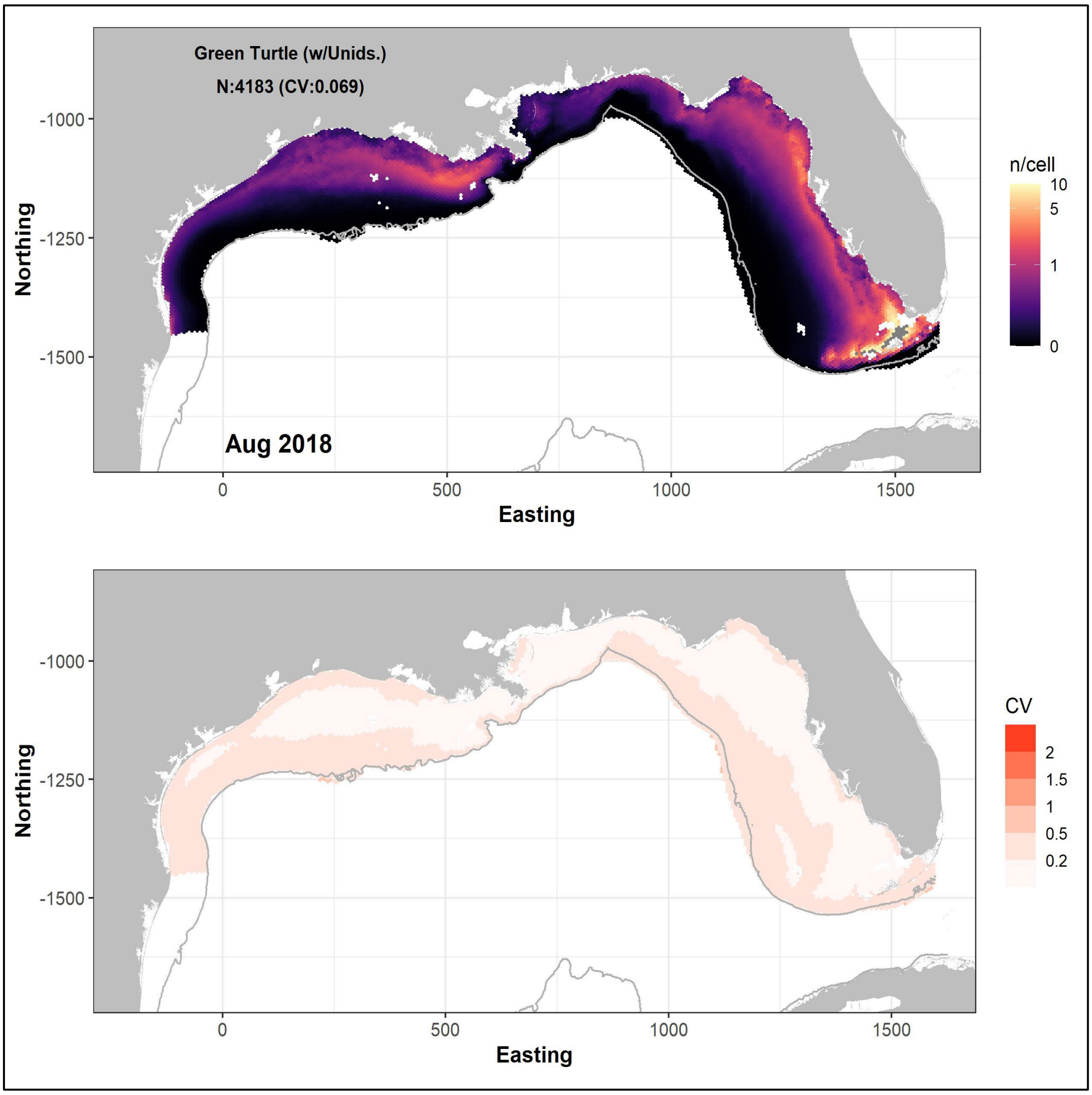

Figure D.2-33. Density model prediction for green turtles including apportioned unidentified turtles in the NGOM in August 2018.

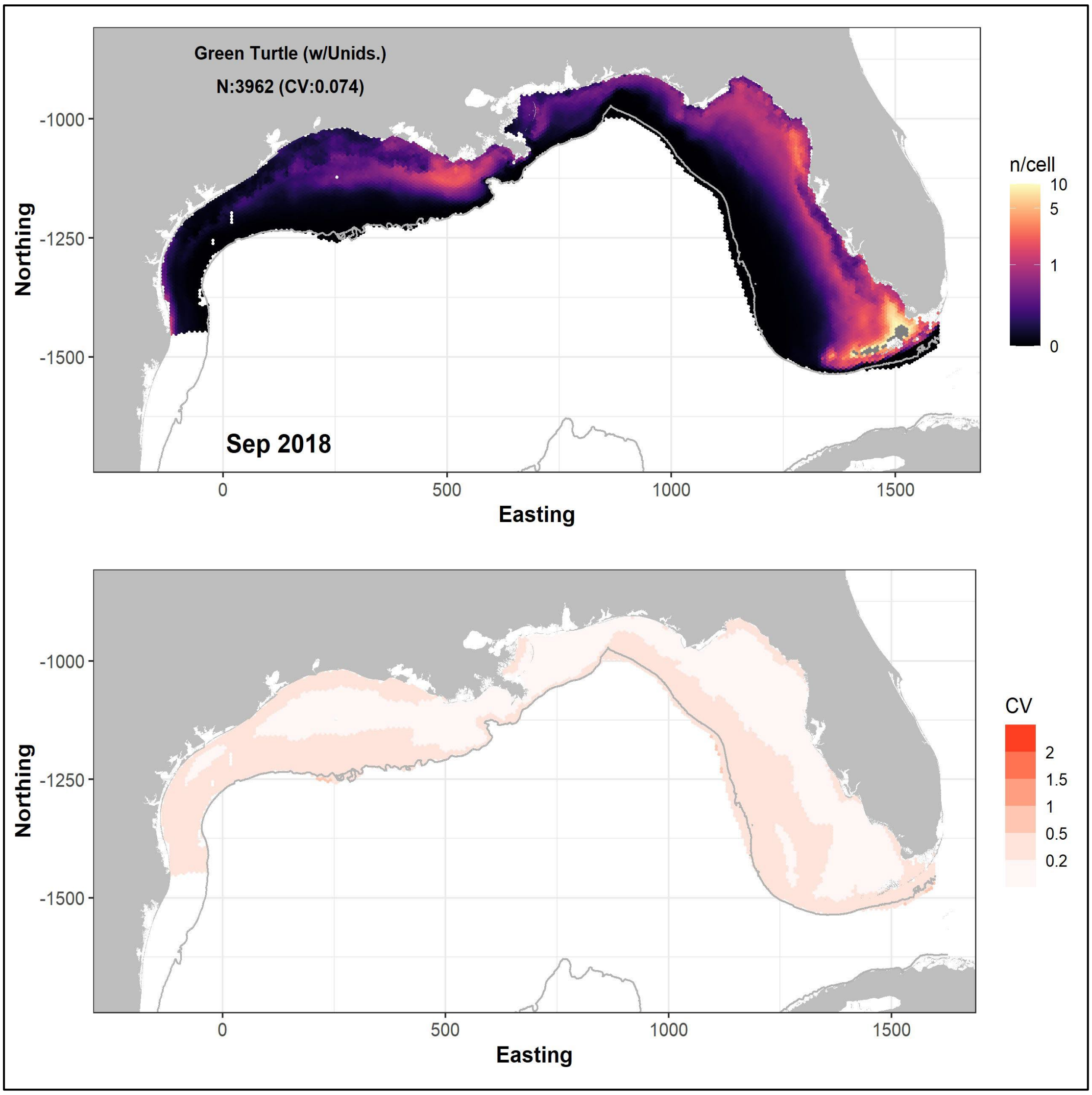

Figure D.2-34. Density model prediction for green turtles including apportioned unidentified turtles in the NGOM in September 2018.

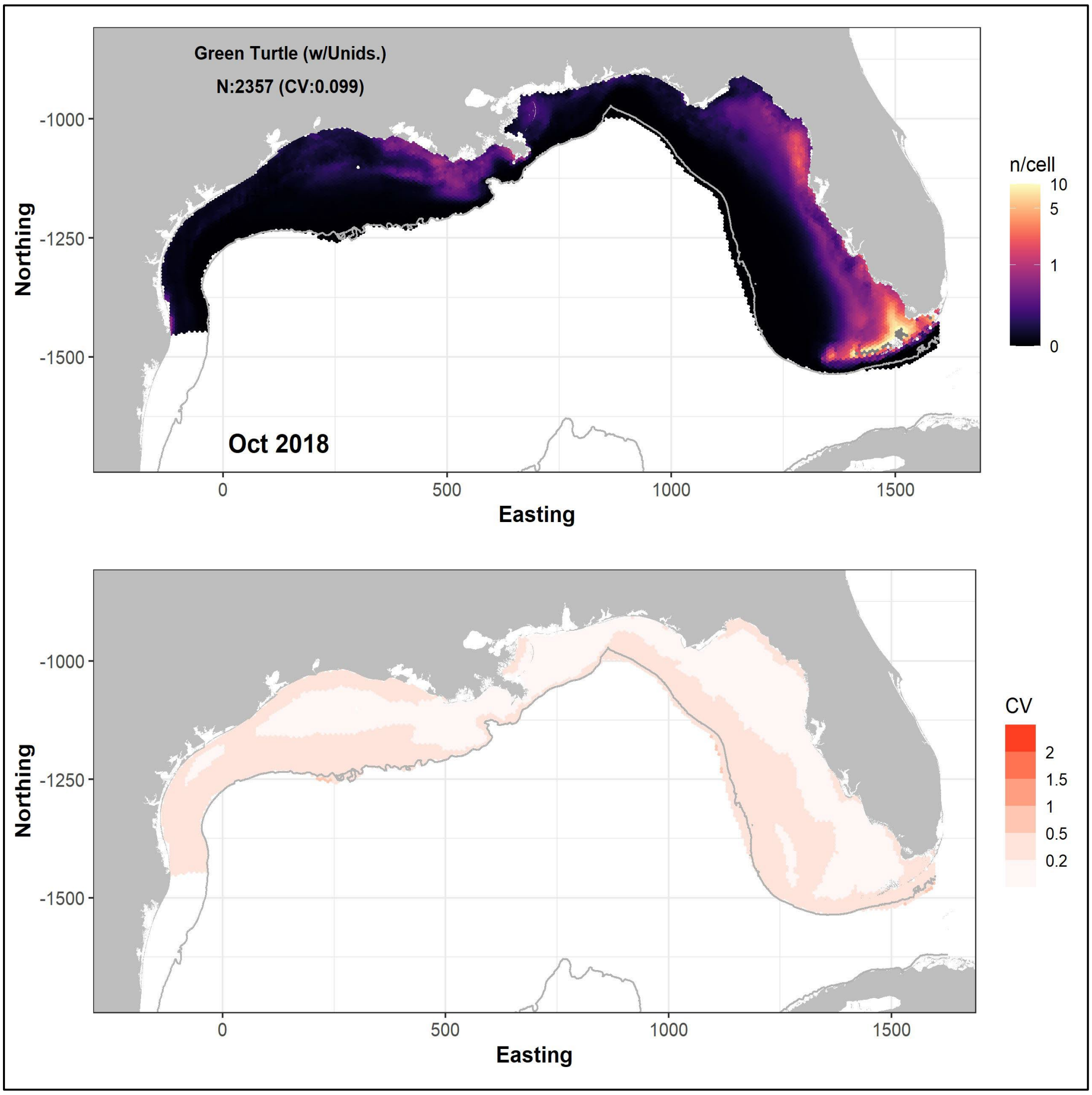

Figure D.2-35. Density model prediction for green turtles including apportioned unidentified turtles in the NGOM in October 2018.

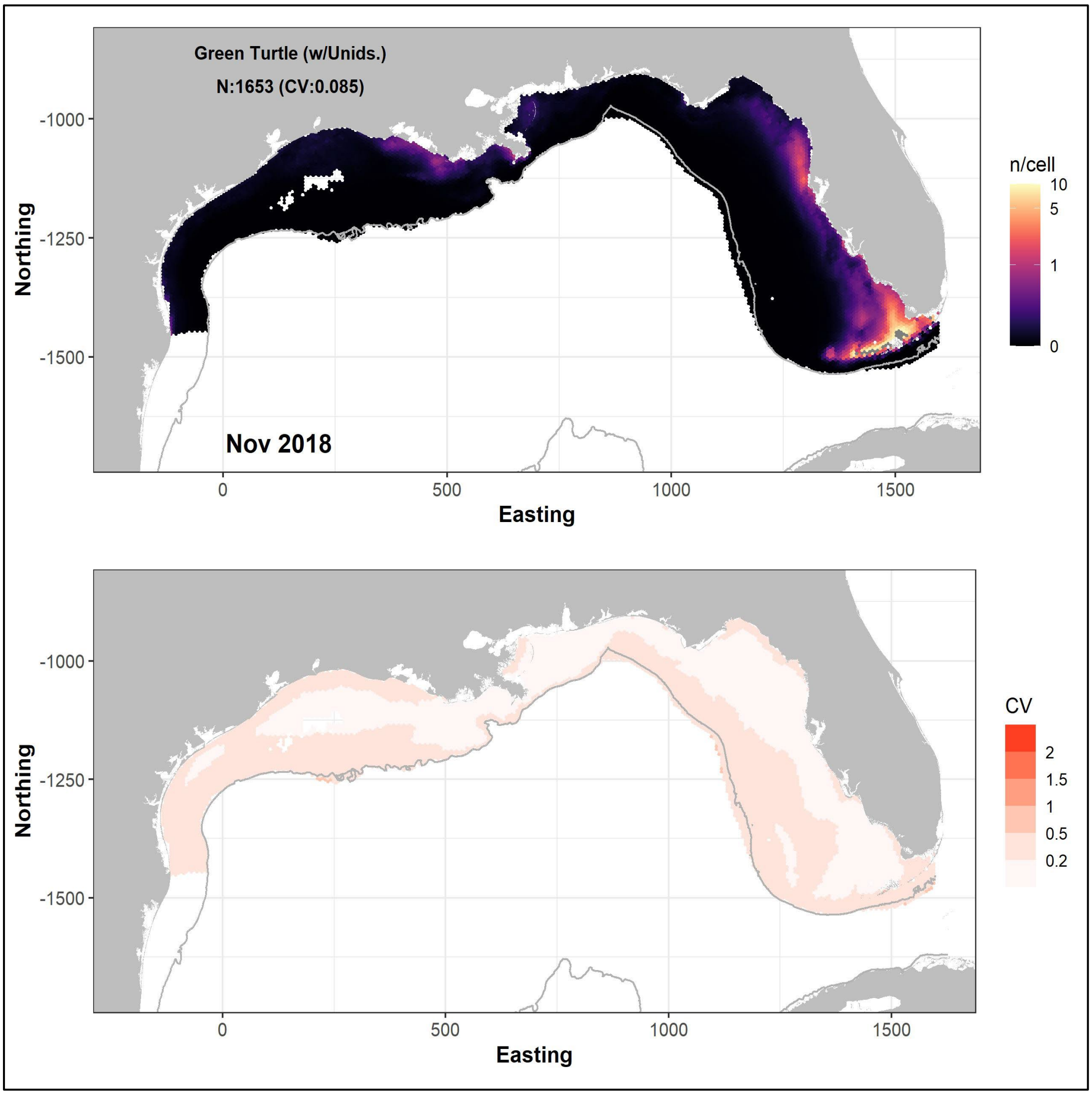

Figure D.2-36. Density model prediction for green turtles including apportioned unidentified turtles in the NGOM in November 2018.

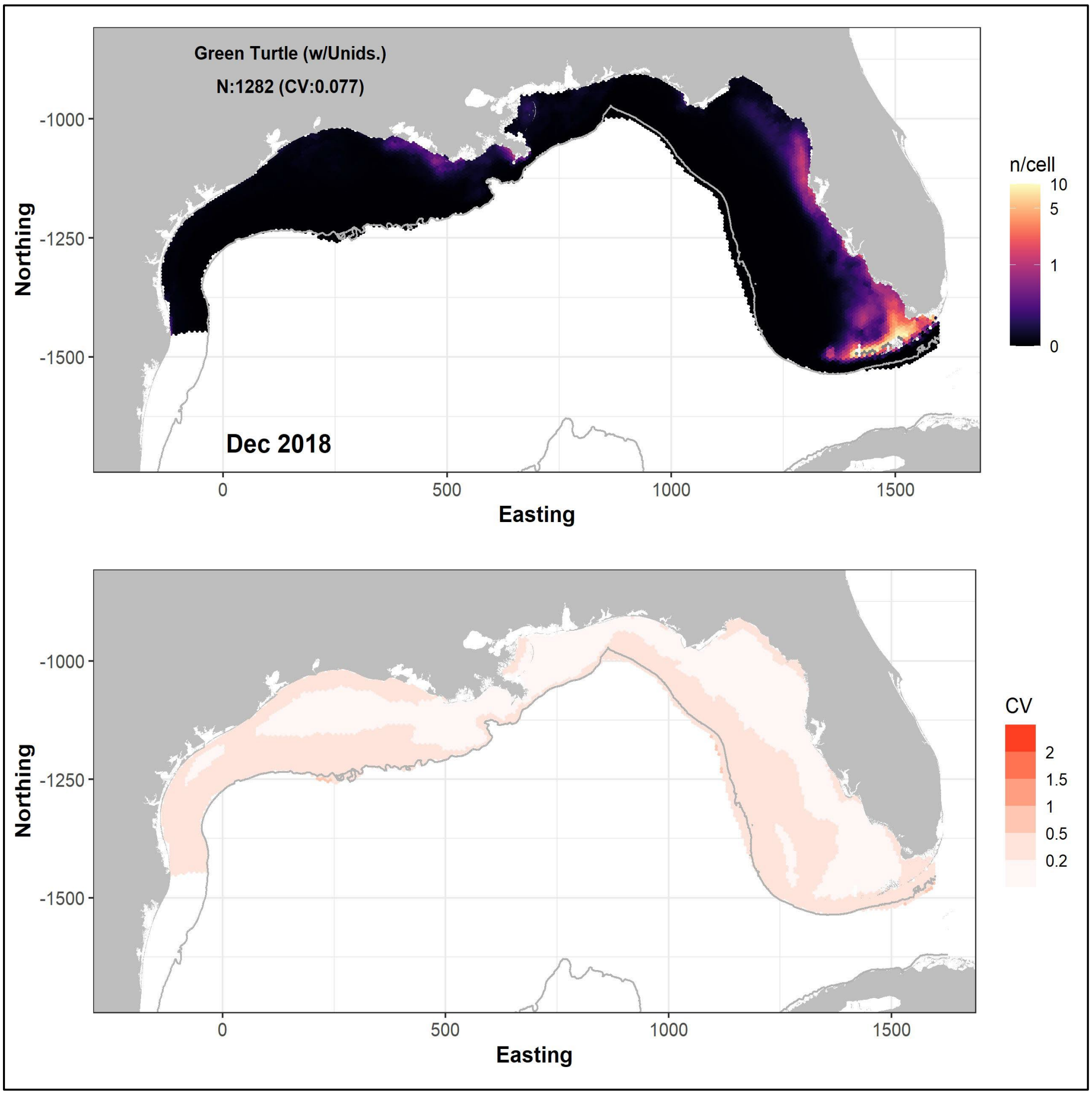

Figure D.2-37. Density model prediction for green turtles including apportioned unidentified turtles in the NGOM in December 2018.

D.2.5.3 Projected Density throughout the Gulf of Mexico

While aerial survey effort was restricted to the NGOM, green turtles occur throughout the northern and southern GOM. The projection of the resulting SDM beyond the NGOM assumes that species-habitat relationships are consistent, and it is unknown if this assumption is reliable. To evaluate the potential density of green turtles outside of the US Economic Exclusive Zone (EEZ), the SDM was projected throughout the GOM. These results should be interpreted with caution given the extrapolation outside of the surveyed area (Figures D.2-38–D.2-49).

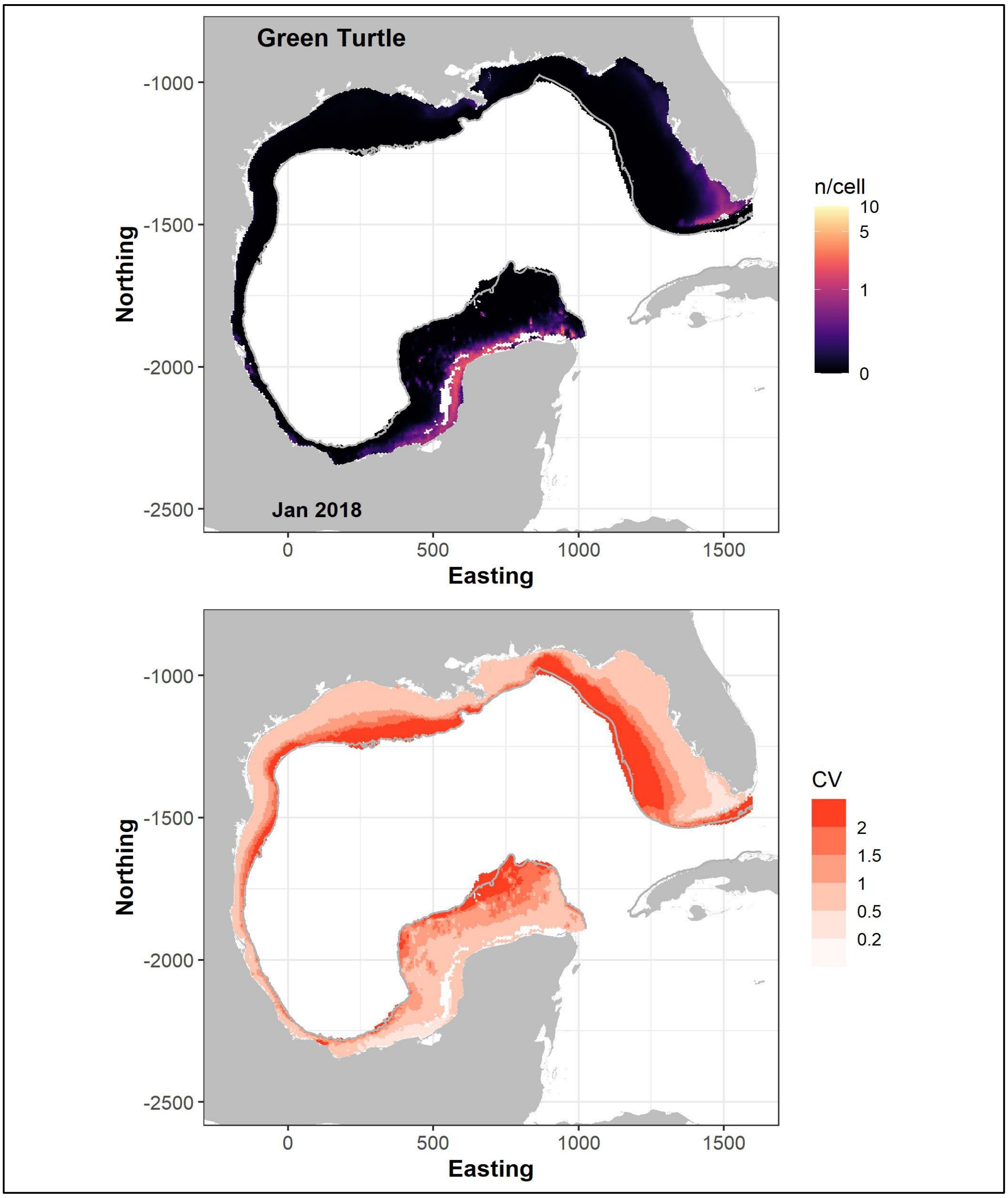

Figure D.2-38. Projected density model for shelf green turtles in the entire GOM for January 2018.

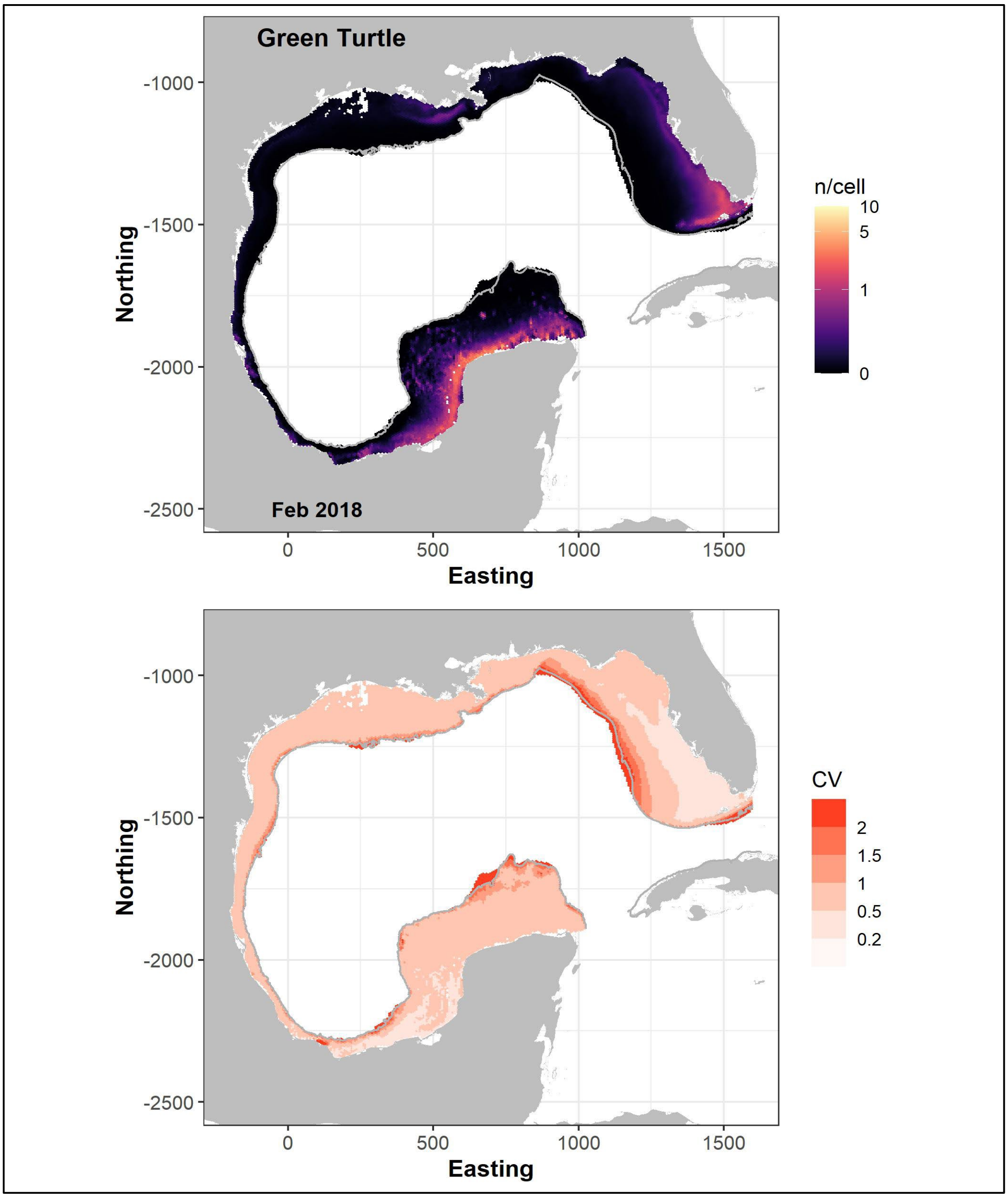

Figure D.2-39. Projected density model for shelf green turtles in the entire GOM for February 2018.

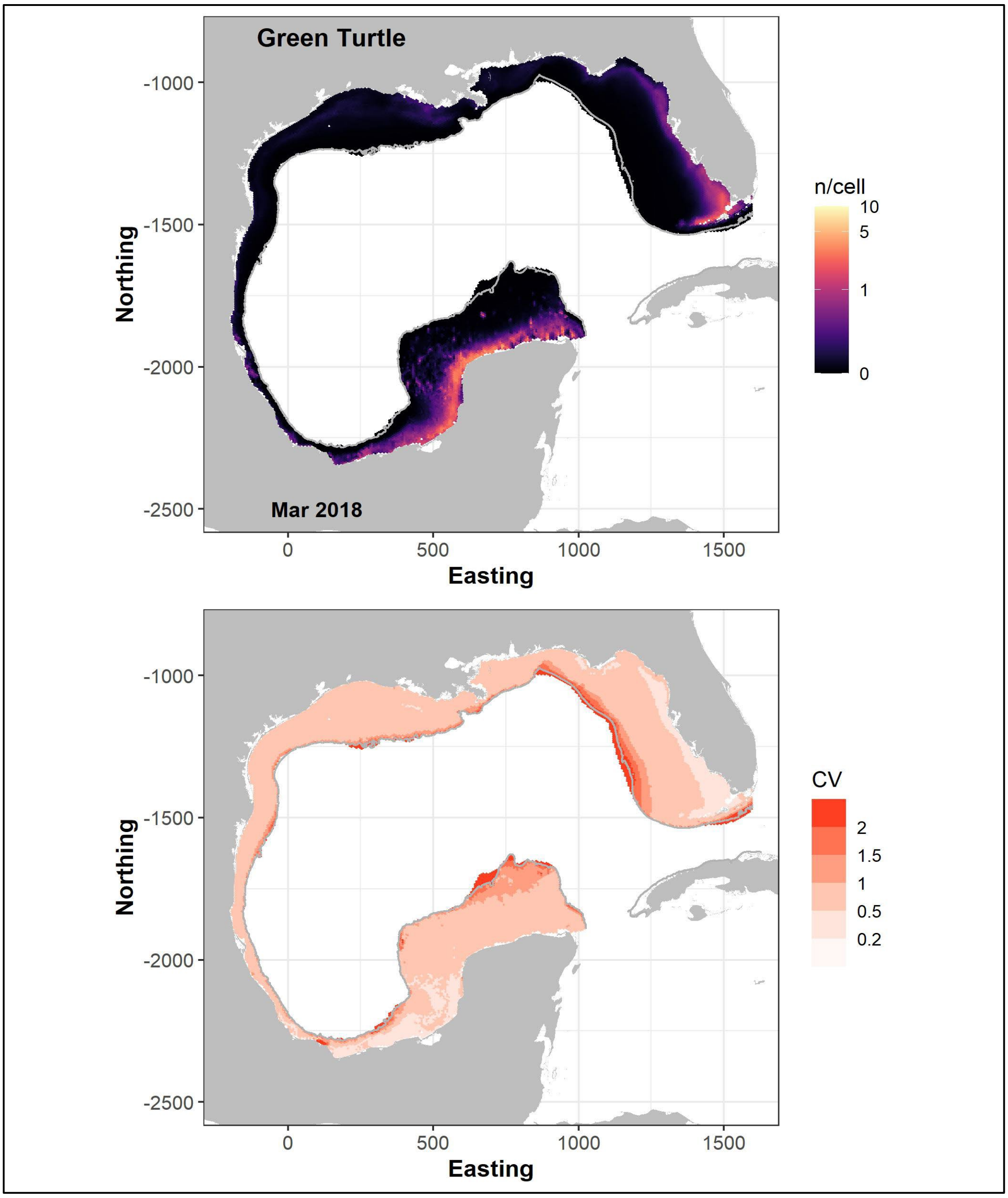

Figure D.2-40. Projected density model for shelf green turtles in the entire GOM for March 2018.

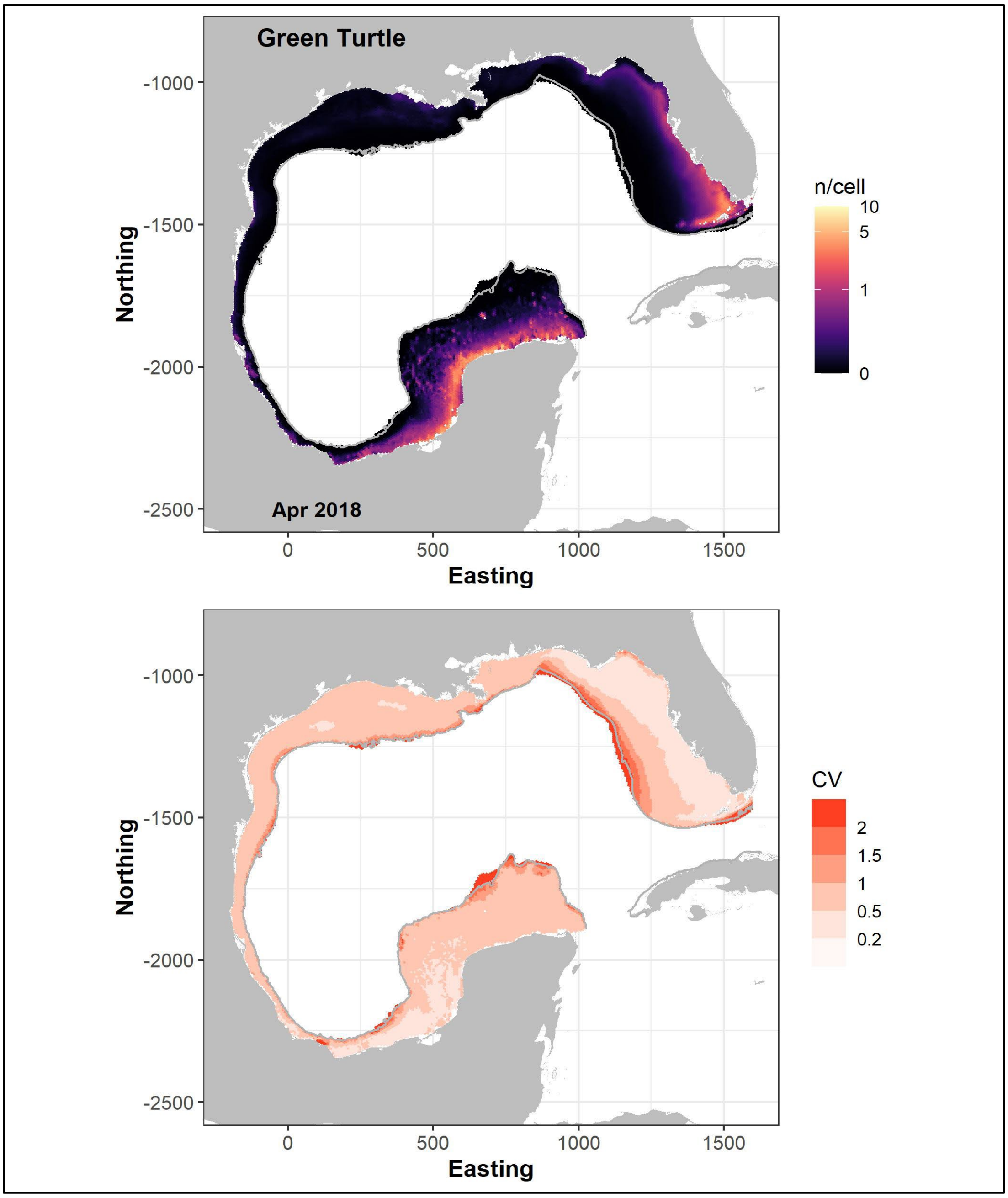

Figure D.2-41. Projected density model for shelf green turtles in the entire GOM for April 2018.

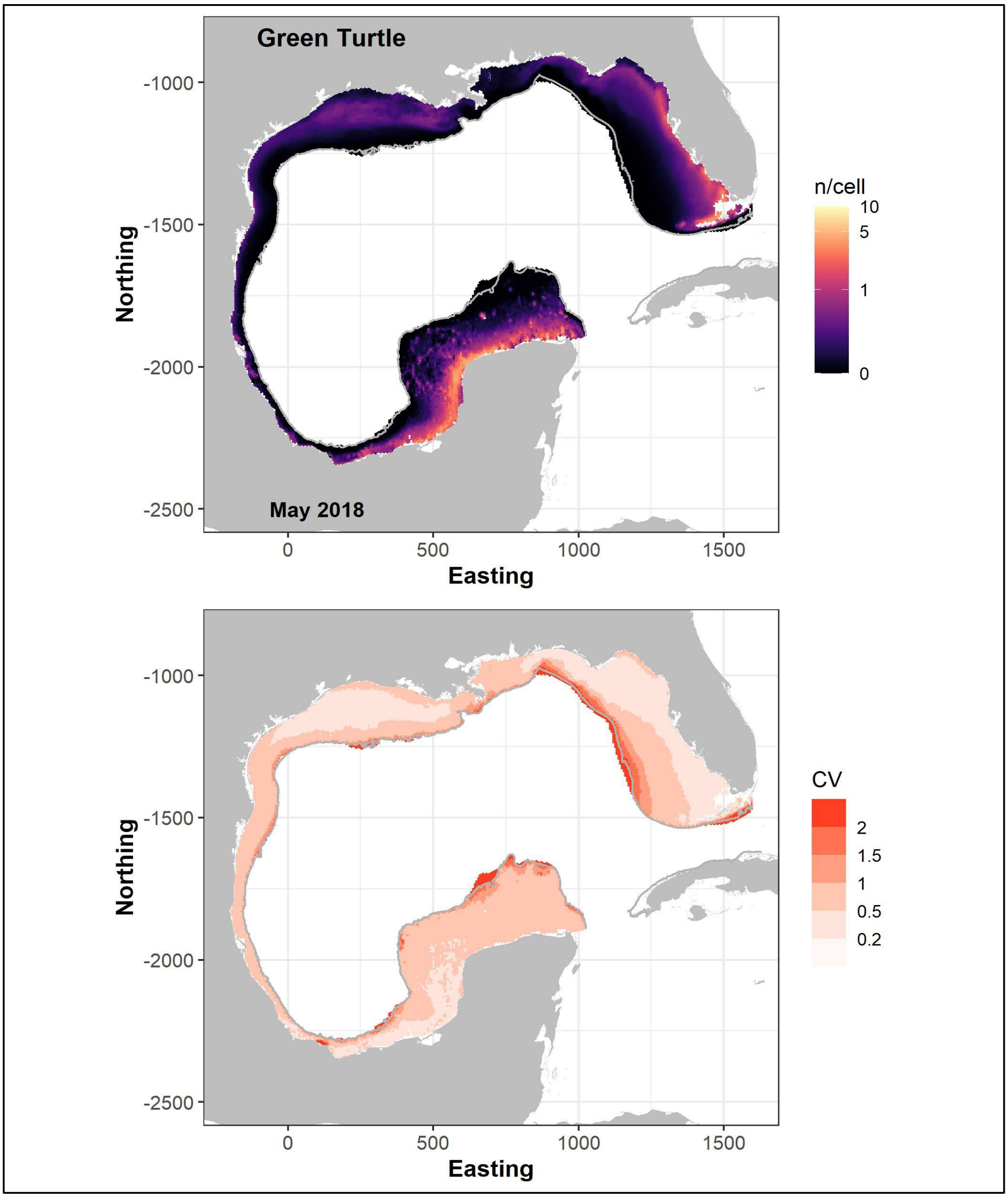

Figure D.2-42. Projected density model for shelf green turtles in the entire GOM for May 2018.

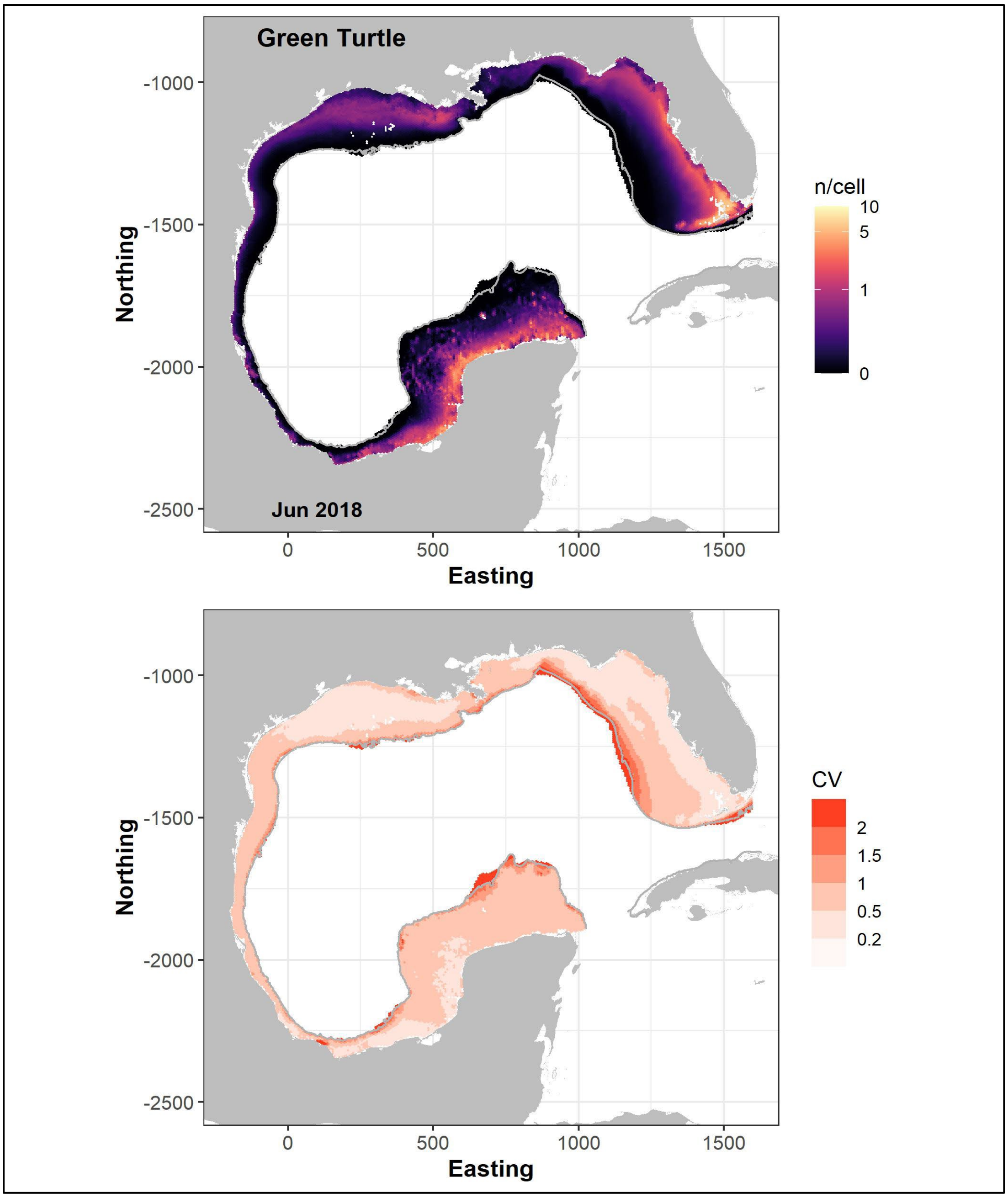

Figure D.2-43. Projected density model for shelf green turtles in the entire GOM for June 2018.

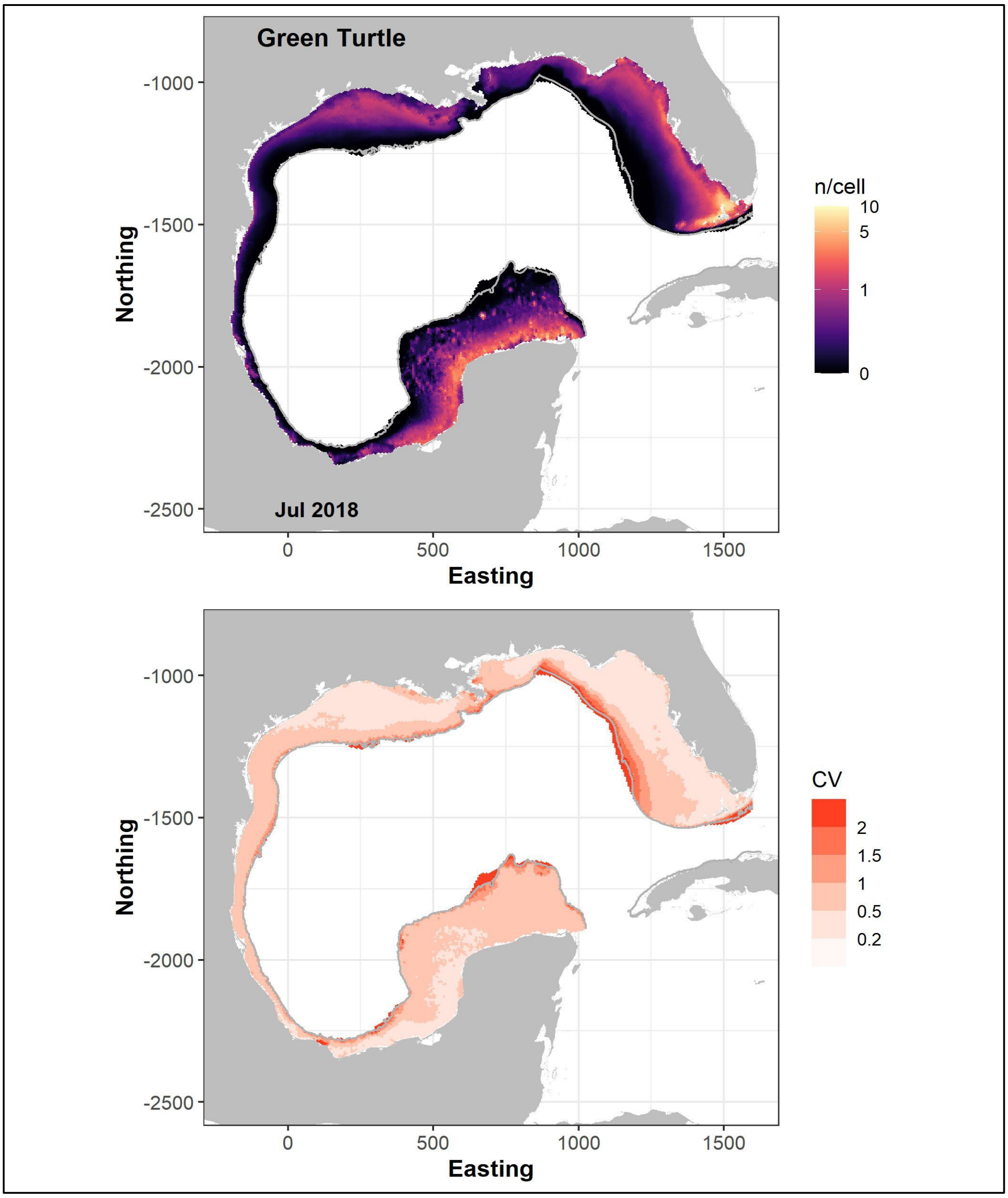

Figure D.2-44. Projected density model for shelf green turtles in the entire GOM for July 2018.

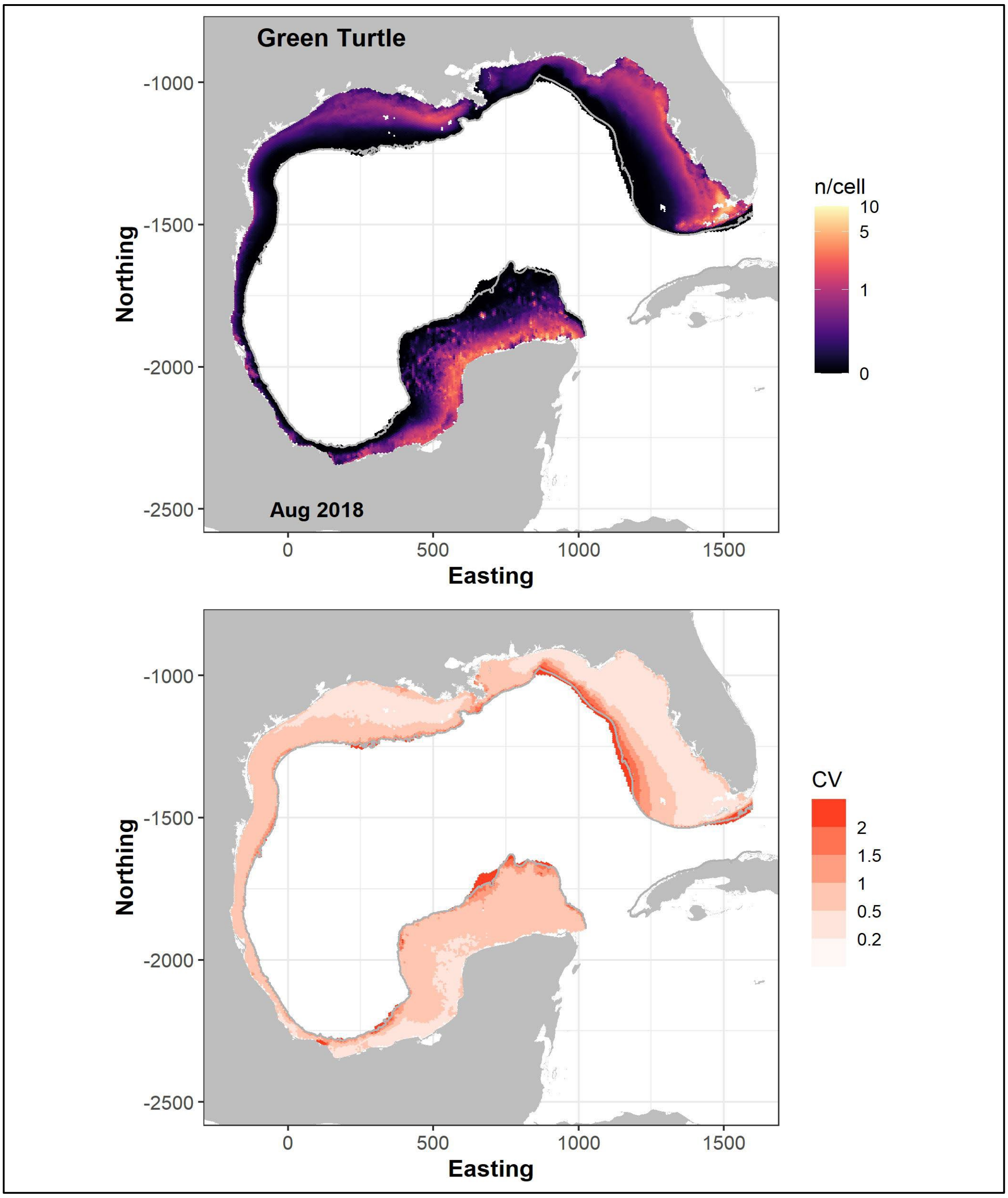

Figure D.2-45. Projected density model for shelf green turtles in the entire GOM for August 2018.

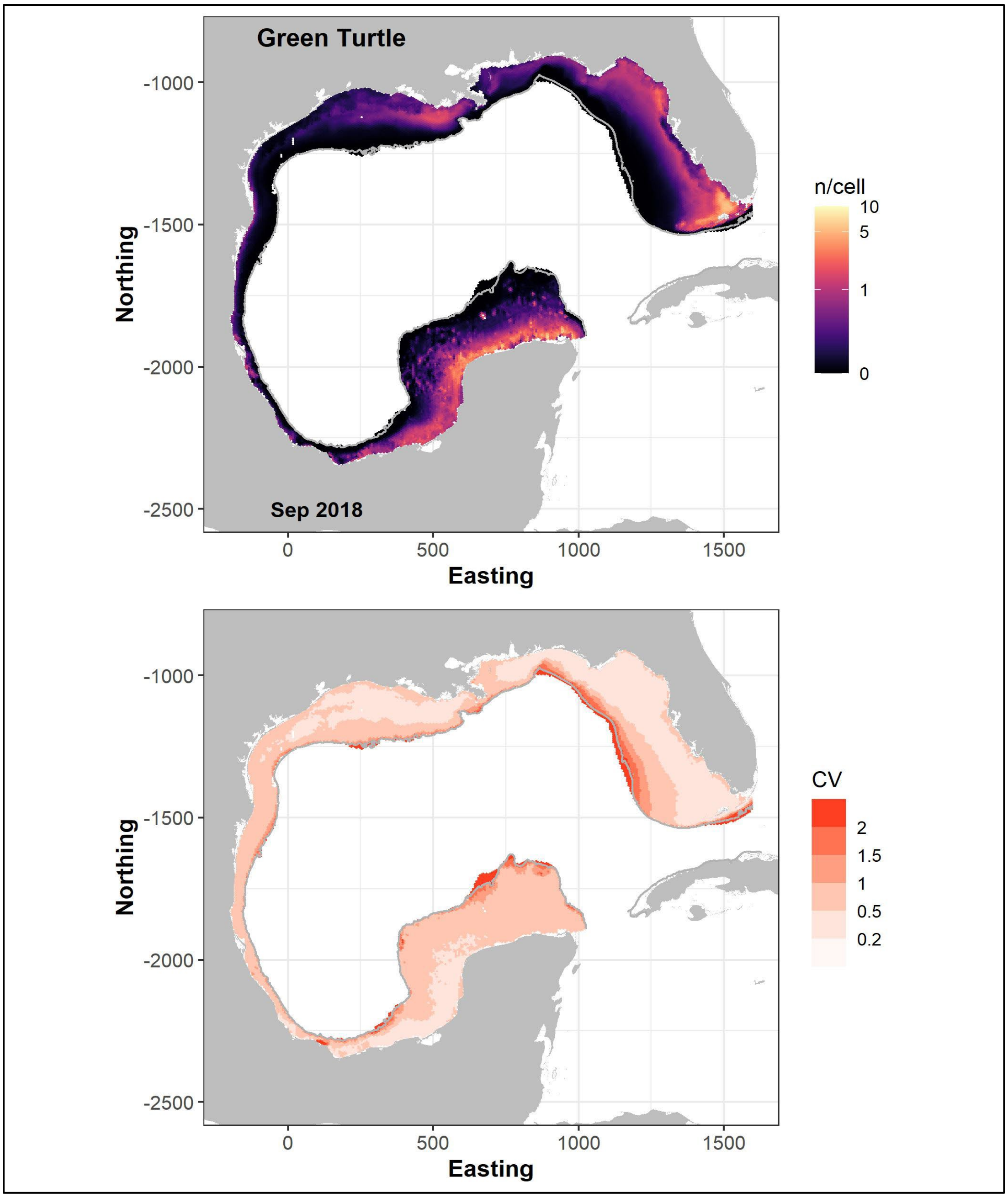

Figure D.2-46. Projected density model for shelf green turtles in the entire GOM for September 2018.

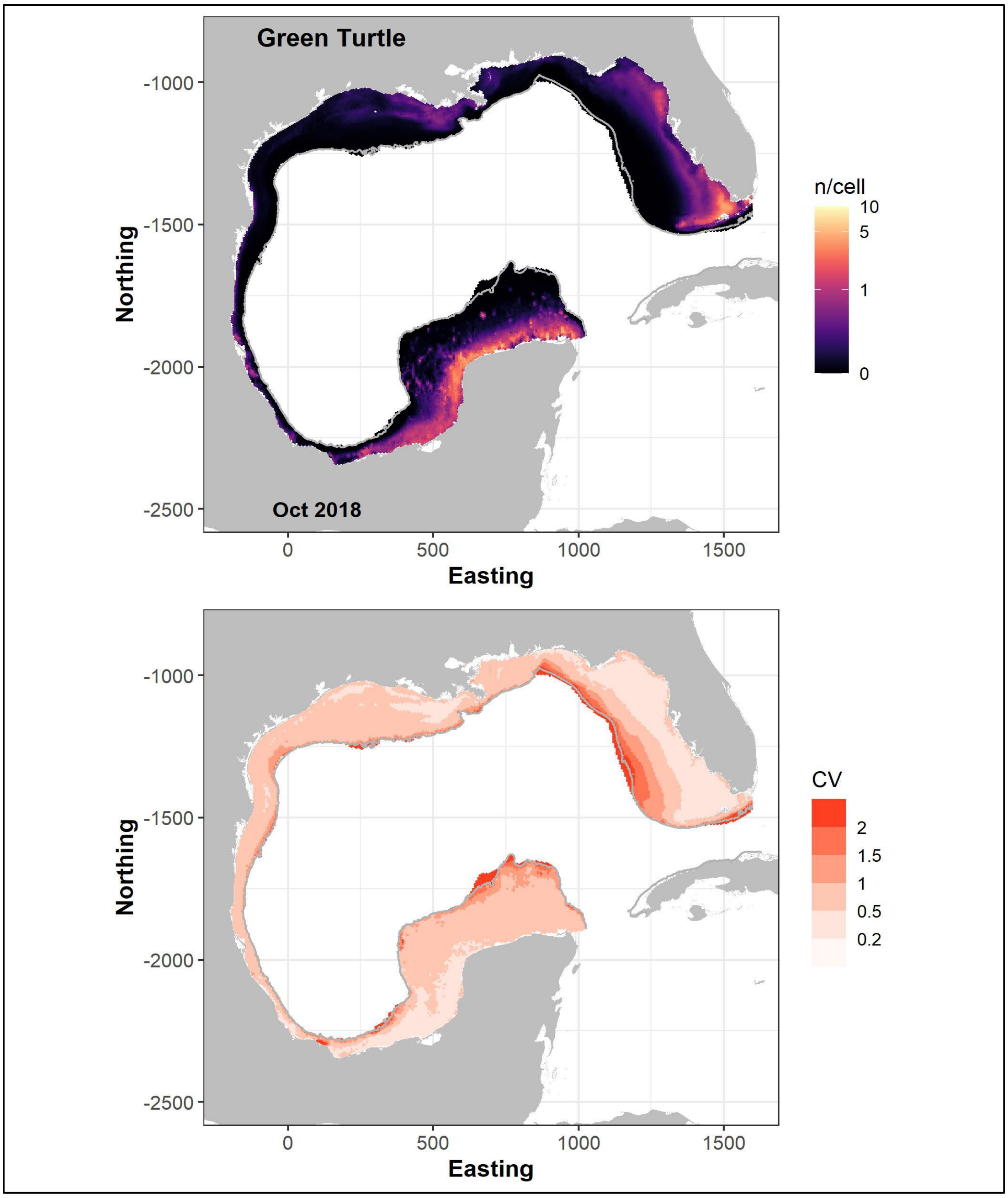

Figure D.2-47. Projected density model for shelf green turtles in the entire GOM for October 2018.

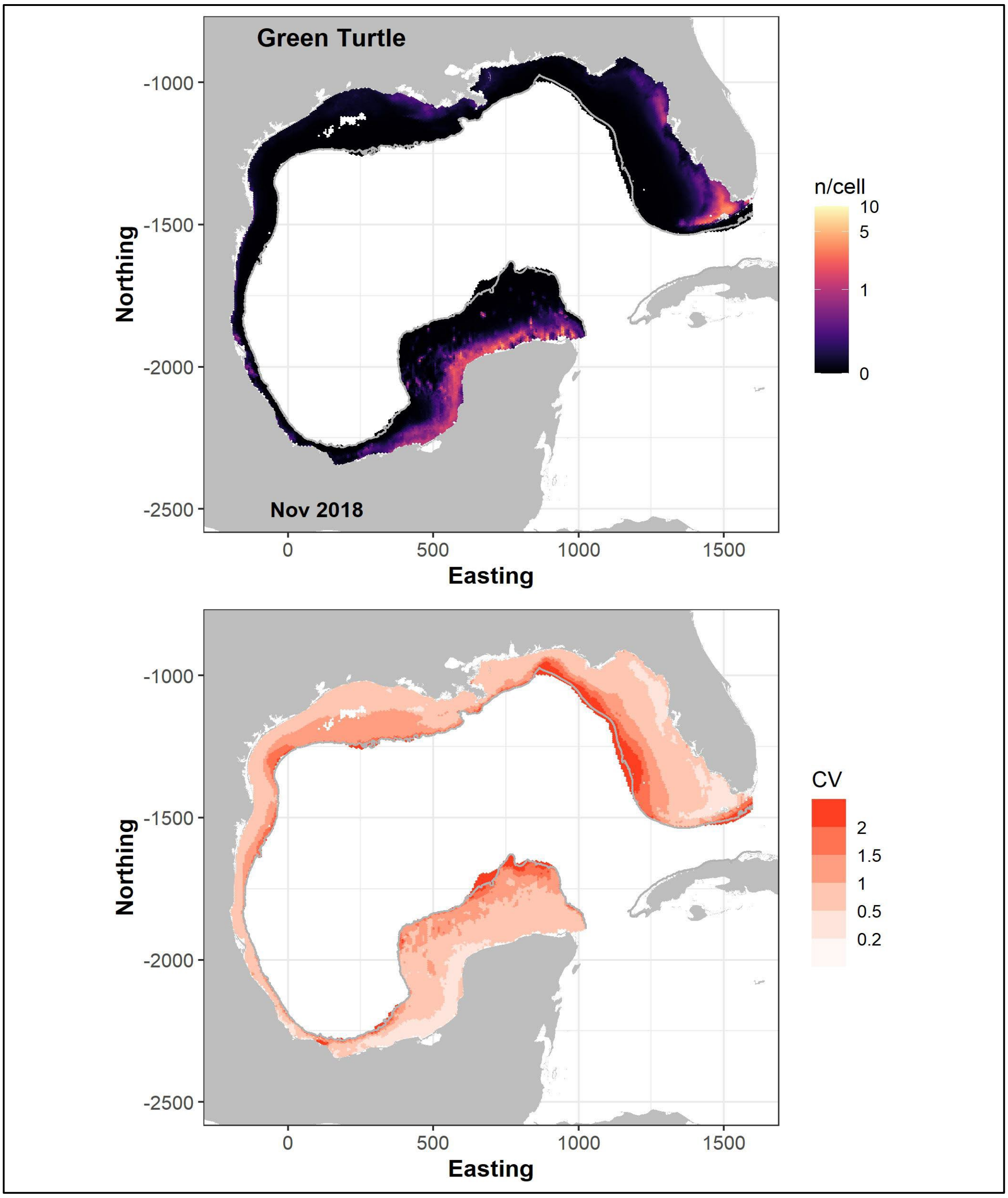

Figure D.2-48. Projected density model for shelf green turtles in the entire GOM for November 2018.

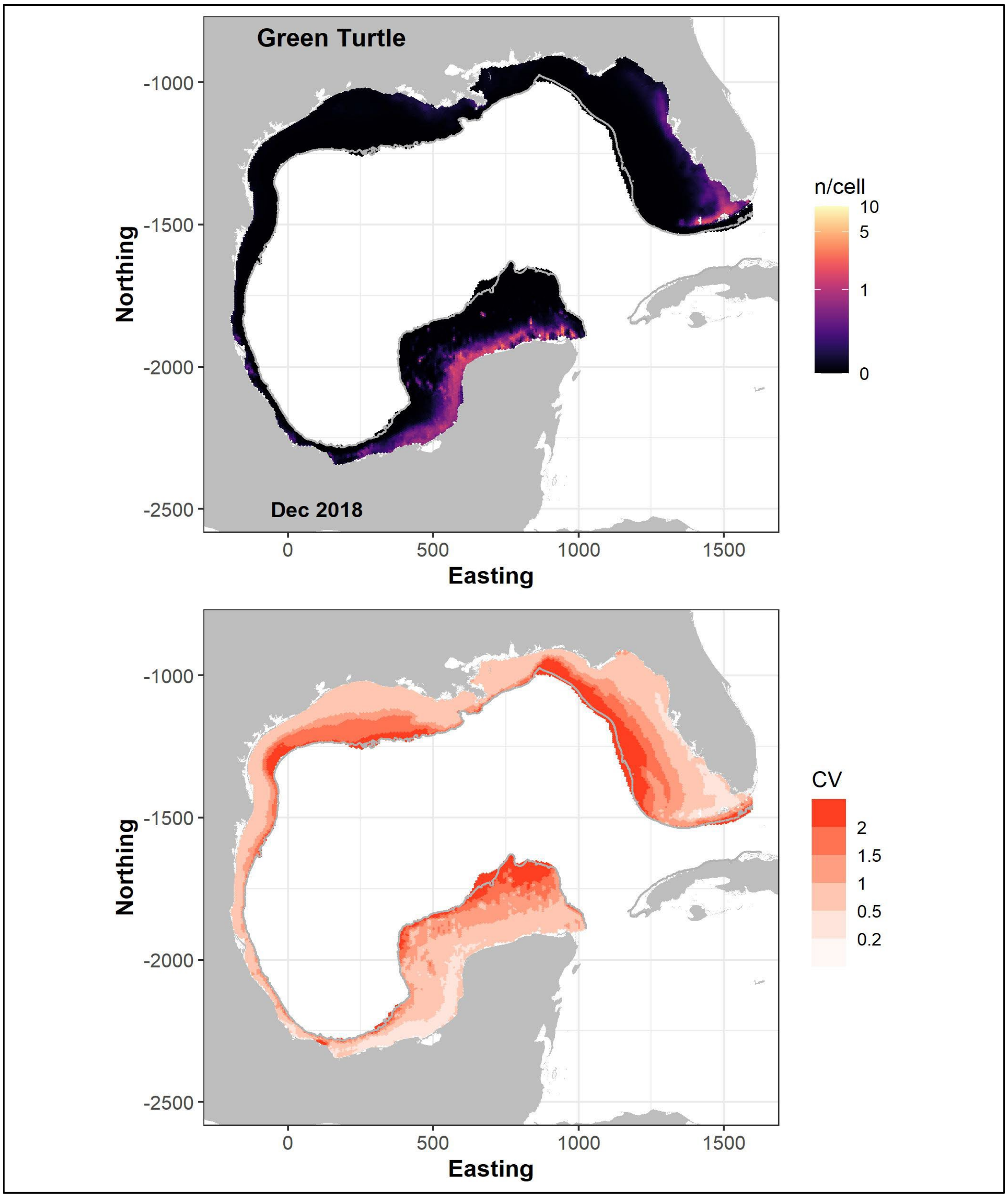

Figure D.2-49. Projected density model for shelf green turtles in the entire GOM for December 2018.

D.2.5.4 Average Monthly Density: 2015–2019

Prediction maps were generated using monthly environmental parameters for the period of 2015–2019. The posterior distribution of the GAM parameters was sampled 1,000 times to generate a distribution of model coefficients that reflect the statistical uncertainty in the parameter estimation. Predictions of animal density were generated for each month in the 2015–2019 period based on each of these 1,000 parameter sets. In this way, both inter-annual variability in environmental conditions and model uncertainty were included in the resulting samples. The monthly predictions were examined to identify sampled parameters that generated extreme predicted densities, and these extreme values

were excluded from the bootstrap sample before variance estimation. These extreme values, associated with density predictions many orders of magnitude higher than the observed median, reflect projection of the model predictions into poorly sampled parameter space. It was not necessary to trim the bootstrap iterations for green turtles. The resulting distribution of realizations was used to summarize predicted average densities by month and to calculate metrics of uncertainty. The average monthly abundance for green turtles in US waters is shown in Table D.2-5 (Figures D.2-50–D.2-61).

Table D.2-5. Monthly average abundance of green turtles in US shelf waters 2015–2019

Month	Abundance	CV
January	1,909	0.443
February	2,656	0.494
March	3,784	0.405
April	5,297	0.360
May	6,556	0.318
June	9,275	0.314
July	10,159	0.322
August	9,775	0.329
September	8,086	0.342
October	4,778	0.358
November	3,194	0.355
December	2,855	0.454

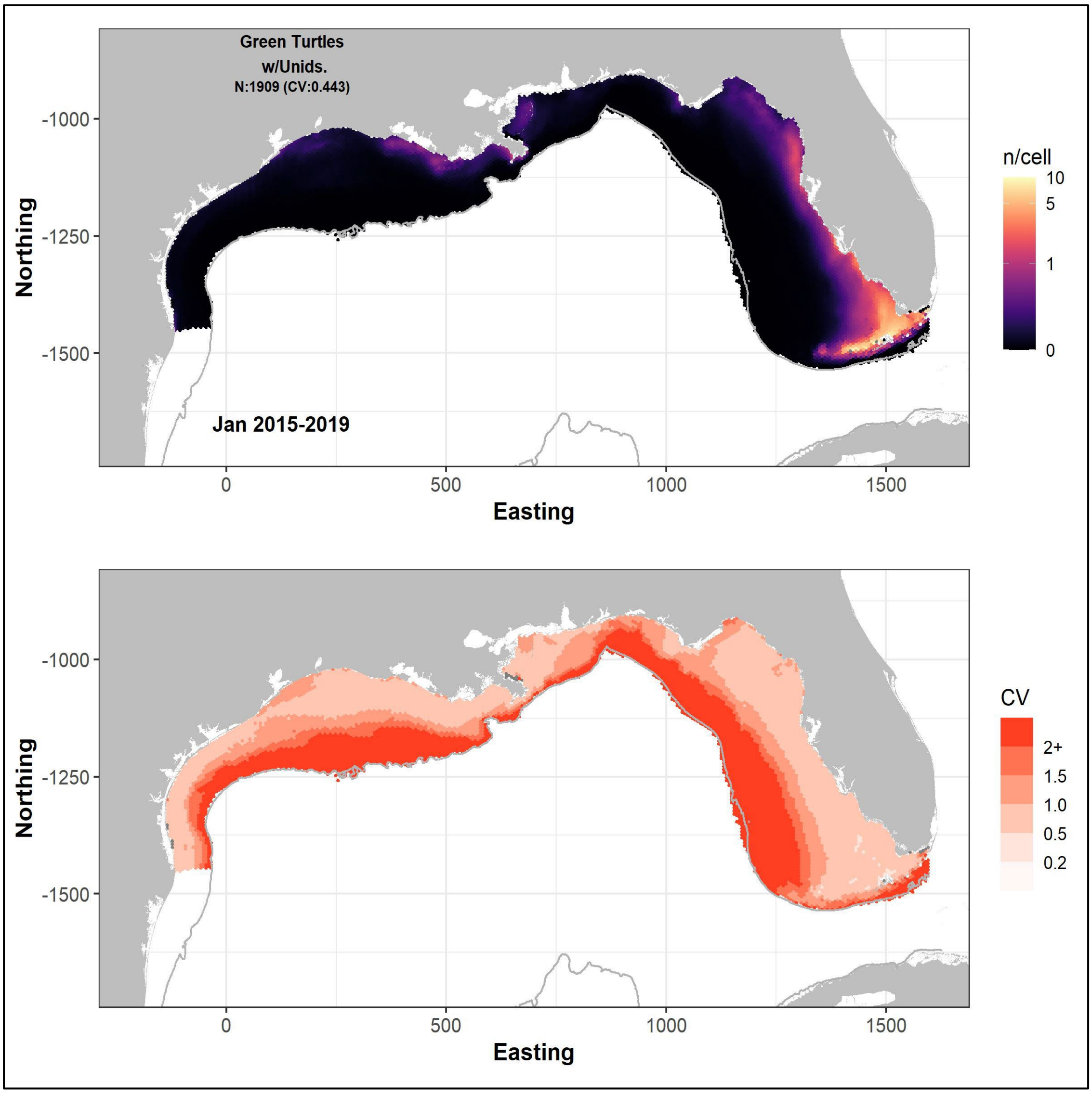

Figure D.2-50. Density model prediction for shelf green turtles in the NGOM for the months of January 2015–2019.

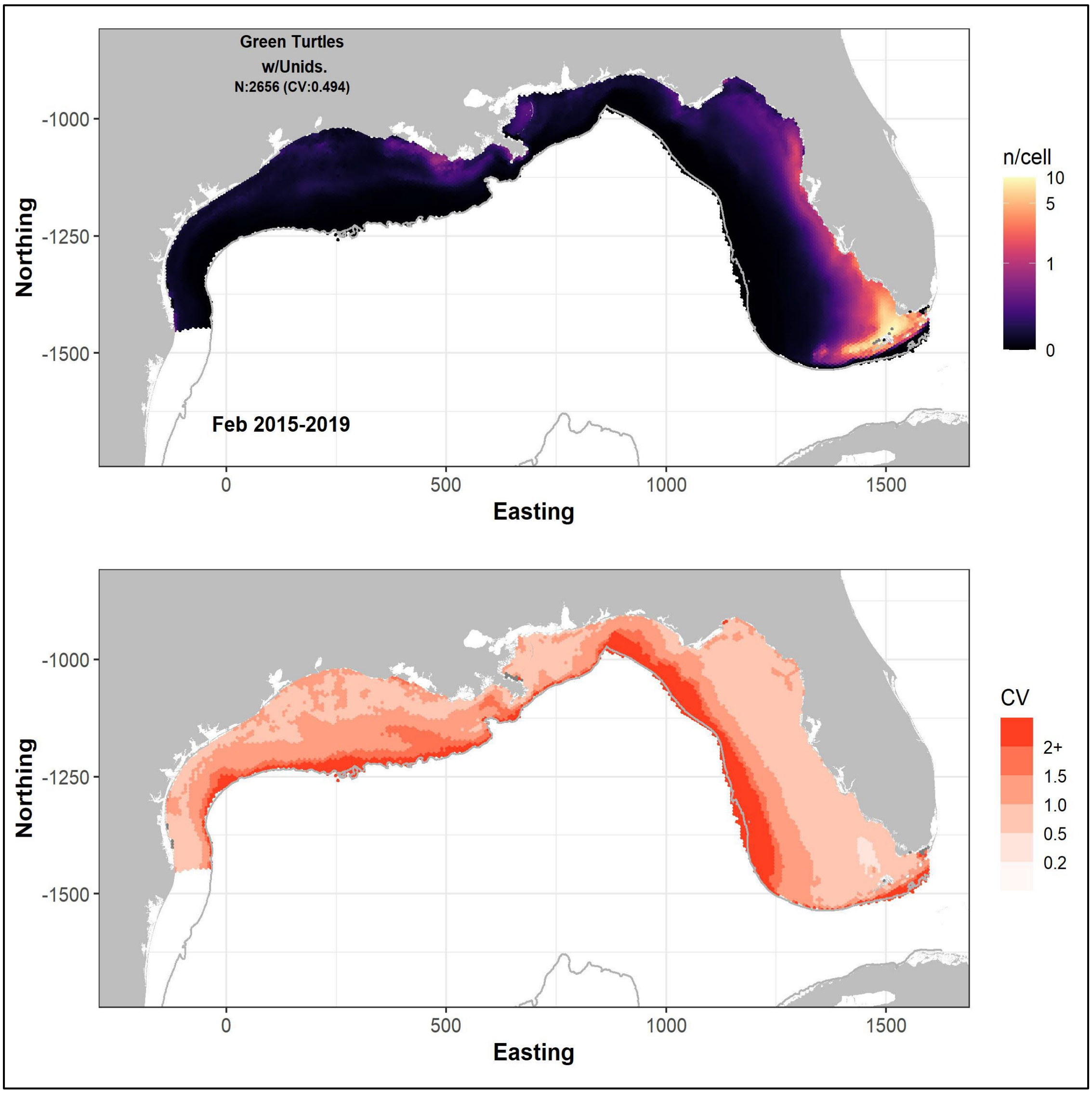

Figure D.2-51. Density model prediction for shelf green turtles in the NGOM for the months of February 2015–2019.

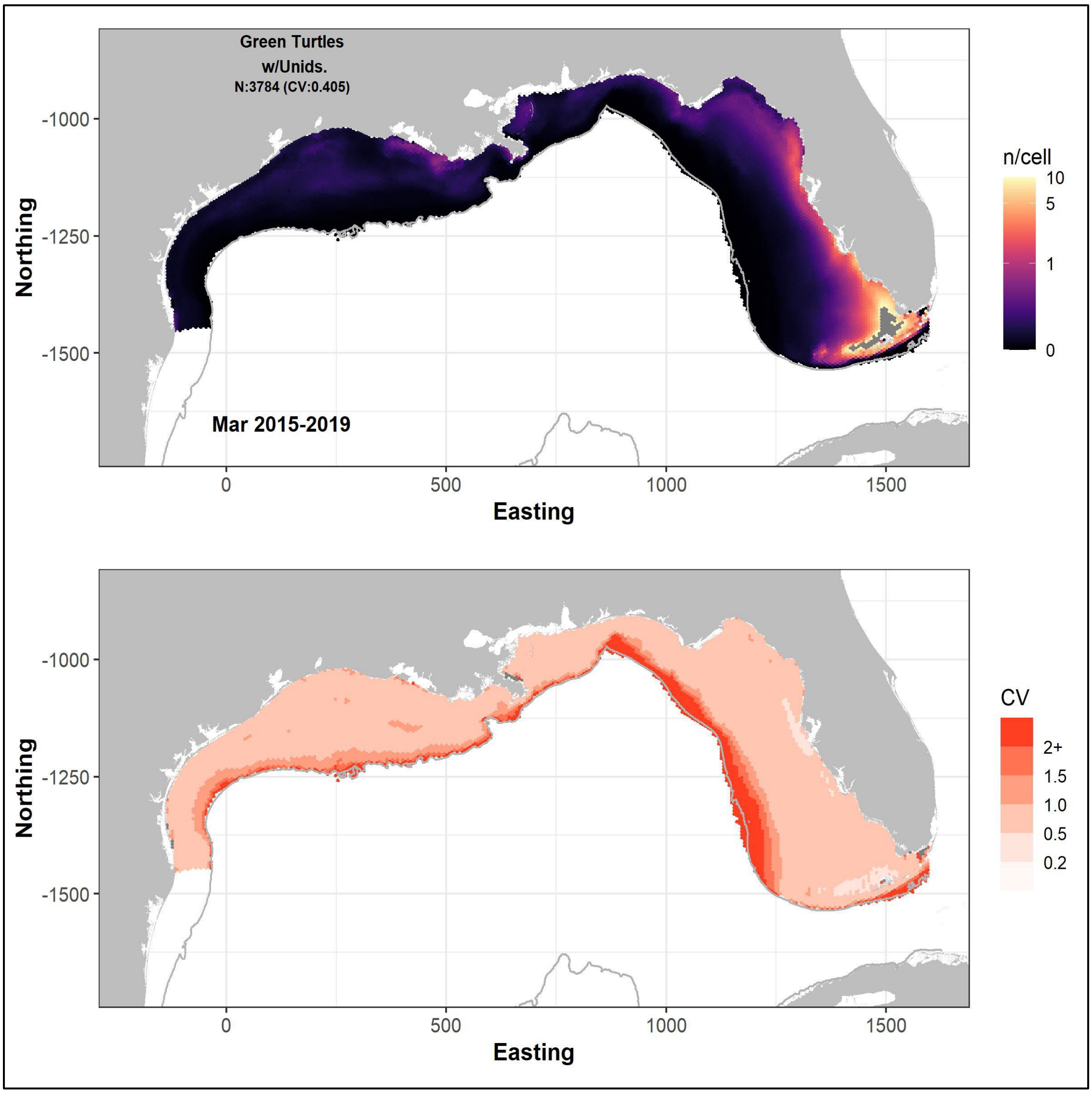

Figure D.2-52. Density model prediction for shelf green turtles in the NGOM for the months of March 2015–2019.

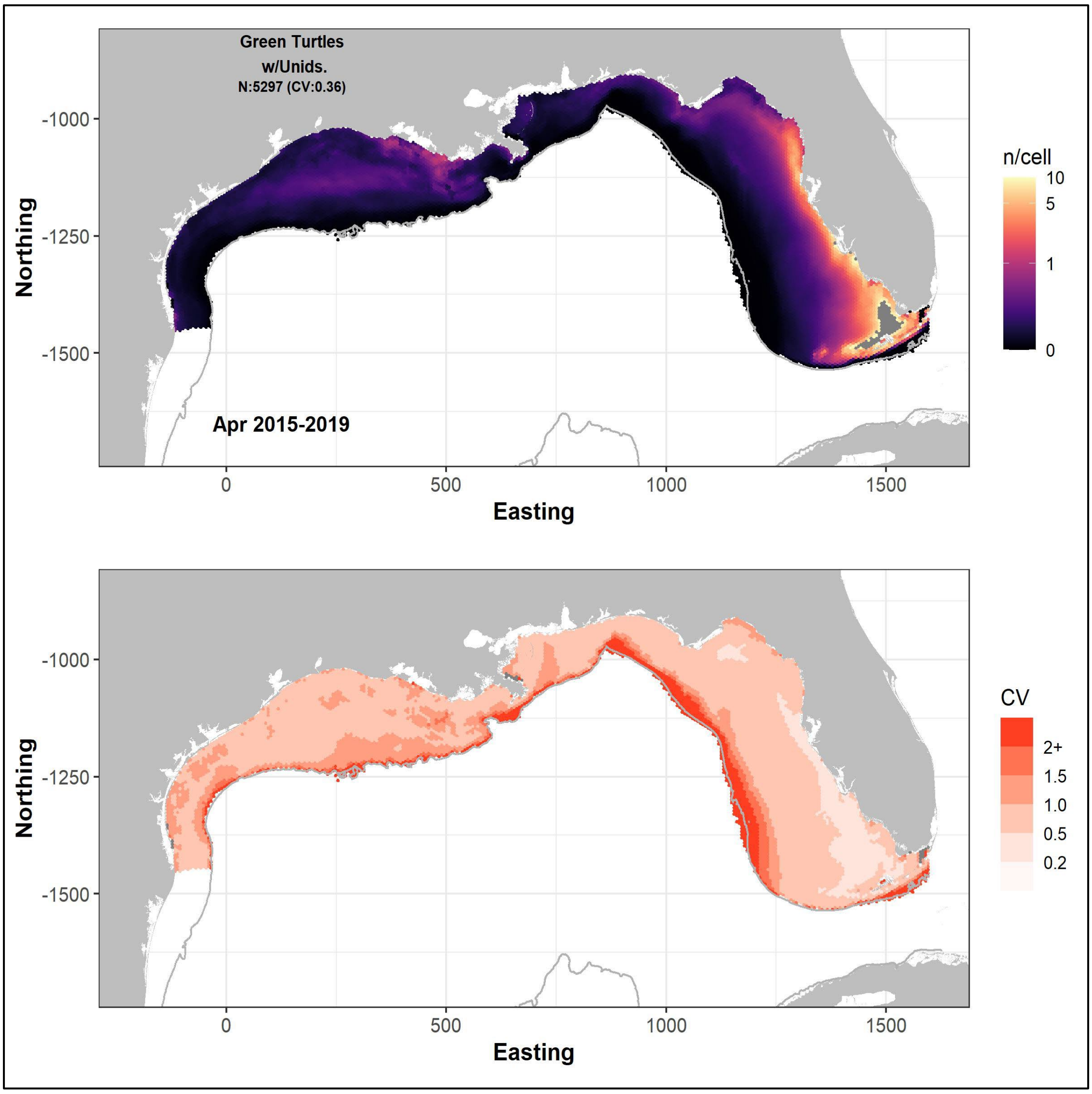

Figure D.2-53. Density model prediction for shelf green turtles in the NGOM for the months of April 2015–2019.

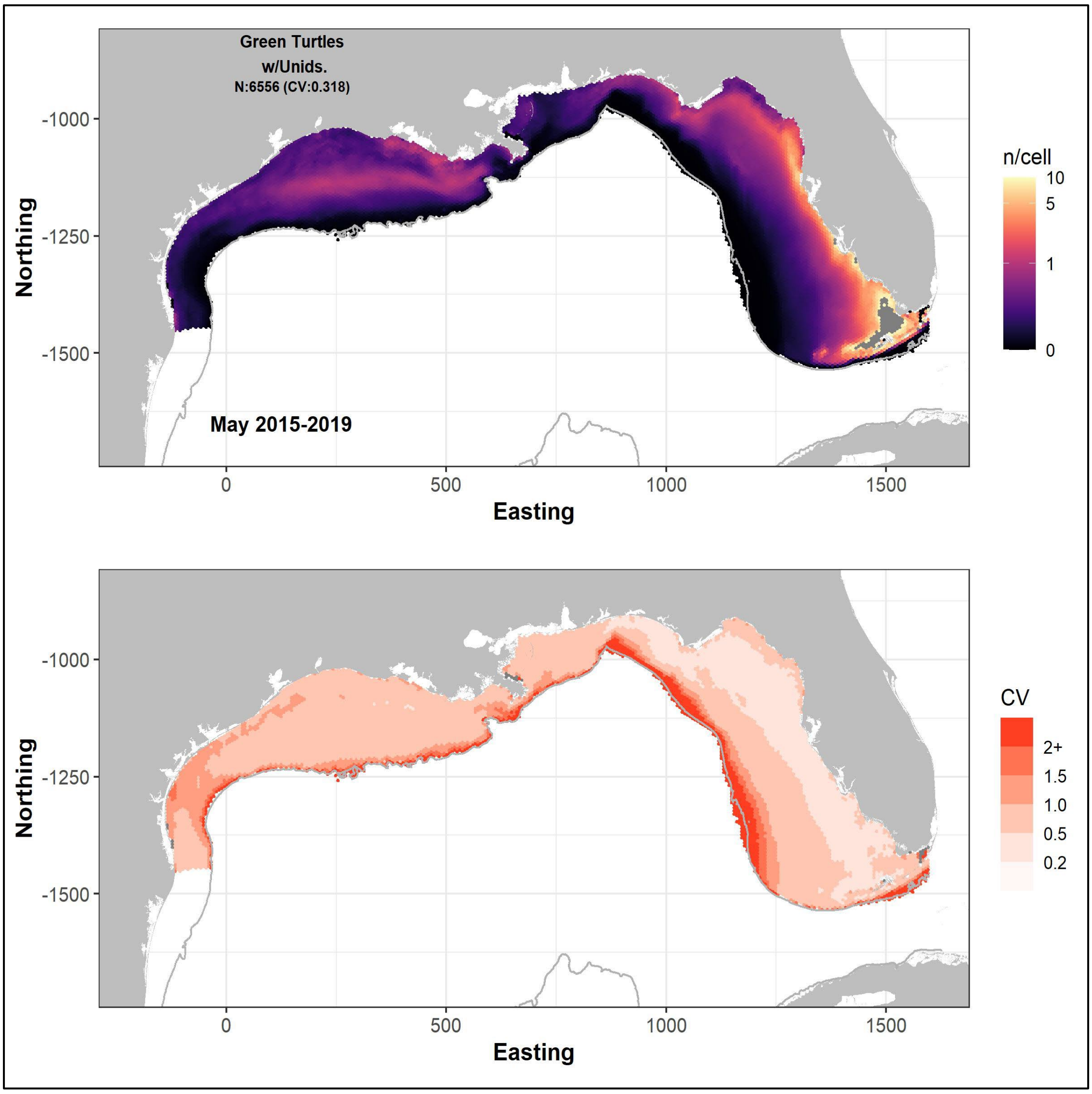

Figure D.2-54. Density model prediction for shelf green turtles in the NGOM for the months of May 2015–2019.

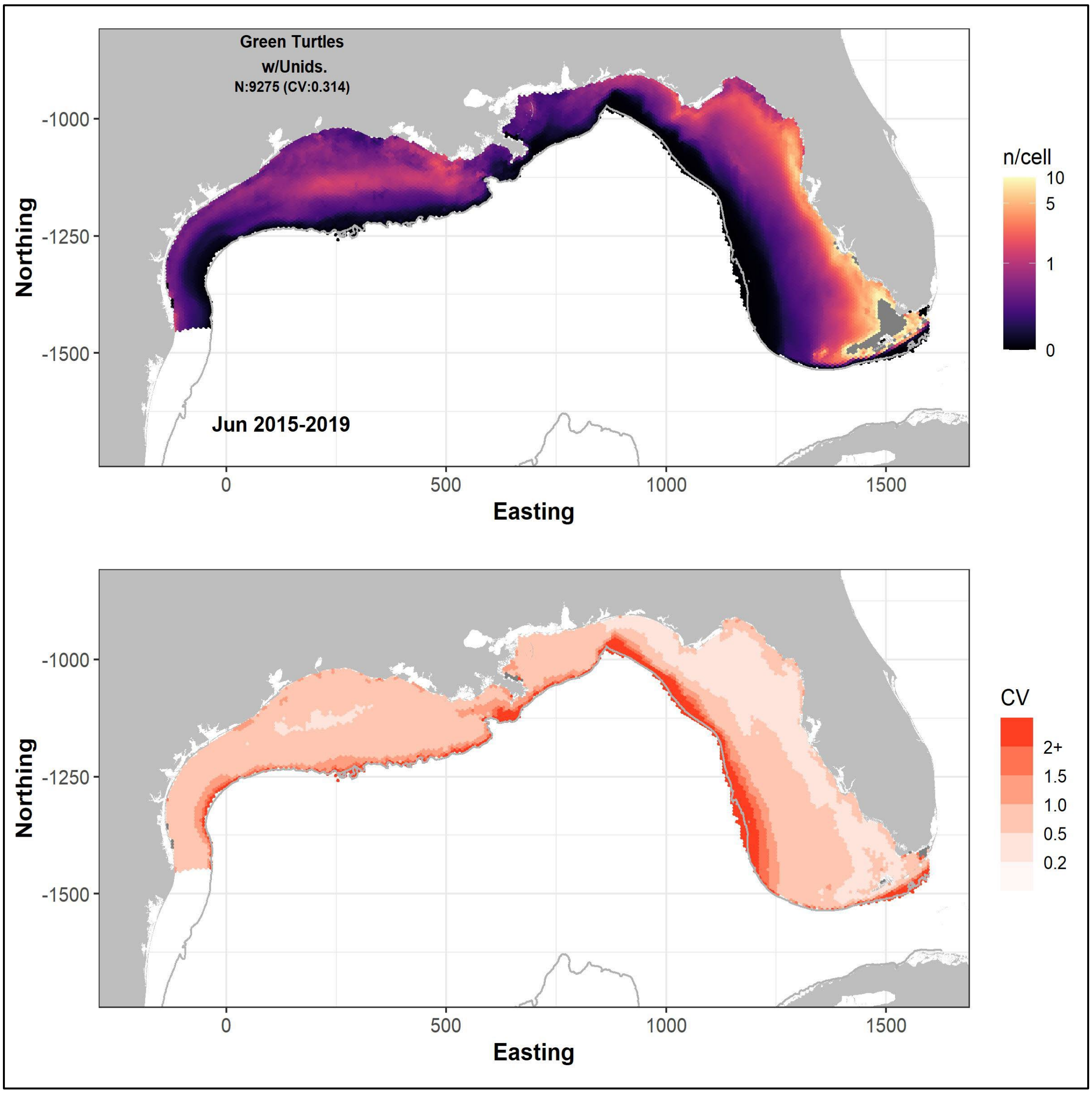

Figure D.2-55. Density model prediction for shelf green turtles in the NGOM for the months of June 2015–2019.

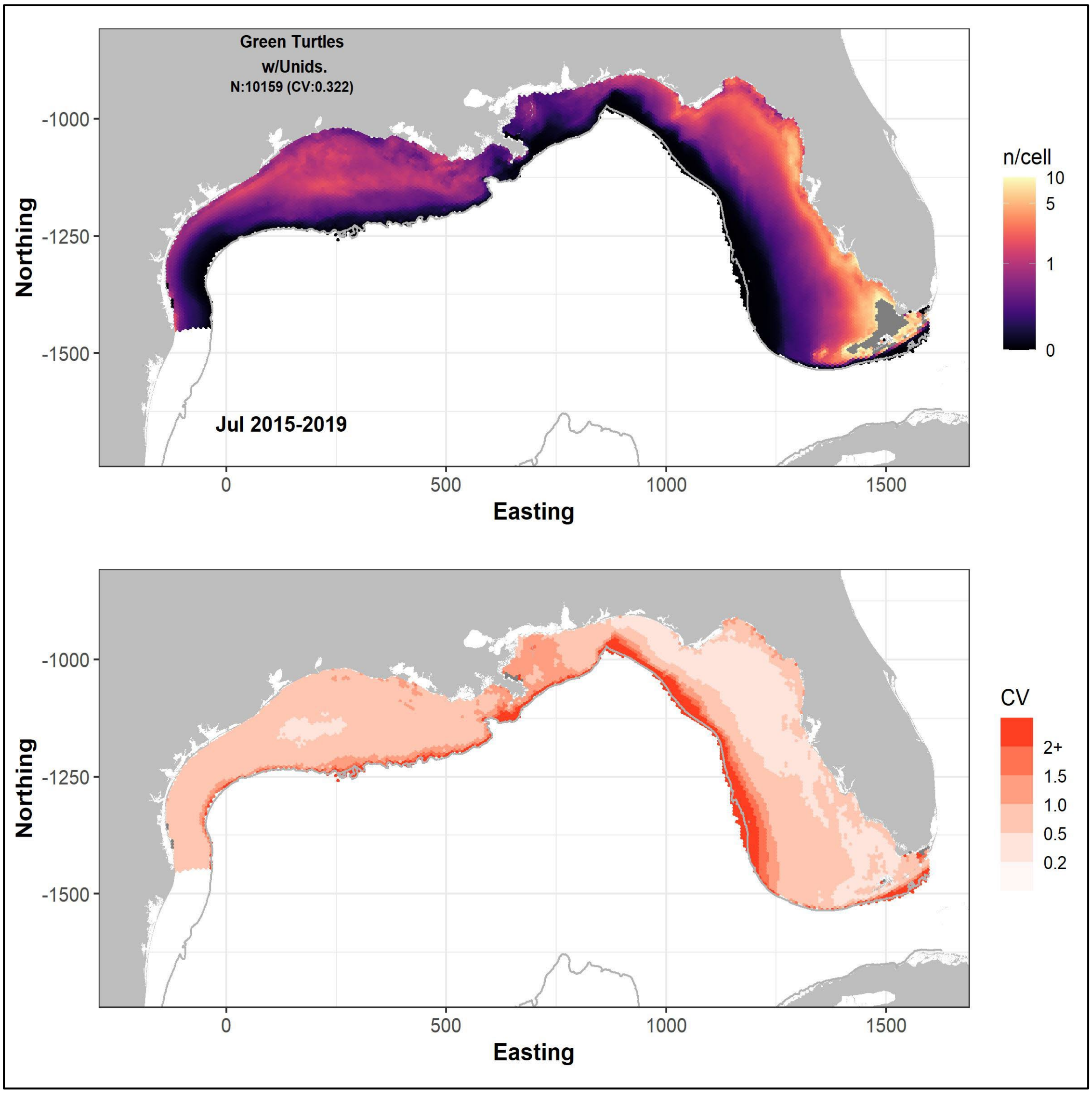

Figure D.2-56. Density model prediction for shelf green turtles in the NGOM for the months of July 2015–2019.

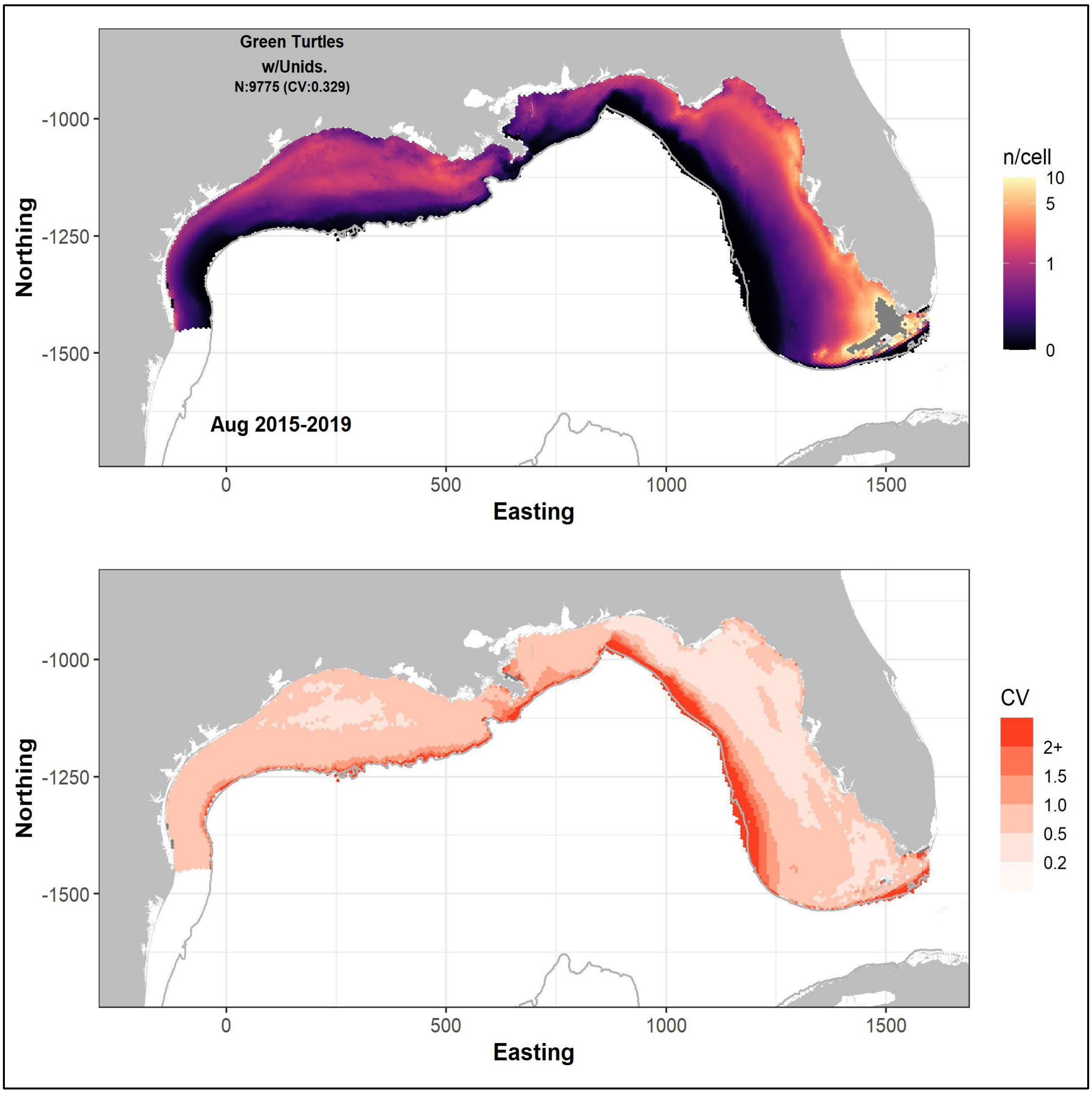

Figure D.2-57. Density model prediction for shelf green turtles in the NGOM for the months of August 2015–2019.

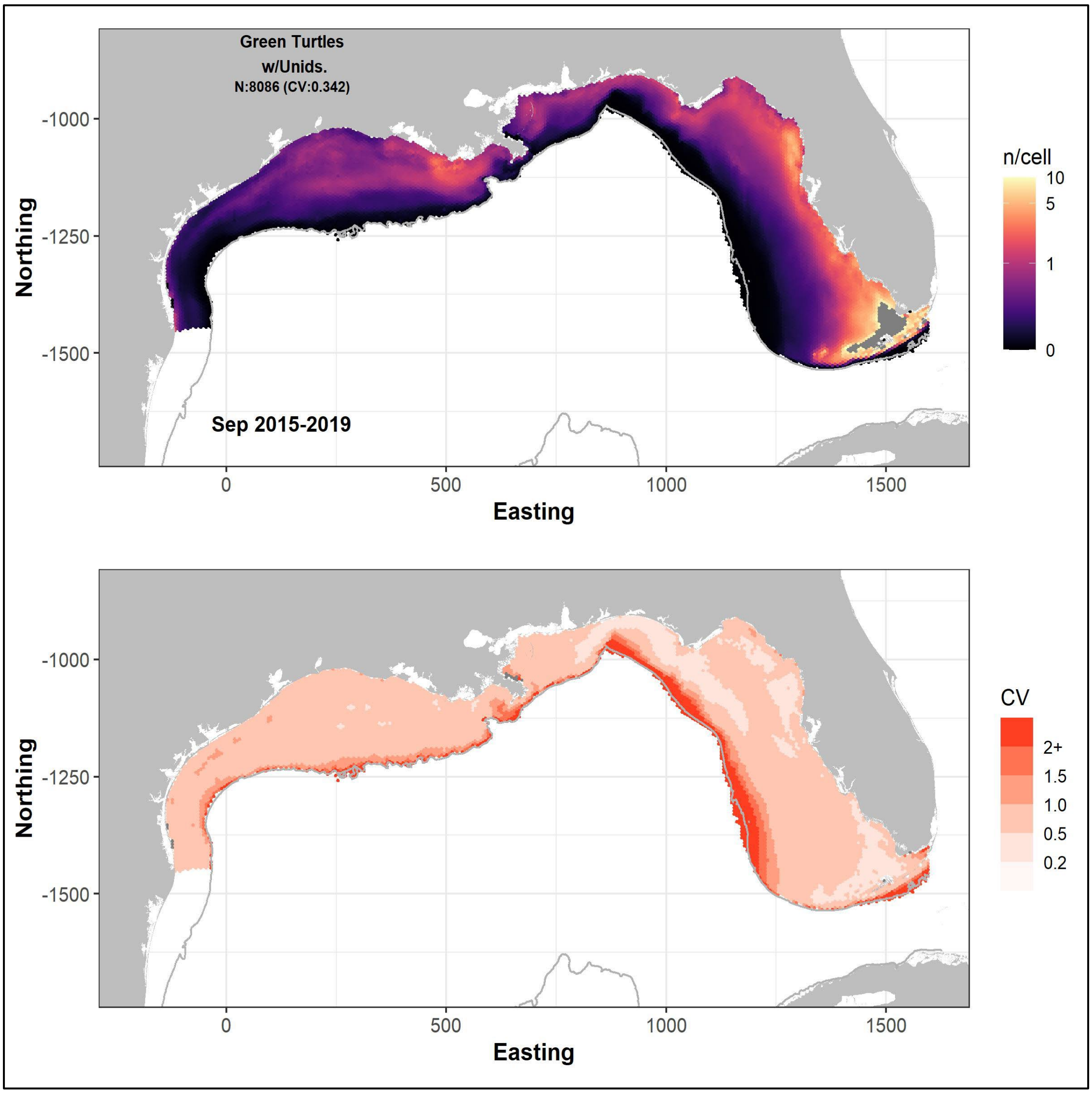

Figure D.2-58. Density model prediction for shelf green turtles in the NGOM for the months of September 2015–2019.

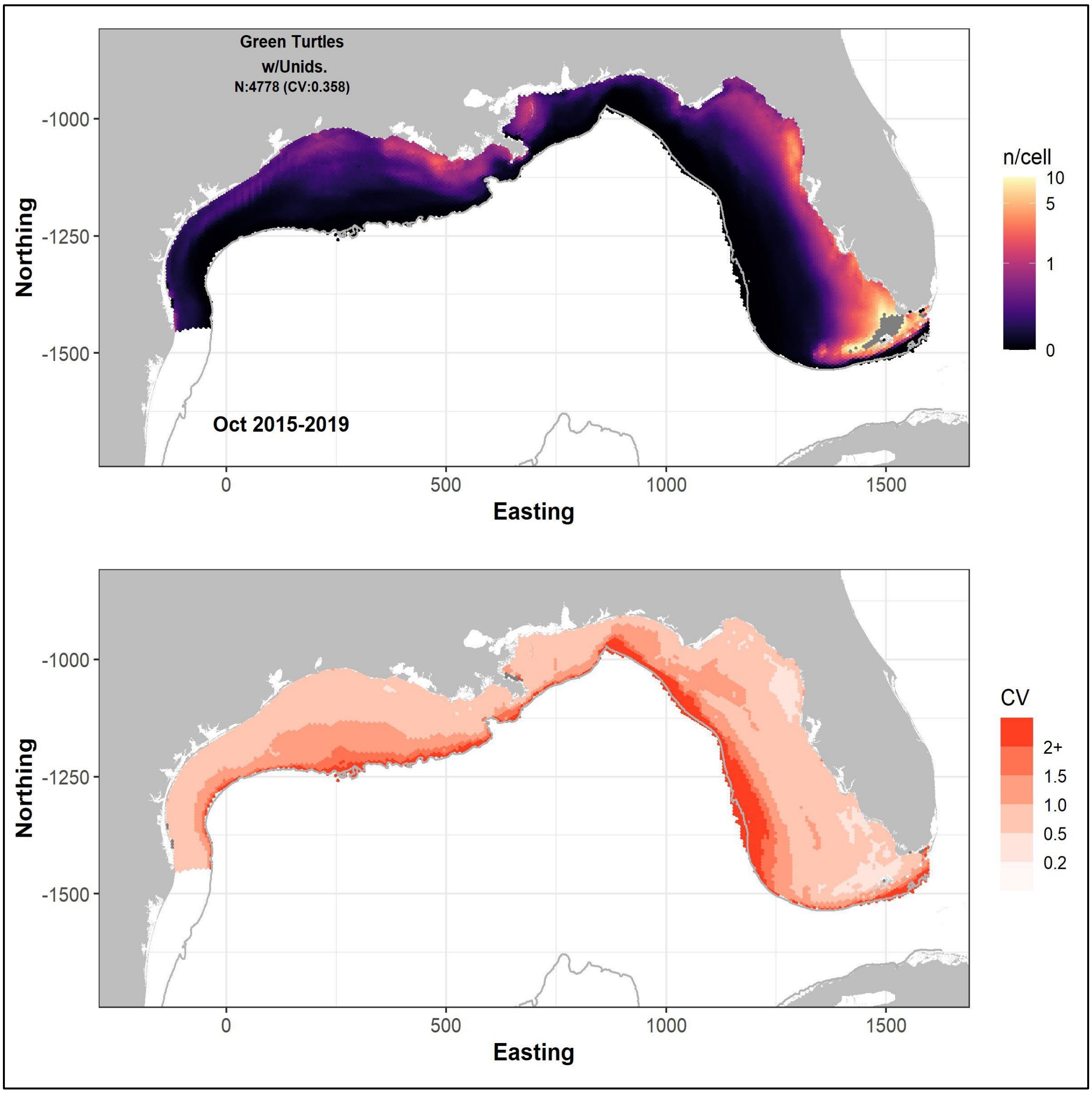

Figure D.2-59. Density model prediction for shelf green turtles in the NGOM for the months of October 2015–2019.

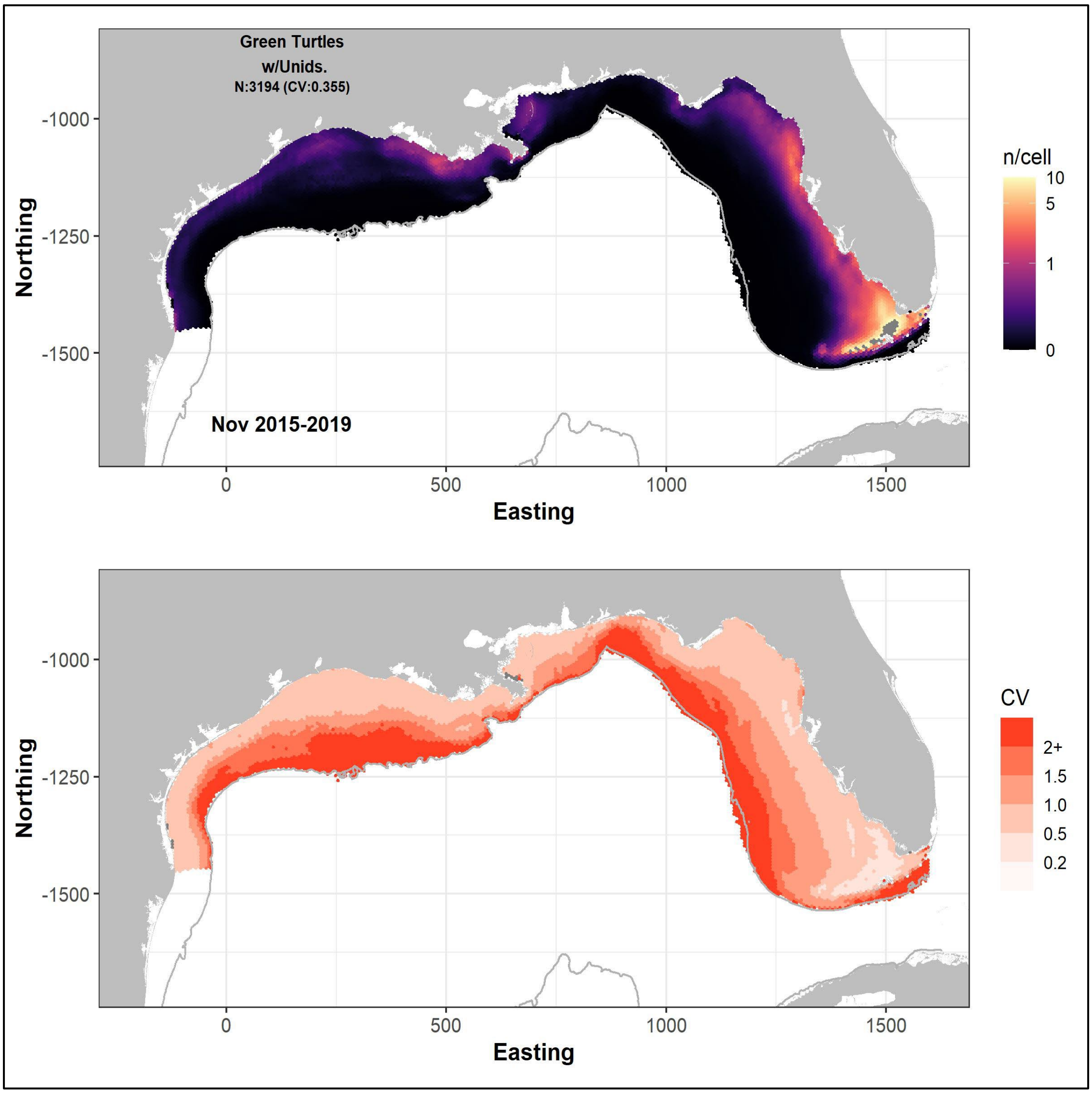

Figure D.2-60. Density model prediction for shelf green turtles in the NGOM for the months of November 2015–2019.

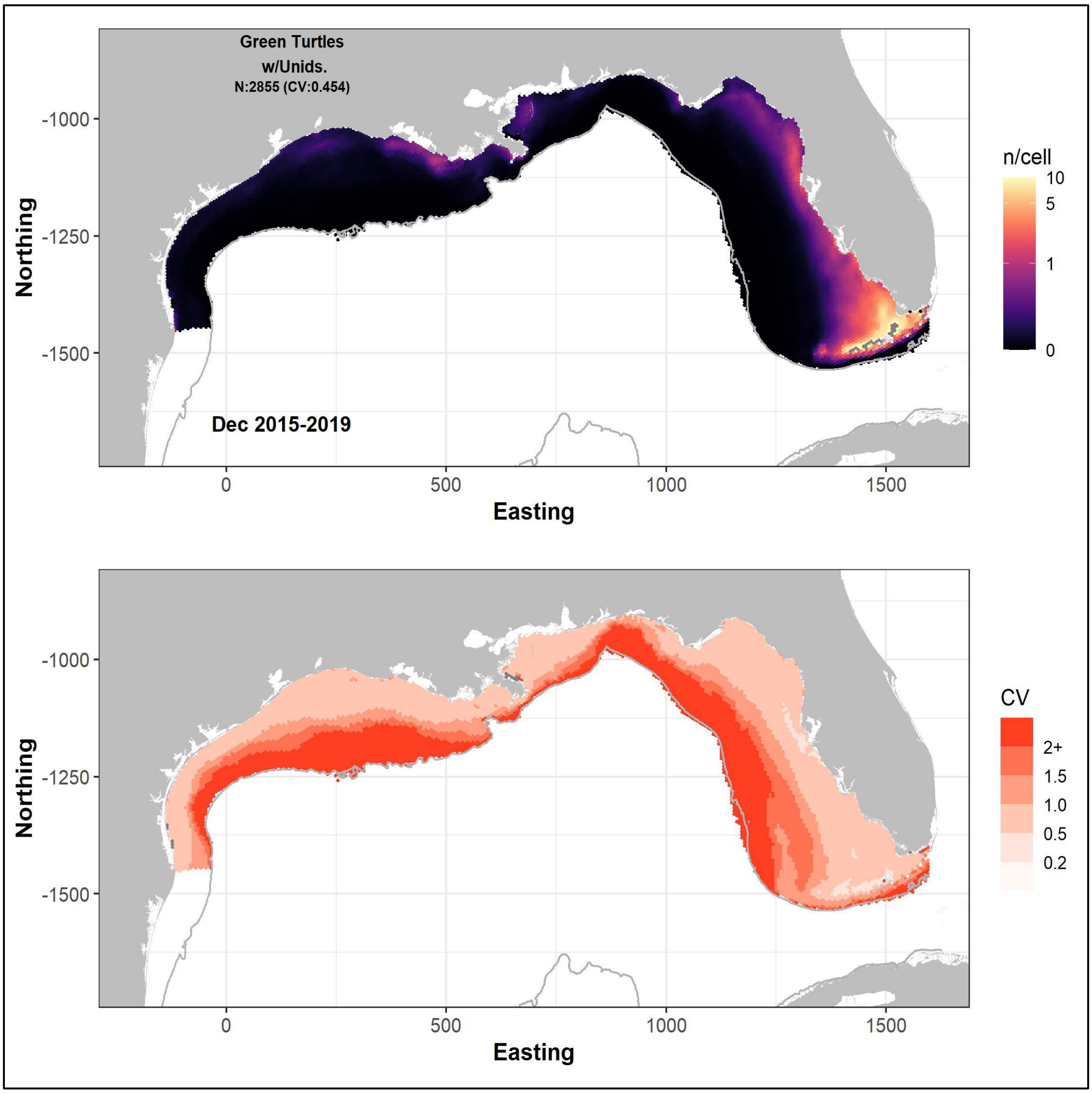

Figure D.2-61. Density model prediction for shelf green turtles in the NGOM for the months of December 2015–2019.

The density models for green turtles were summarized seasonally (Winter: Dec–Feb, Spring: Mar–May, Summer: Jun–Aug, Fall: Sep–Nov) and by Bureau of Ocean Energy Management (BOEM) planning area to generate abundance and CVs that reflect uncertainty in both model parameters and interannual variation in environmental conditions for each area (Table D.2-6).

Table D.2-6. Seasonal abundance (CV) of green turtles in US shelf waters during 2015–2019 for BOEM planning areas

Season	Eastern	Central	Western
Winter	936 (0.55)	116 (0.71)	46 (0.89)
Spring	2,142 (0.43)	352 (0.79)	200 (0.86)
Summer	4,119 (0.34)	963 (0.51)	632 (0.47)
Fall	2,181 (0.58)	535 (0.74)	196 (0.8)

D.2.5.5 Gulf-Wide Average Monthly Density: 2015–2019

Prediction maps were generated using monthly environmental parameters for the period of 2015–2019 extrapolating the model for green turtles throughout the GOM. As noted above, these extrapolations should be treated with caution given the potential for changing species-environment relationships in unsampled areas (Figures D.2-62–D.2-73).

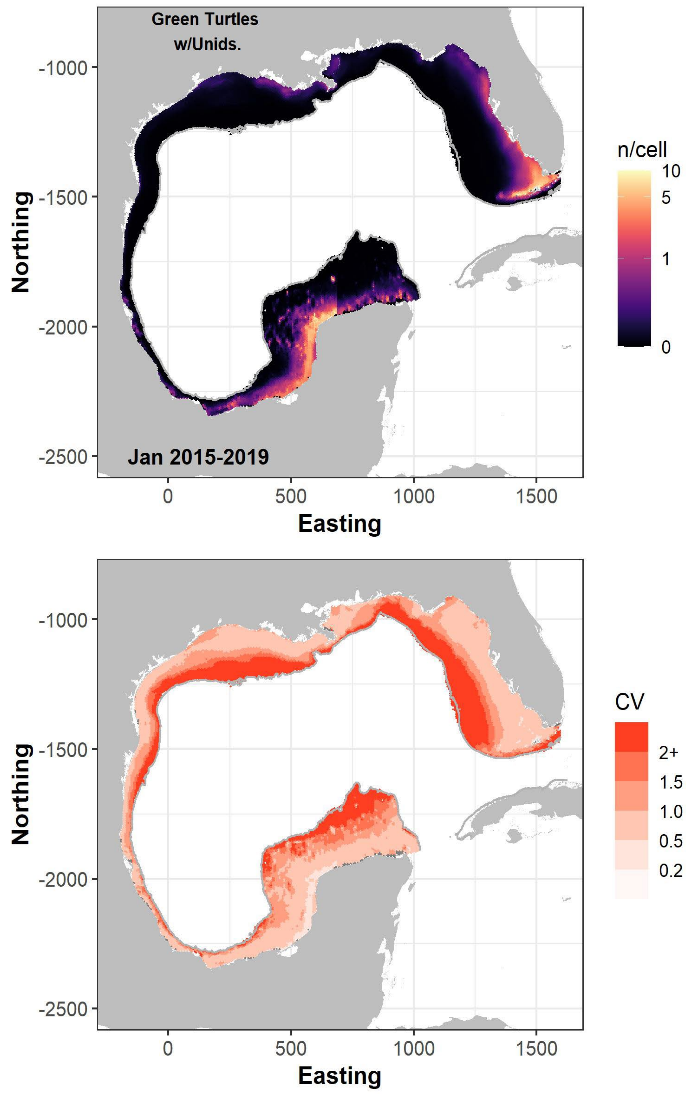

Figure D.2-62. Projected density model for shelf green turtles in the entire GOM for the months of January 2015–2019.

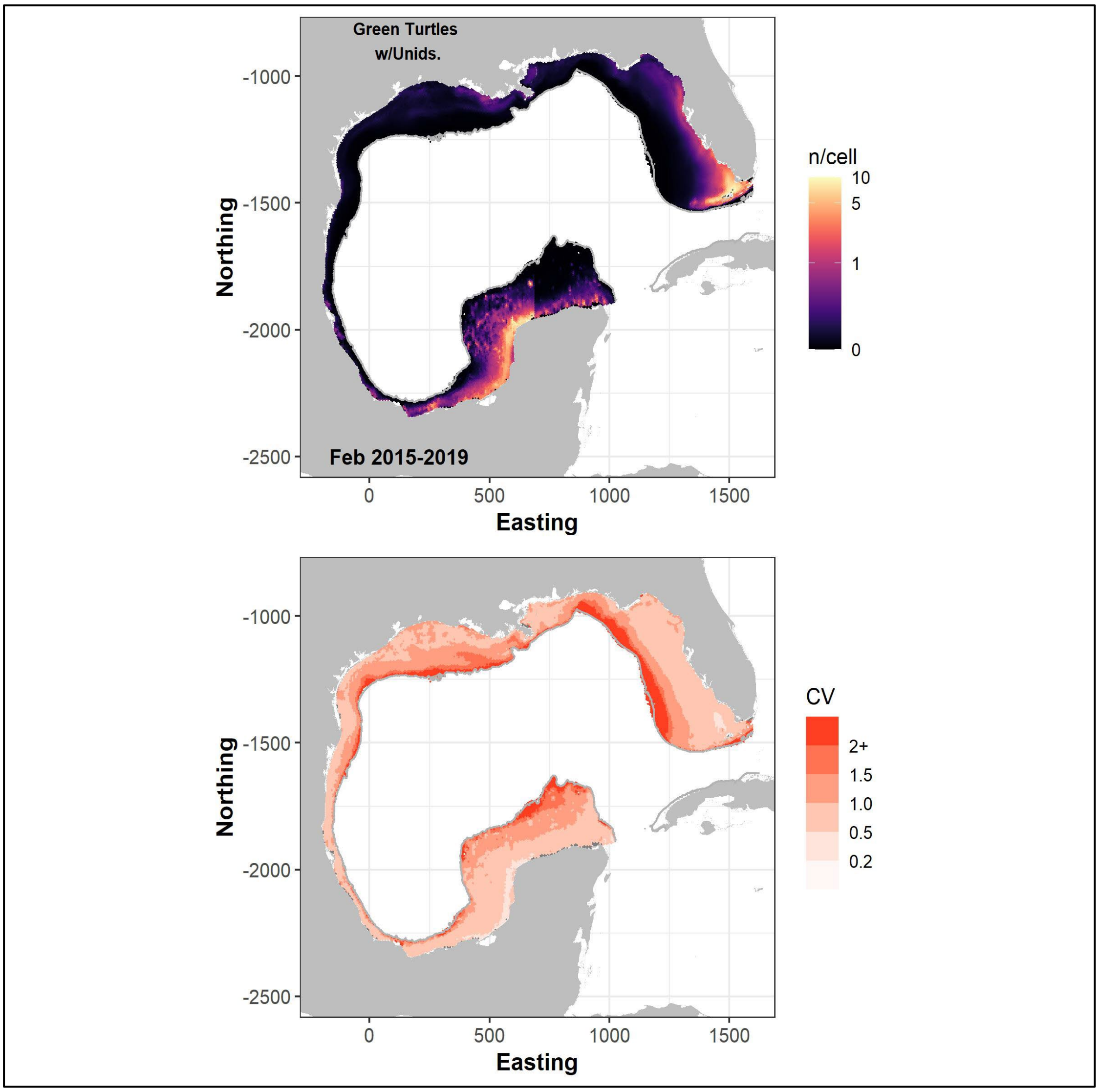

Figure D.2-63. Projected density model for shelf green turtles in the entire GOM for the months of February 2015–2019.

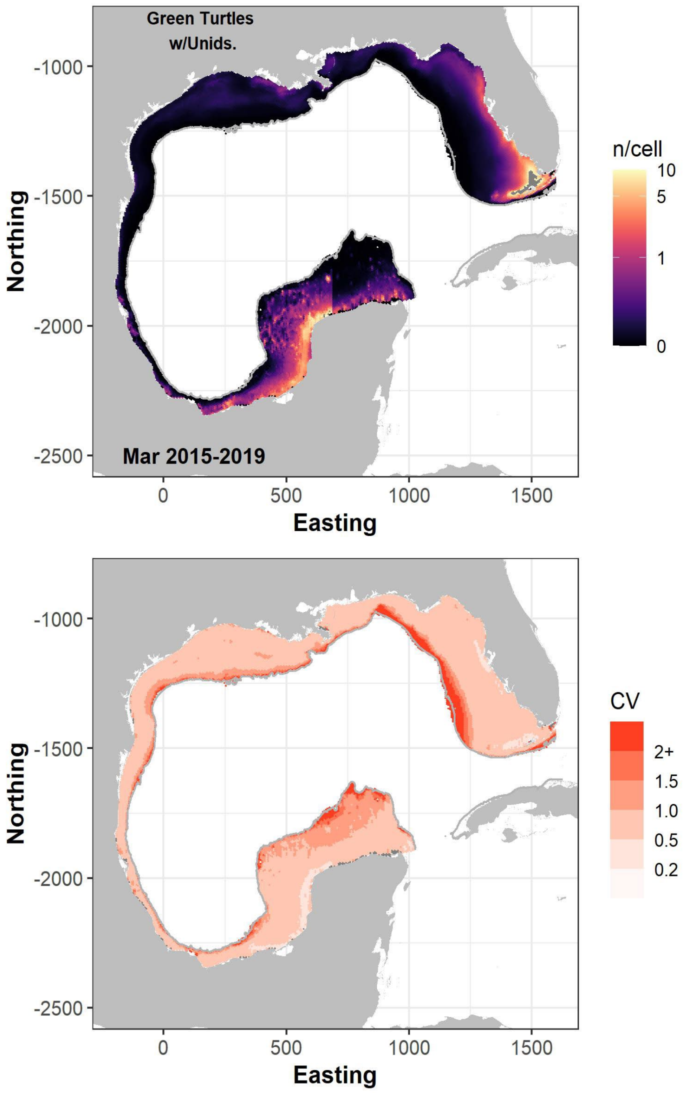

Figure D.2-64. Projected density model for shelf green turtles in the entire GOM for the months of March 2015–2019.

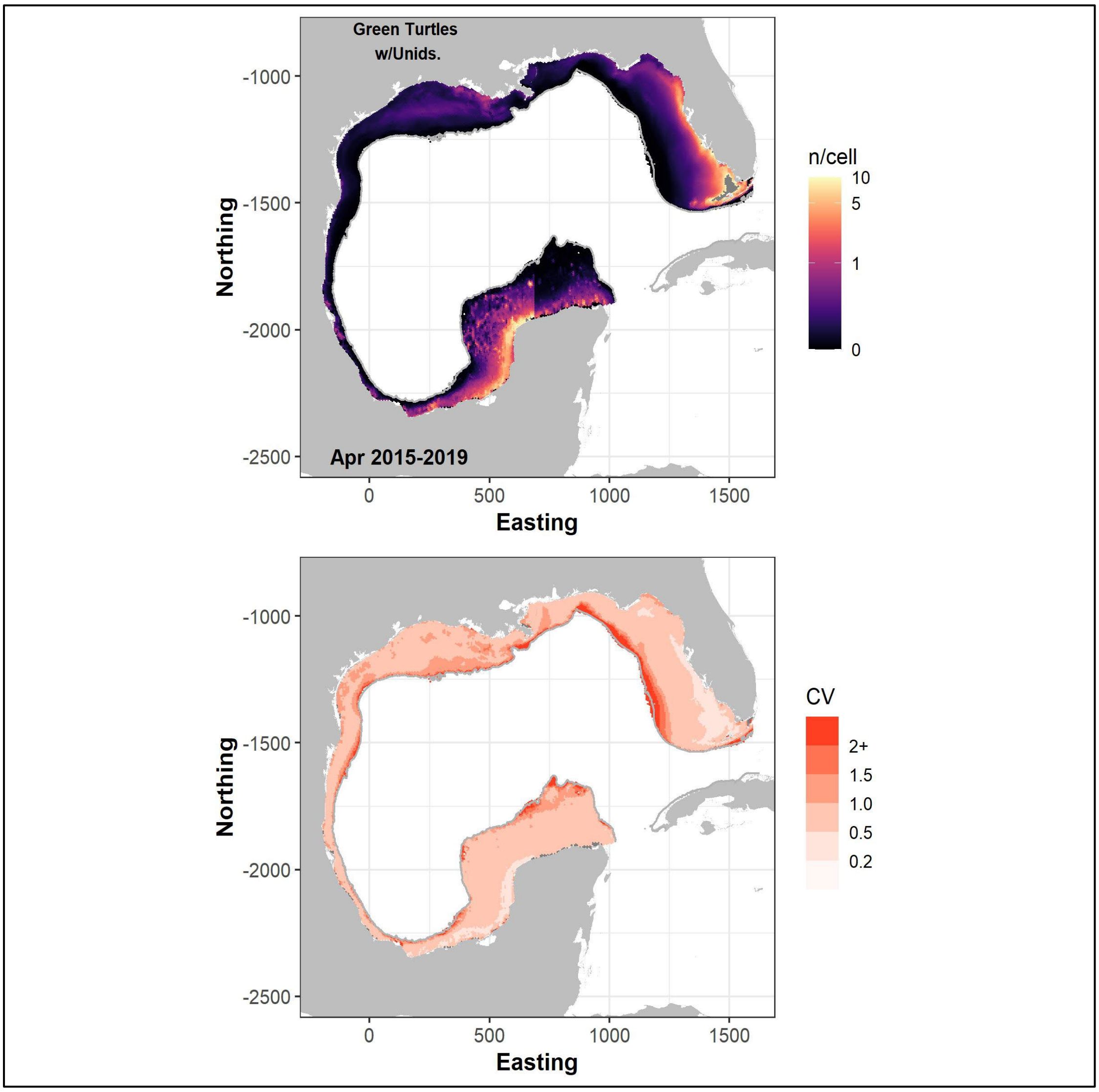

Figure D.2-65. Projected density model for shelf green turtles in the entire GOM for the months of April 2015–2019.

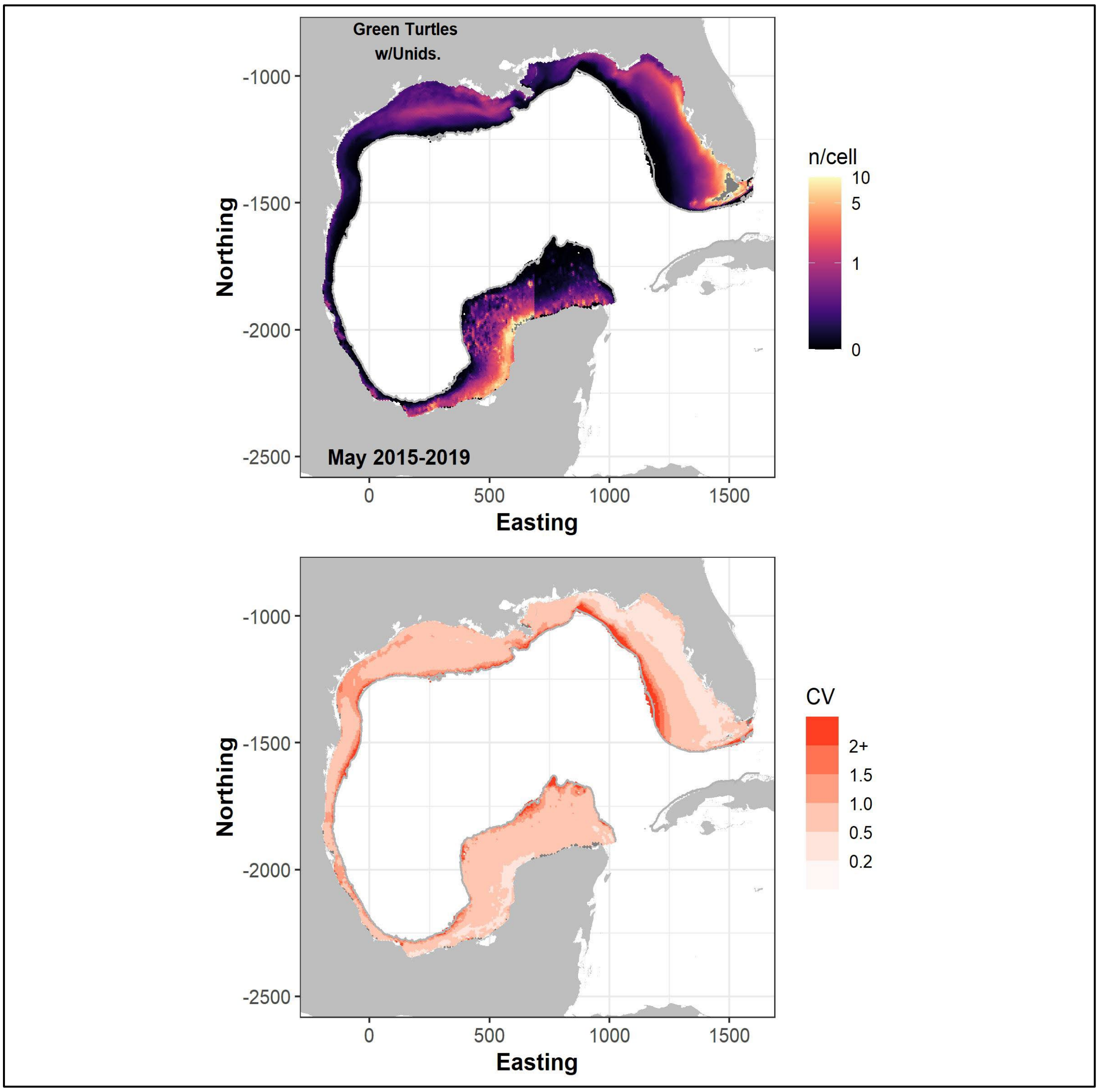

Figure D.2-66. Projected density model for shelf green turtles in the entire GOM for the months of May 2015–2019.

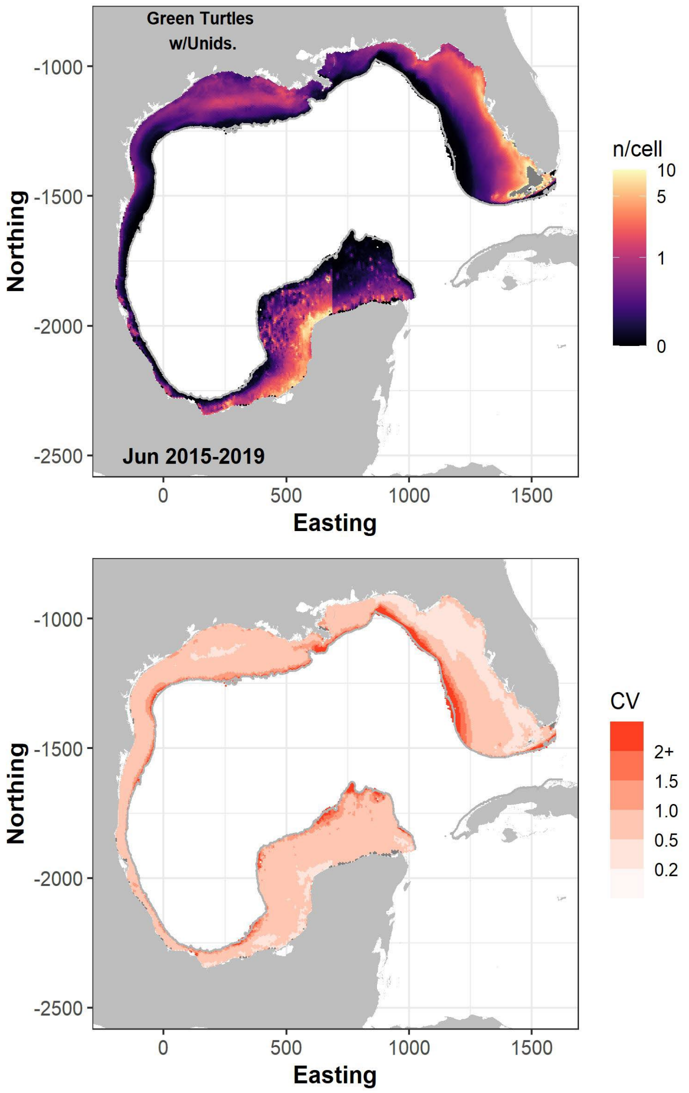

Figure D.2-67. Projected density model for shelf green turtles in the entire GOM for the months of June 2015–2019.

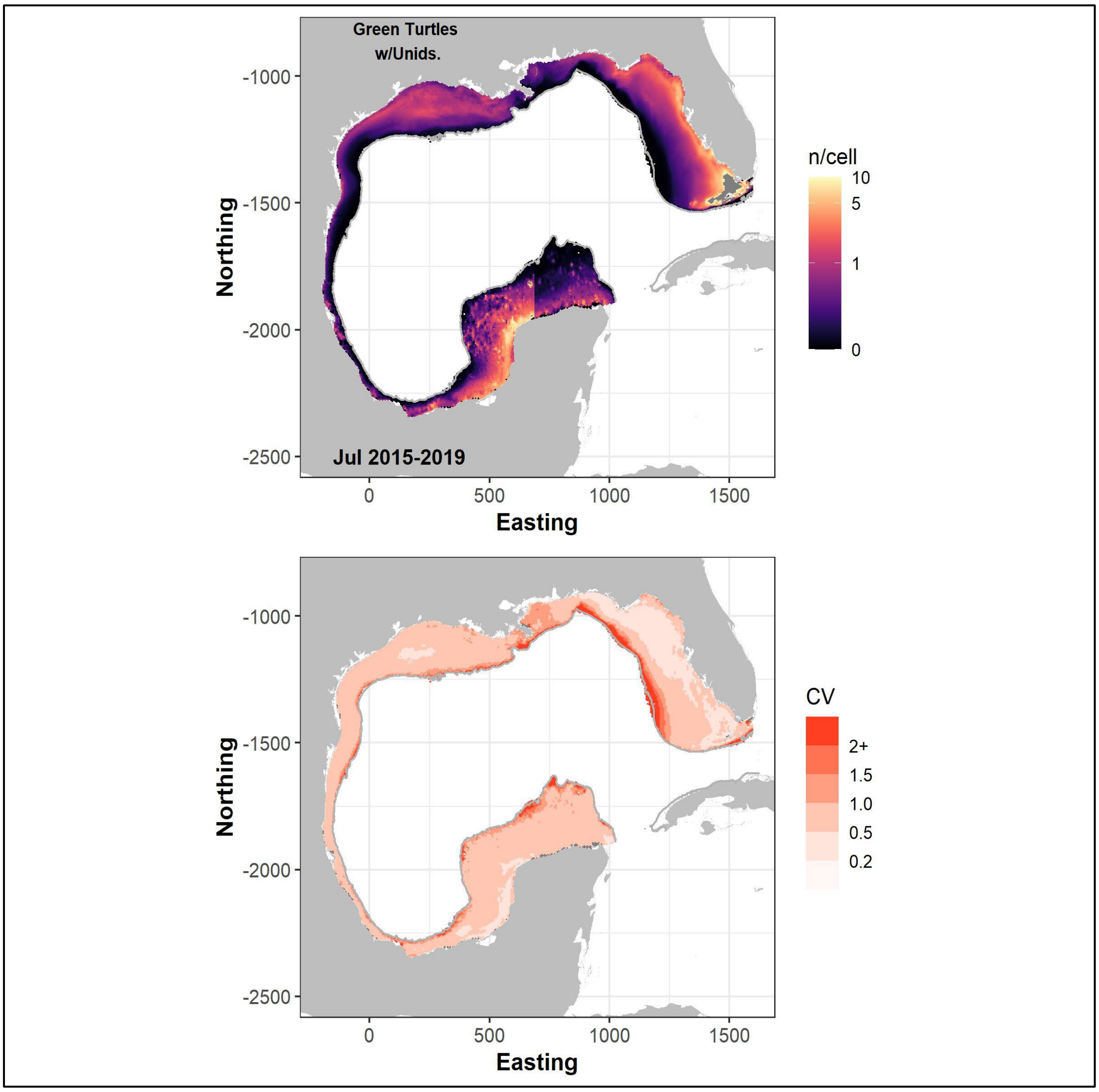

Figure D.2-68. Projected density model for shelf green turtles in the entire GOM for the months of July 2015–2019.

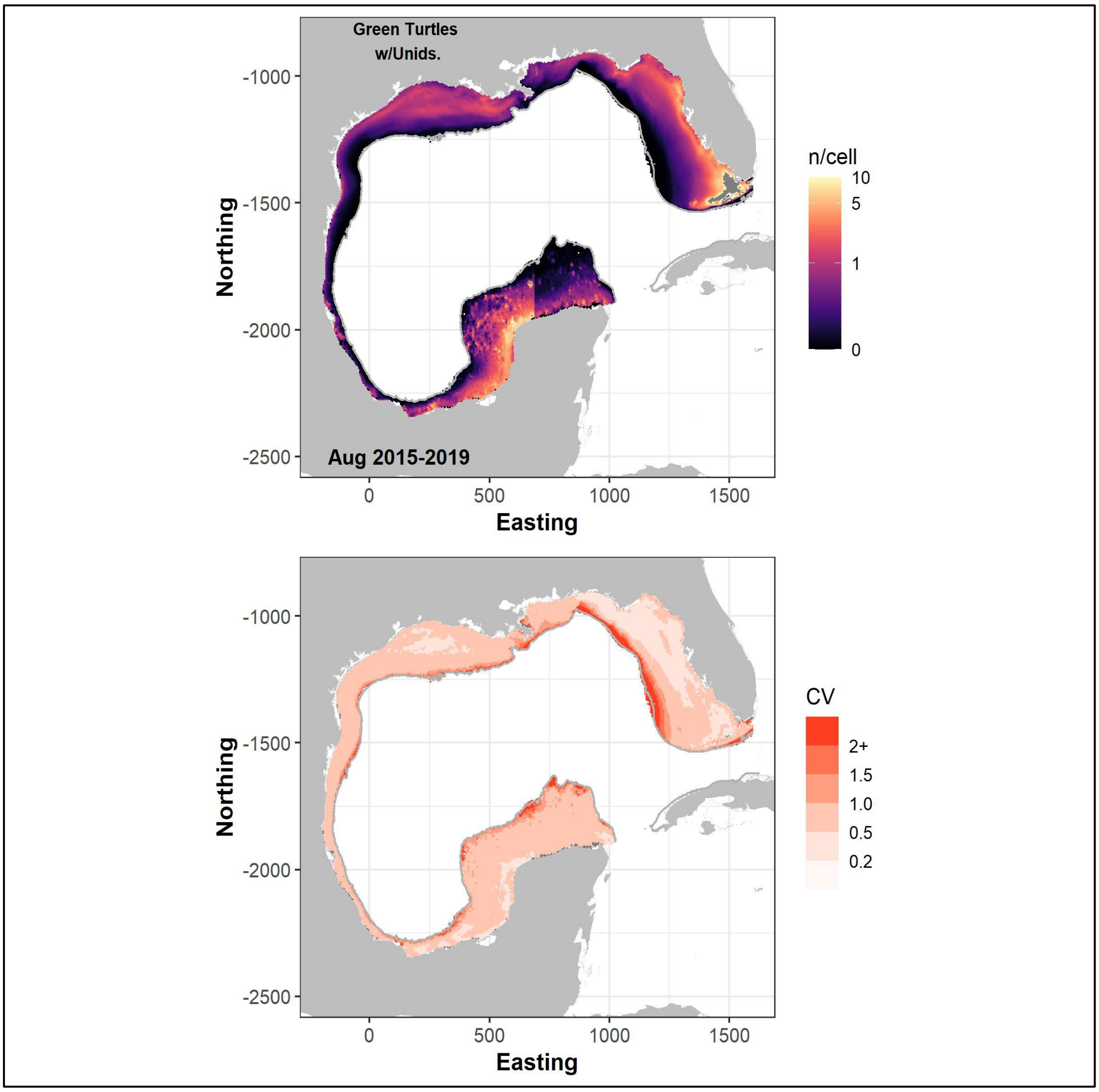

Figure D.2-69. Projected density model for shelf green turtles in the entire GOM for the months of August 2015–2019.

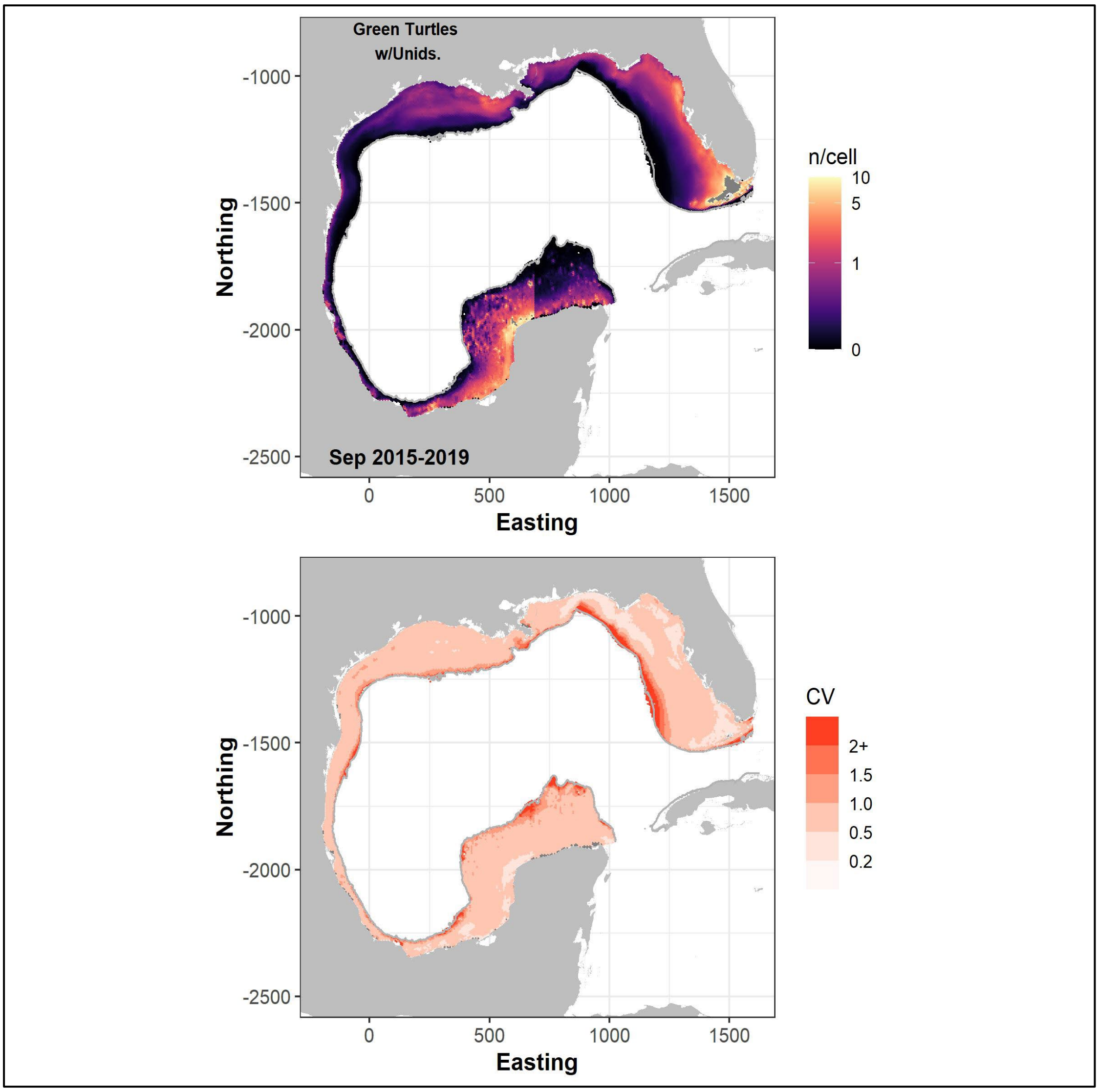

Figure D.2-70. Projected density model for shelf green turtles in the entire GOM for the months of September 2015–2019.

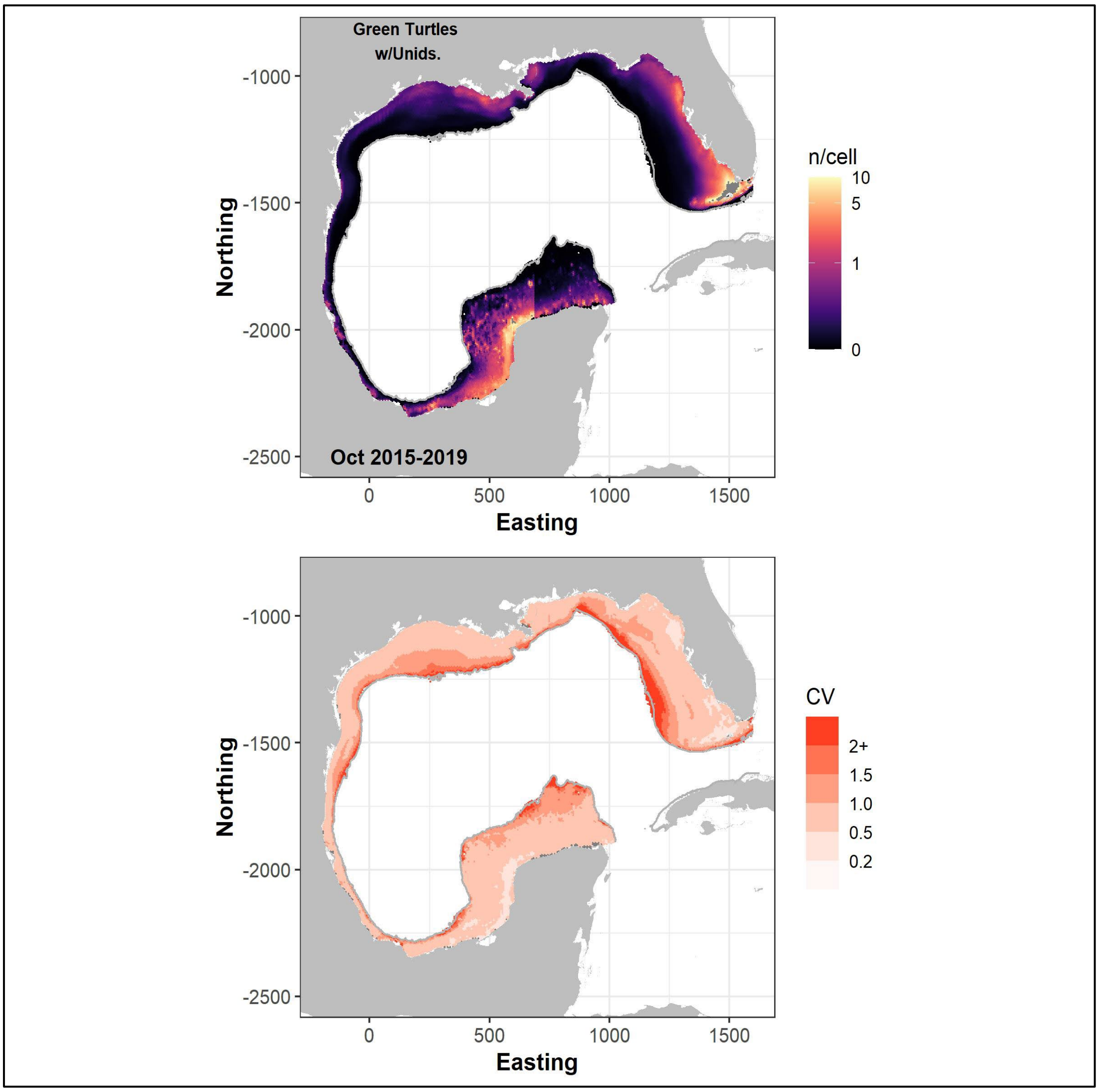

Figure D.2-71. Projected density model for shelf green turtles in the entire GOM for the months of October 2015–2019.

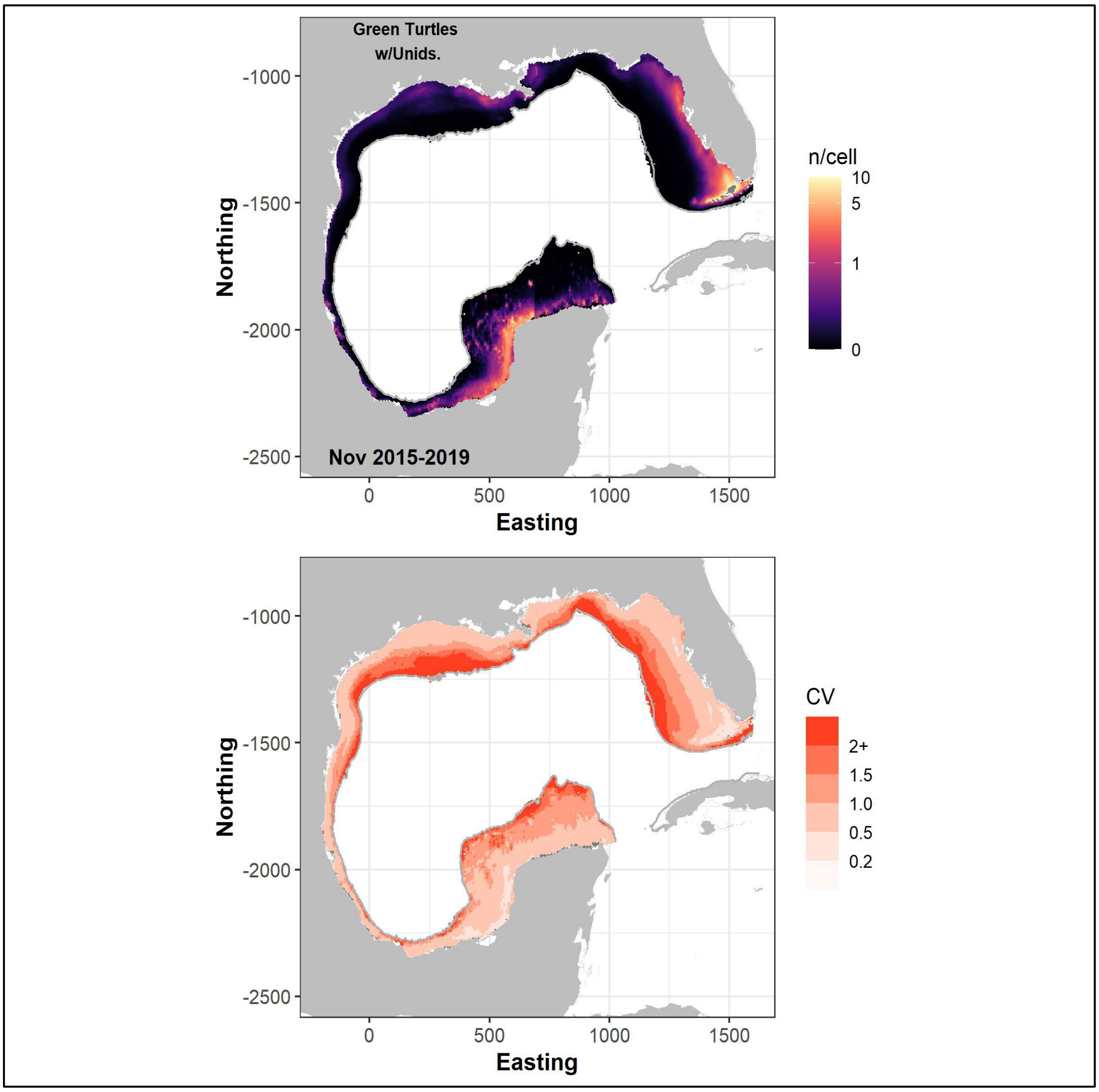

Figure D.2-72. Projected density model for shelf green turtles in the entire GOM for the months of November 2015–2019.

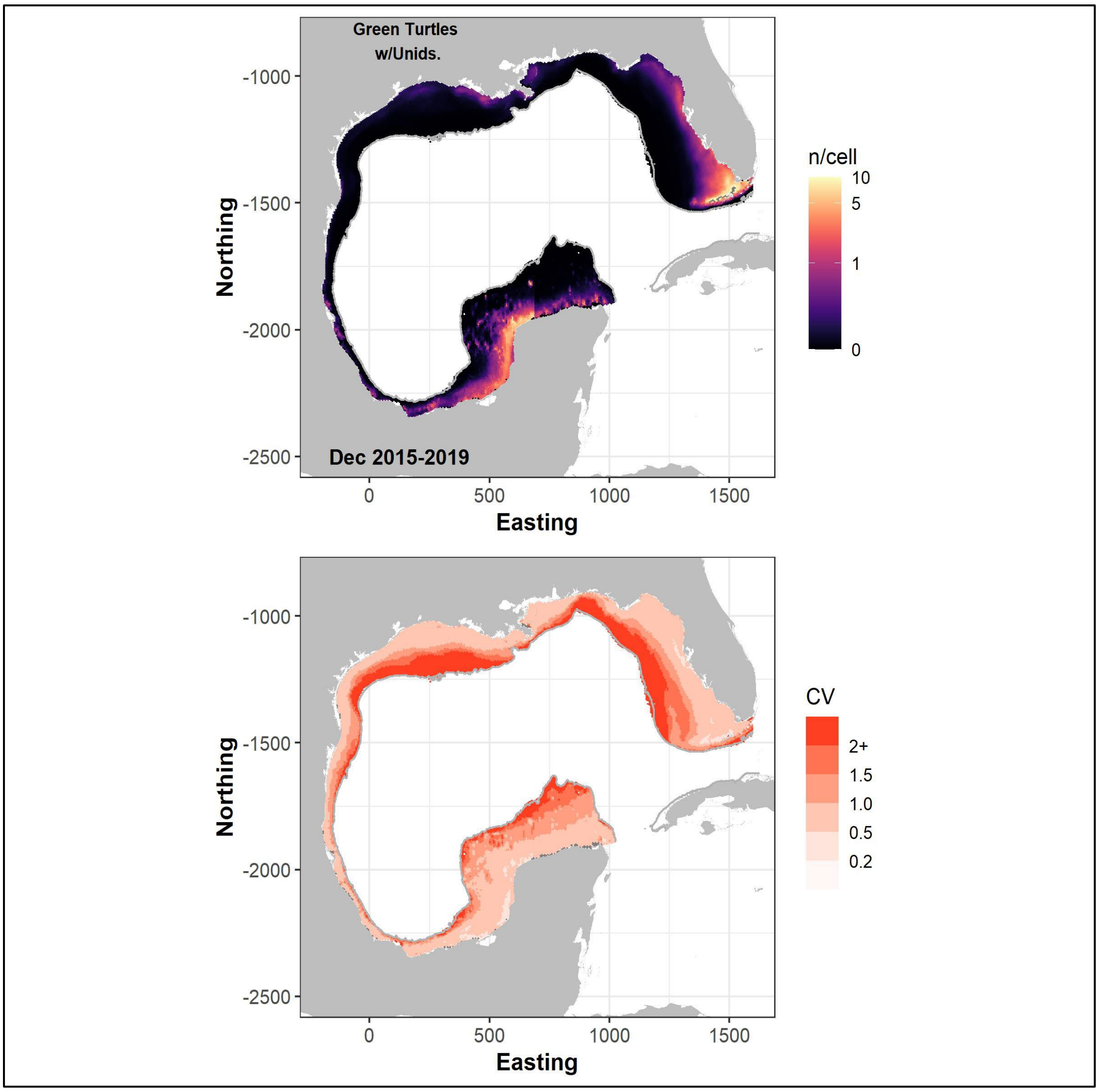

Figure D.2-73. Projected density model for shelf green turtles in the entire GOM for the months of December 2015–2019.

D.3 Gulf of Mexico Kemp's Ridley Turtle Density Models

Photo credit: NOAA Fisheries/Kate Sampson

This section describes the development of spatial density models (SDMs) for Kemp's ridley turtles (*Lepidochelys kempii*) occurring over the continental shelf based upon seasonal aerial surveys conducted in 2011–2012 and 2017–2018, including average abundance prediction maps generated using monthly environmental parameters for the period of 2015–2019. This section also includes projected density and prediction maps for shelf waters of the entire Gulf of Mexico (GOM).

D.3.1 Survey Data and Sightings

Aerial line-transect surveys were conducted over the continental shelf of the northern Gulf of Mexico (NGOM) in a survey region extending from the shoreline to the shelf break (approximately the 200 m isobath) between Key West, Florida and the US-Mexico border near Brownsville, Texas. Each survey was conducted in a NOAA Twin Otter flying at a survey altitude of 183 m (600 ft) and an approximate speed of 100 knots. Survey tracklines were spaced approximately 20 km apart and were oriented so as to be perpendicular to the shoreline. The aircraft was equipped with two large bubble windows in the forward portion of the aircraft (left and right sides) and one right bubble window and a belly window in the aft portion of the aircraft to allow effective visualization of the trackline (see Figure 2 in the GoMMAPPS project final report). Surveys were conducted using two independent teams to allow estimation of detection probability in within the surveyed strip and on the trackline using Mark Recapture Distance Sampling (MRDS) approaches. Aerial surveys were conducted in spring 2011, summer 2011, fall 2011, and winter 2012 as part of the Natural Resource Damage Assessment (NRDA) associated with the *Deepwater Horizon* oil spill. Additional surveys were conducted in the summer of 2017, winter 2018, and fall 2018 as part of the Gulf of Mexico Marine Assessment Program for Protected Species (GoMMAPPS). Additional details about the survey design and execution are contained in Garrison et al. (2022). The total number of Kemp's ridley turtle groups sighted is shown in Table D.3-1.

Table D.3-1. Kemp's ridley turtles observed for each survey included in this analysis

Survey	Groups	Individuals
TOSE11F	218	230
TOSE11Sp	13	13
TOSE11Su	136	143
TOSE12W	233	251
TOSE17Su	111	113
TOSE18F	83	83
TOSE18W	231	249

During summer and fall, Kemp's ridley turtles were observed primarily in the central NGOM and in the northwestern GOM at intermediate depths over the continental shelf. During winter months, high densities of Kemp's ridley turtles were also observed off the northwestern coast of Florida (Figure D.3-1).

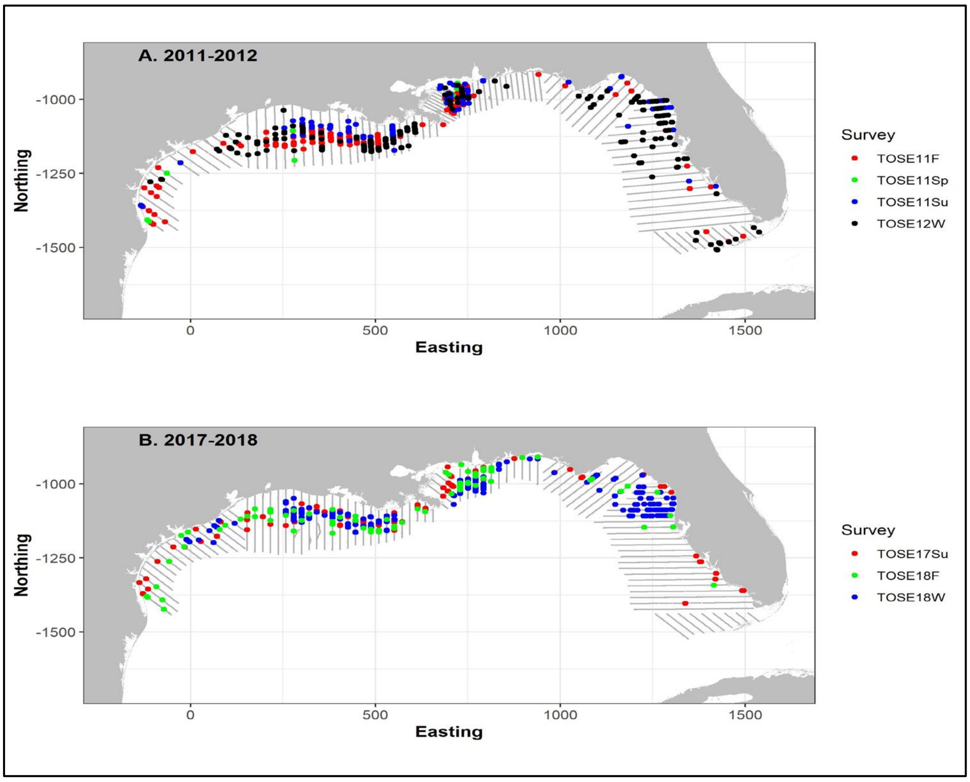

Figure D.3-1. Survey effort and Kemp's ridley turtle sightings during (A) 2011–2012 and (B) 2017–2018.

D.3.2 Distribution of Sightings and Physical Oceanography during Each Survey

The distribution of Kemp's ridley turtle sightings and surface temperature and chlorophyll-a concentrations are shown in Figures D.3-2–D.3-8.

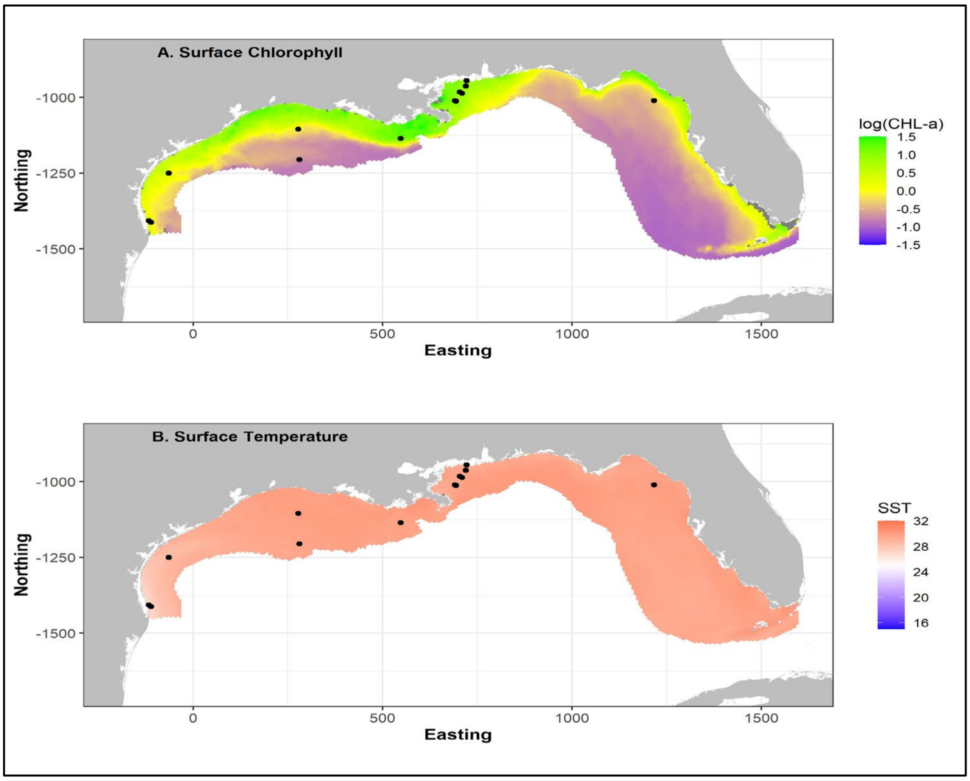

Figure D.3-2. Kemp's ridley turtle sightings during spring 2011.

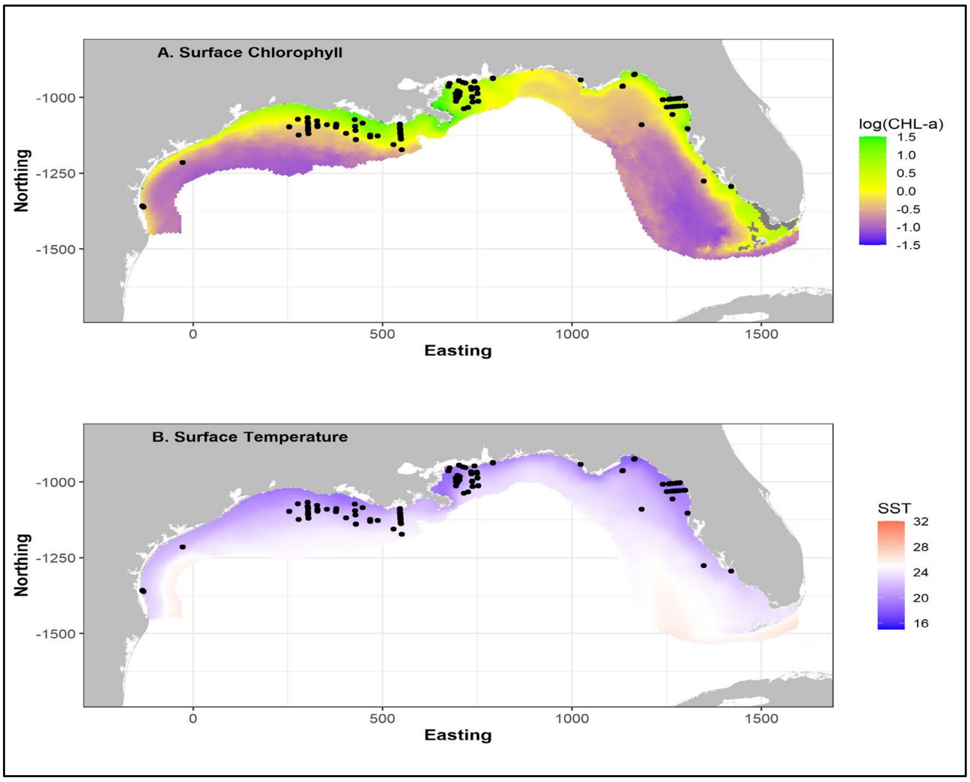

Figure D.3-3. Kemp's ridley turtle sightings during summer 2011.

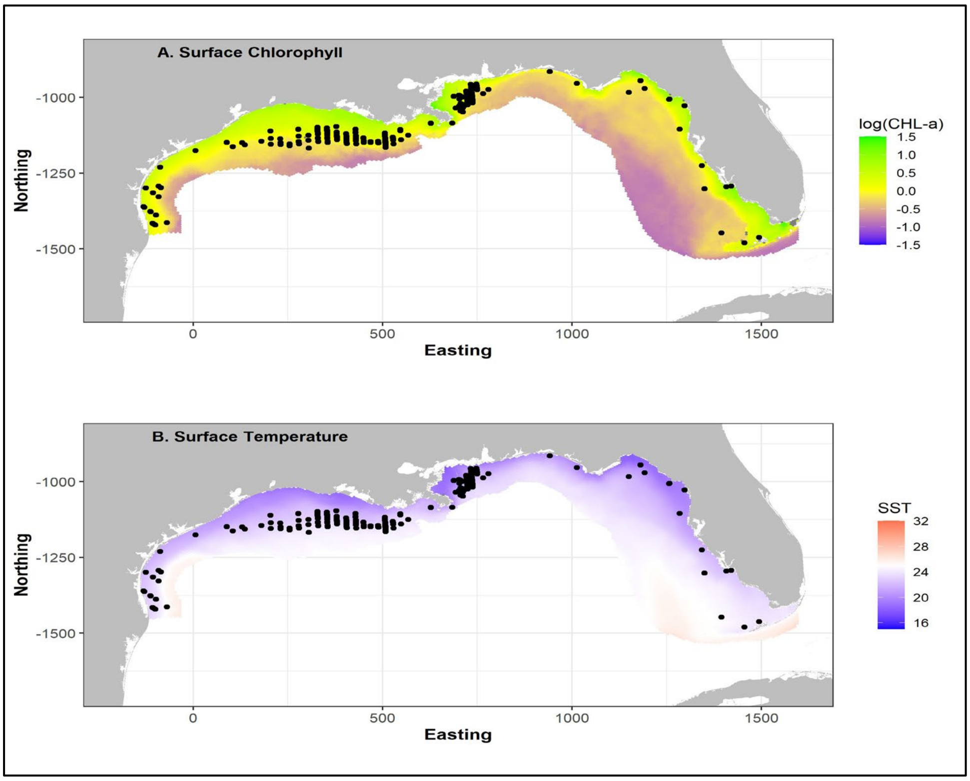

Figure D.3-4. Kemp's ridley turtle sightings during fall 2011.

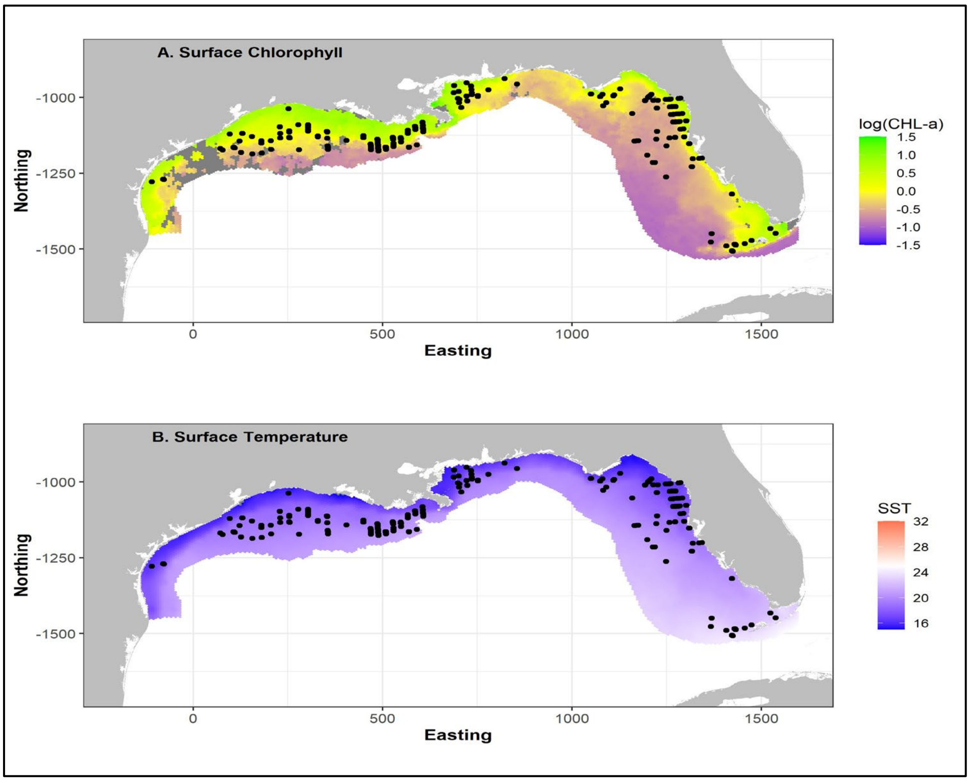

Figure D.3-5. Kemp's ridley turtle sightings during winter 2012.

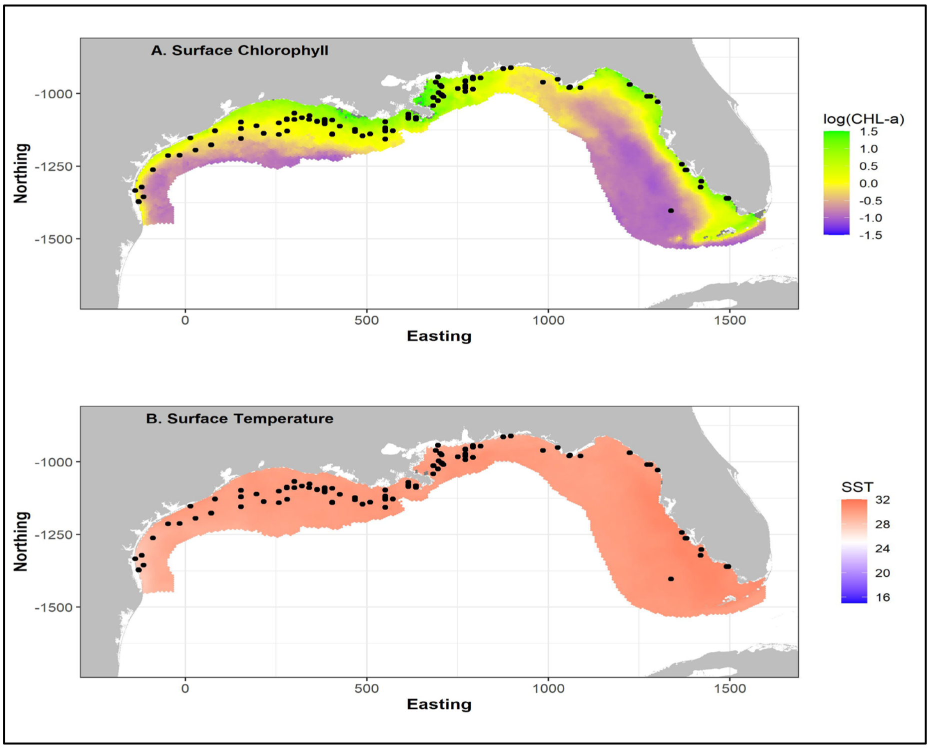

Figure D.3-6. Kemp's ridley turtle sightings during summer 2017.

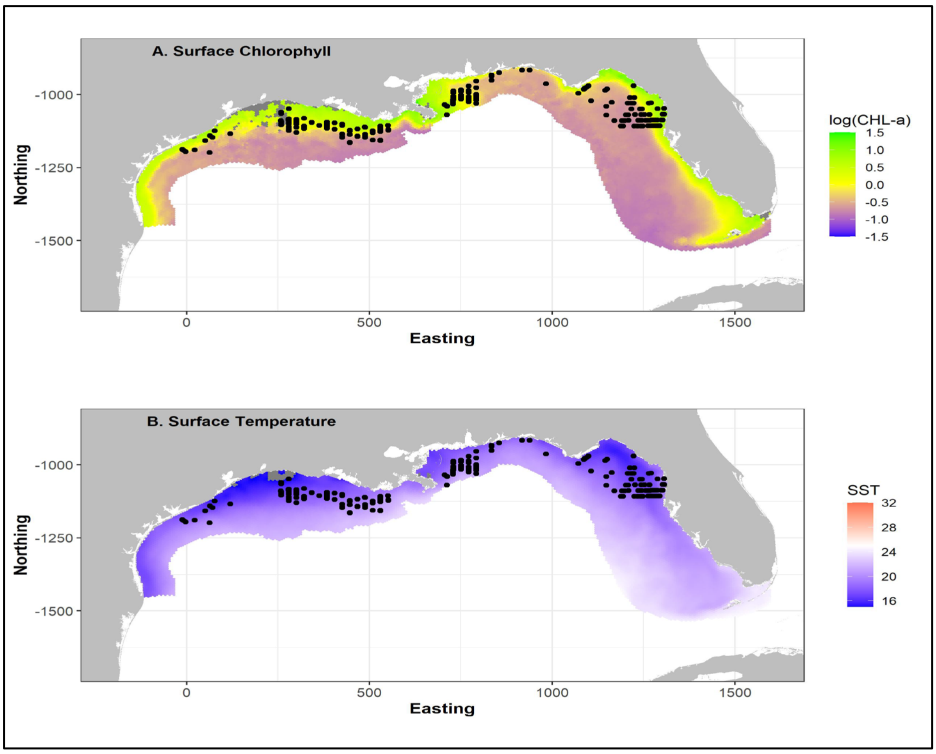

Figure D.3-7. Kemp's ridley turtle sightings during winter 2018.

Note that survey effort was incomplete in the northeastern GOM during this survey.

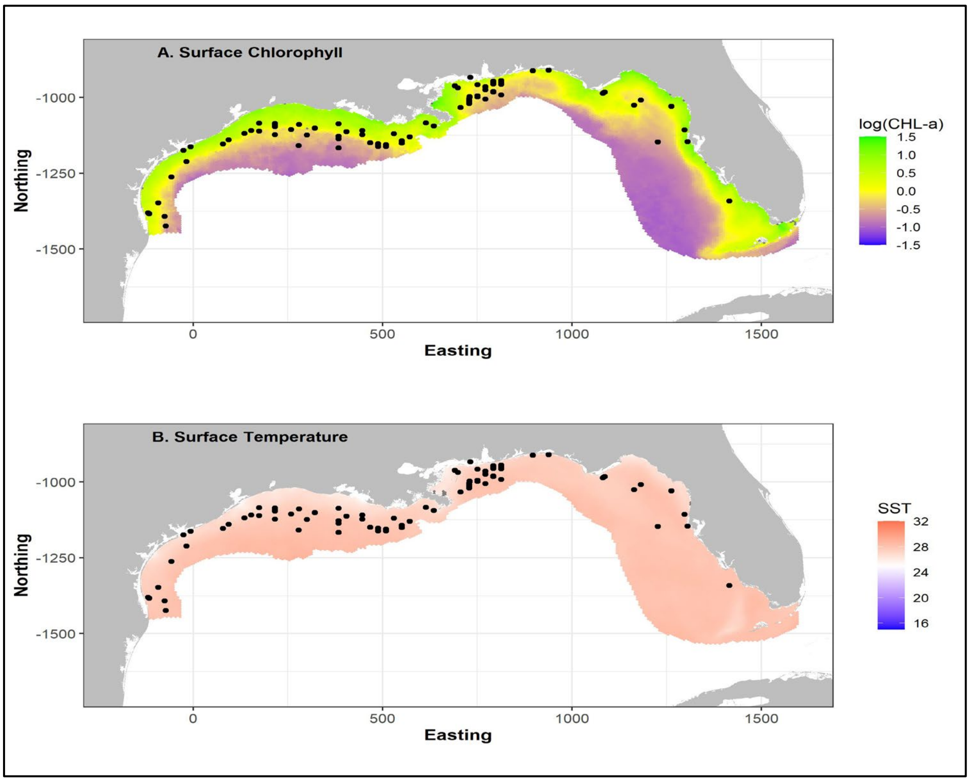

Figure D.3-8. Kemp's ridley turtle sightings during fall 2018.

D.3.3 Distance Analysis and Detection Probability

Detection probability within the surveyed strip was estimated using MRDS approaches. Covariates considered for inclusion in the detection function included sea state, cloud cover, water turbidity, and sun penetration. In addition, the correlation between the ln(group size) and perpendicular sighting distance (PSD) was examined, but there was no relationship between group size and detection distances, so group size was not considered for inclusion in the model.

The best model was selected by first examining the distribution of PSD and selecting an appropriate right truncation distance and key function. Then, all combinations of detection covariates were considered for both the detection function and mark-recapture portion of the model, and the model with the lowest Akaike's Information Criterion (AIC) was selected. The best model used a hazard-rate key function with a right truncation distance of 300 m. No covariates were included in the distance component of the model. Cloud Cover, Turbidity, and an interaction term with observer position were included in the mark-recapture component of the model (Table D.3-2).

Table D.3-2. Parameters included in the detection probability function

(MCDS = Multiple covariate distance sampling)

Model	Parameter	Estimate	SE
MCDS	MCDS Intercept	4.716	0.027
MRDS	MRDS Intercept	1.784	0.375
MRDS	Distance	0.002	0.003
MRDS	Observer	-1.047	0.152
MRDS	Cloud Cover	-0.087	0.058
MRDS	Turbidity	-0.229	0.139
MRDS	Distance x Observer	-0.001	0.001

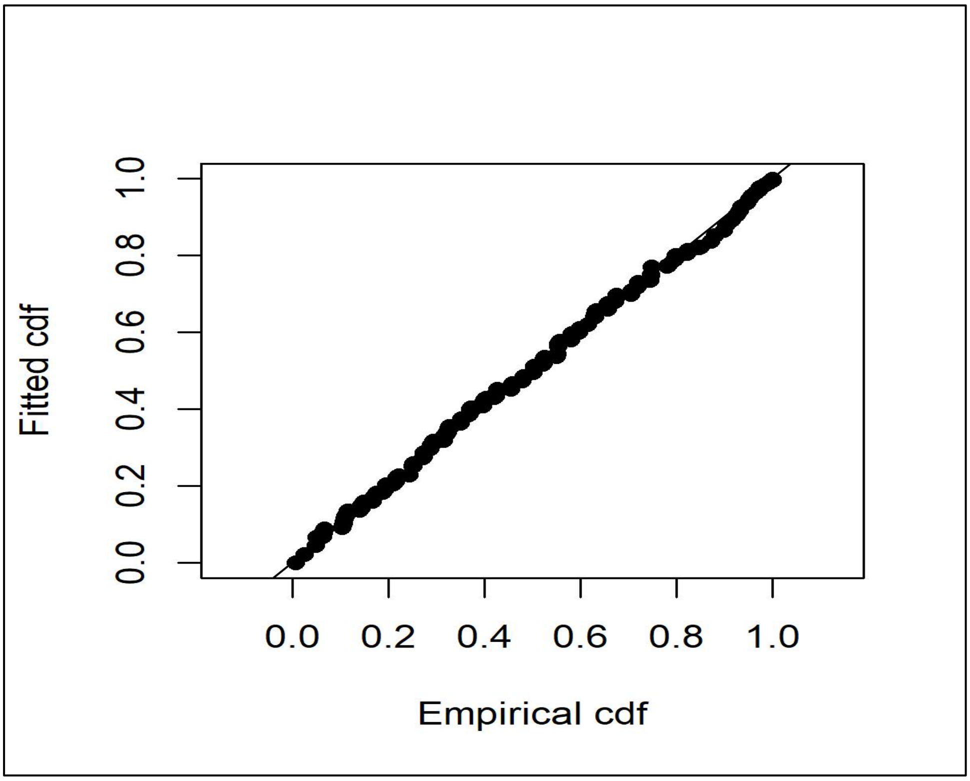

Figure D.3-9. MRDS detection function Q-Q plot (cdf = cumulative distribution function).

The resulting detection probability function had a good overall fit as indicated by the linear Quantile-Quantile (Q-Q) plot (Figure D.3-9). The Chi-square goodness of fit test p-value was 0 (Chi-square = 46.52, df = 10) indicating some deviation from the expected model especially in the mark-recapture component at high PSD. However, the Cramer-von Mises test p-value was 0.261 (test statistic = 0.203) suggesting an adequate model fit overall.

The estimated detection probability on the trackline is shown in Table D.3-3, and the detection probability function is shown in Figure D.3-10.

Table D.3-3. Estimated detection probability and number of detections in the surveyed area from Multiple Covariate Distance function

Parameter	Estimate	SE	CV
Detection probability	0.463	0.012	0.026
Team 1 p(0)	0.552	0.043	0.078
Team 2 p(0)	0.303	0.029	0.096
Combined p(0)	0.686	0.039	0.057
Overall Avg. Detection Prob.	0.318	0.020	0.063

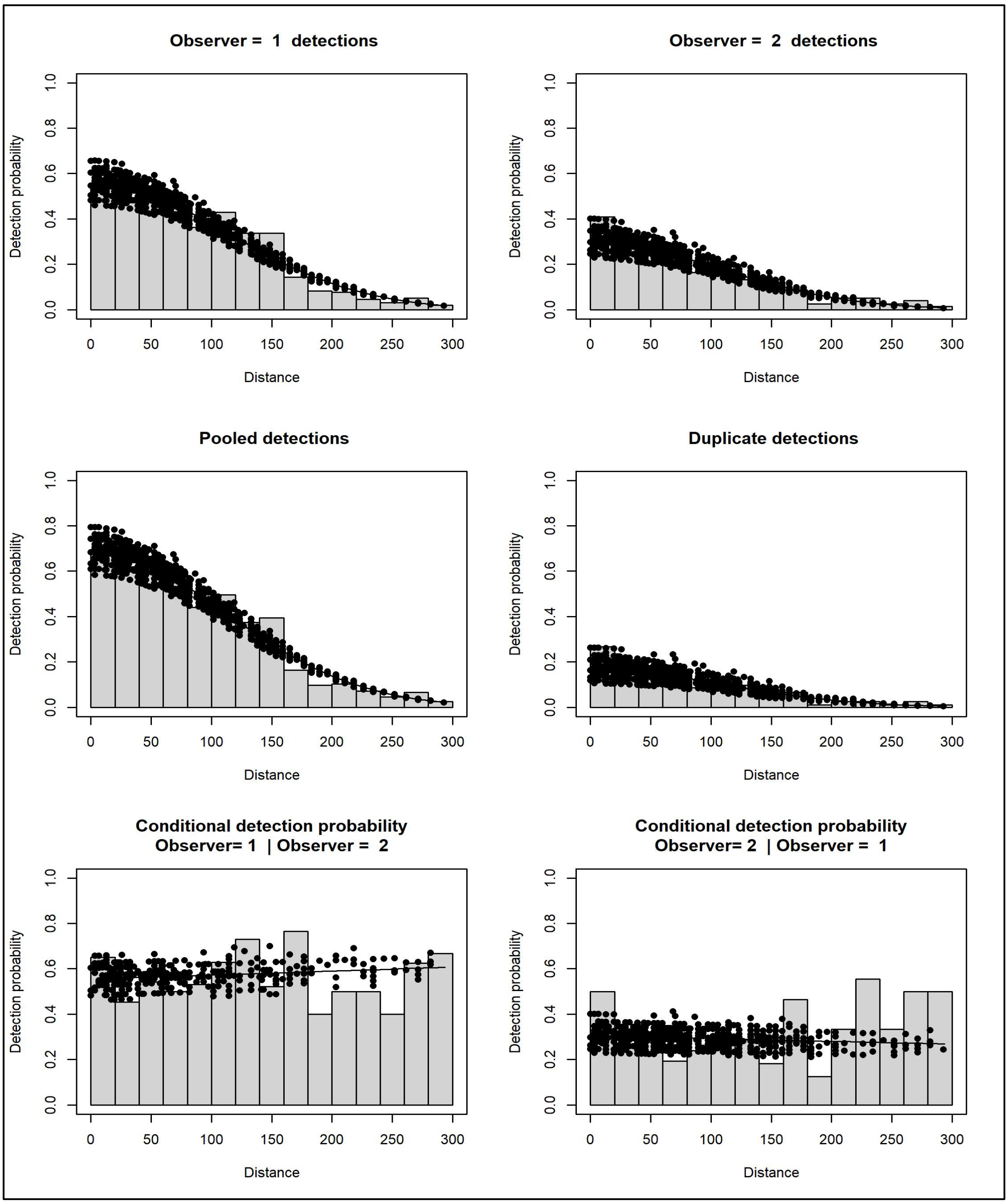

Figure D.3-10. Mark-recapture distance sampling detection probability.

D.3.3.1 Estimating Availability Bias

Kemp's ridley turtles spend a significant amount of time underwater where they are not available to be counted by aerial observers. The amount of time below the surface varies both spatially and temporally as a function of the behavioral state of the turtles (e.g., feeding vs. traveling) and in response to environmental conditions. To account for availability bias, we applied a generalized additive model (GAM) of Kemp's ridley turtle occurrence in the upper 2 m of the water column based upon an extensive database of telemetry tag data (Roberts et al. 2022). This GAM used environmental variables to predict the probability that Kemp's ridley turtles would be near the surface and available to the aerial survey team. For Kemp's ridley turtles, significant environmental predictors of availability included season, sea surface temperature, distance from the shelf break, water depth, salinity, the occurrence of fronts, and spatial location. The probability that each turtle observed in the aerial survey was near the surface was predicted based upon the environmental conditions at the time of observation (Figure D.3-11). The median probability that a Kemp's ridley turtle was at the surface was 0.332 (Inter-quartile range: 0.262–0.390). The number of turtles observed at the location was divided by the estimated probability to account for availability to the survey team. This corrected number was the response variable in the SDM.

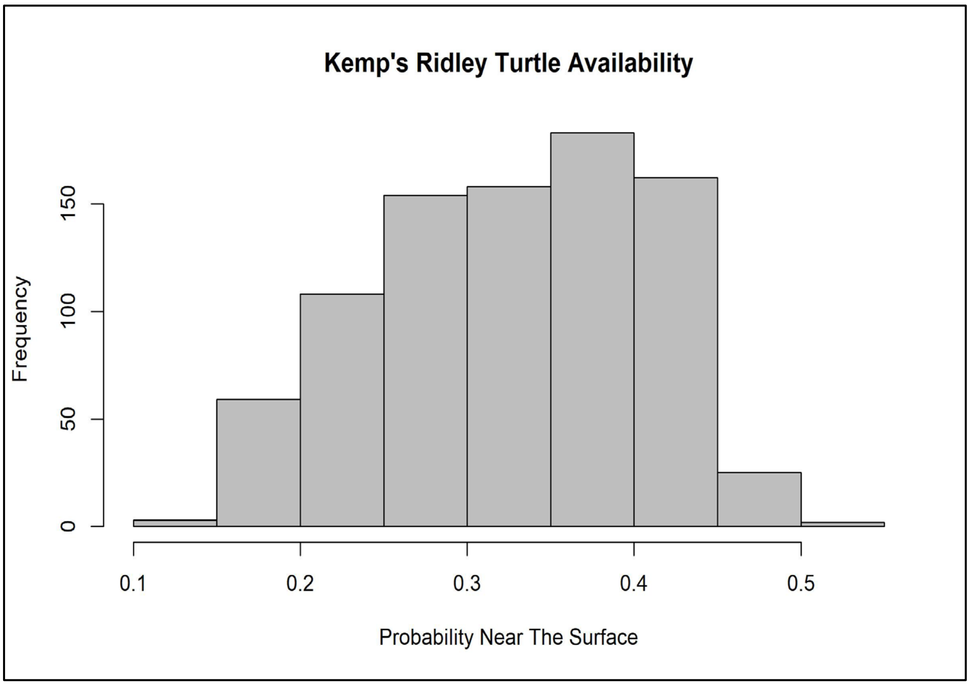

Figure D.3-11. Probability that Kemp's ridley turtles observed during the aerial surveys were near the surface based upon a generalized additive model accounting for spatial and temporal variability in turtle dive behavior.

(Roberts et al. 2022).

D.3.4 Spatial Density Model Selection

A GAM was used to develop a spatial density model to describe the effect of habitat variables on the density and abundance of Kemp's ridley turtles in the NGOM. Survey effort (kilometers of survey trackline) was partitioned into segments within a grid of hexagonal cells of 40 km^2 area and matched to physical oceanographic parameter values within each cell. Each resulting segment was considered a sampling unit within the GAM, and the number of animals observed on the segments was the response variable in a log count model assuming a Tweedie error distribution to account for overdispersed count data. An offset term (ln[strip area]) was included in the model to account for the effective area surveyed within each spatial cell based upon the detection probability function described above and covariates during the survey.

An initial GAM model was fit using all available oceanographic and physiographic variables. A reduced model was the selected including only model terms with p-value < 0.2. This reduced model was compared to the full model using AIC to ensure selection of the best fitting, most parsimonious model. Model fit was assessed through the examination of randomized quantile residuals and the associated Q-Q plot for deviance residuals.

For Kemp's ridley turtles, the selected model included Average Depth (AvgDepth), Sea Surface Temperature (Avg_SST), Distance from Shore (Dist2Shore), Distance from Canyons (Dist2Canyo), Distance from the shelf break (Dist2Shelf), log(chlorophyll-a concentration) (lAvg_Chl), Mixed Layer Depth (Avg_CMEMS_MLD), and the East-West coordinate (Easting) (Table D.3-4). In addition, a factor variable was included in the model to reflect the overall higher density of Kemp's ridley turtles in recent years compared to prior years. The model fit to the data was good with a generally linear Q-Q plot and few outlier residual values (Figure D.3-12).

Table D.3-4. Parameter estimates for the selected Generalized Additive Model

(EDF = effective degrees of freedom)

Term	EDF	Max..EDF	F.Statistic	P.value
s(AvgDepth)	5.717	9	7.94	< 0.001
s(Dist2Shore)	5.579	9	5.314	< 0.001
s(Dist2Shelf)	7.568	9	9.931	< 0.001
s(Dist2Canyo)	5.567	9	4.482	< 0.001
s(lAvg_Chl)	4.496	9	2.63	< 0.001
s(Avg_SST)	7.521	9	29.281	< 0.001
s(Easting)	8.344	9	11.182	< 0.001
s(Avg_CMEMS_MLD)	0.931	9	1.299	< 0.001

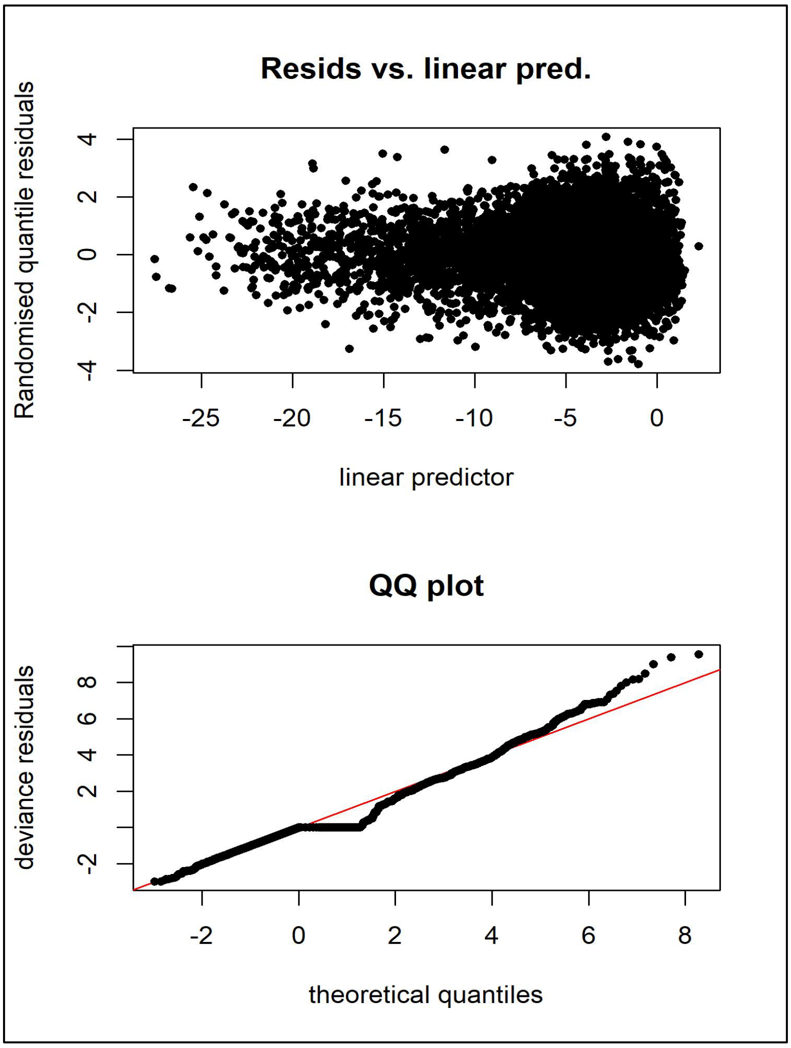

Figure D.3-12. GAM residual plots.

The selected model indicated that Kemp's ridley turtle density was highest at intermediate water depths. Density declined rapidly in waters greater than 15 m depth. The sea surface temperature effect reflects higher densities observed in winter months. The year effect also indicated that observed densities were higher during recent surveys (2017–2018) compared to prior years (2011–2012) (Figure D.3-13).

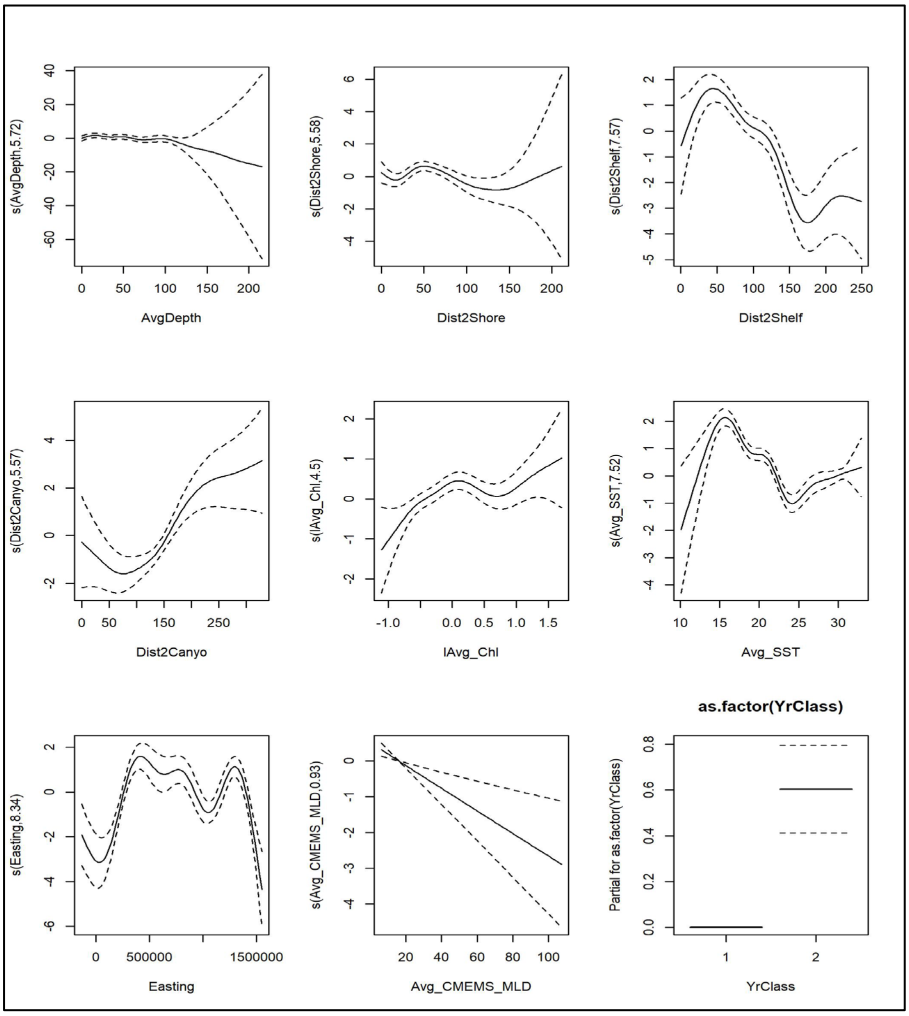

Figure D.3-13. GAM partial plots.

D.3.5 Spatial Density Model Prediction Maps and Model Output

Based upon the selected model, prediction maps were developed based upon monthly average oceanographic variable values for 2018. The estimated uncertainty (coefficient of variation [CV]) reflects only uncertainty in the GAM model fit and does not account for uncertainty in the detection probability function.

D.3.5.1 Northern Gulf of Mexico

Monthly prediction maps demonstrate variability in animal density resulting from variability in the underlying physical oceanography (Figures D.3-14–D.3-25).

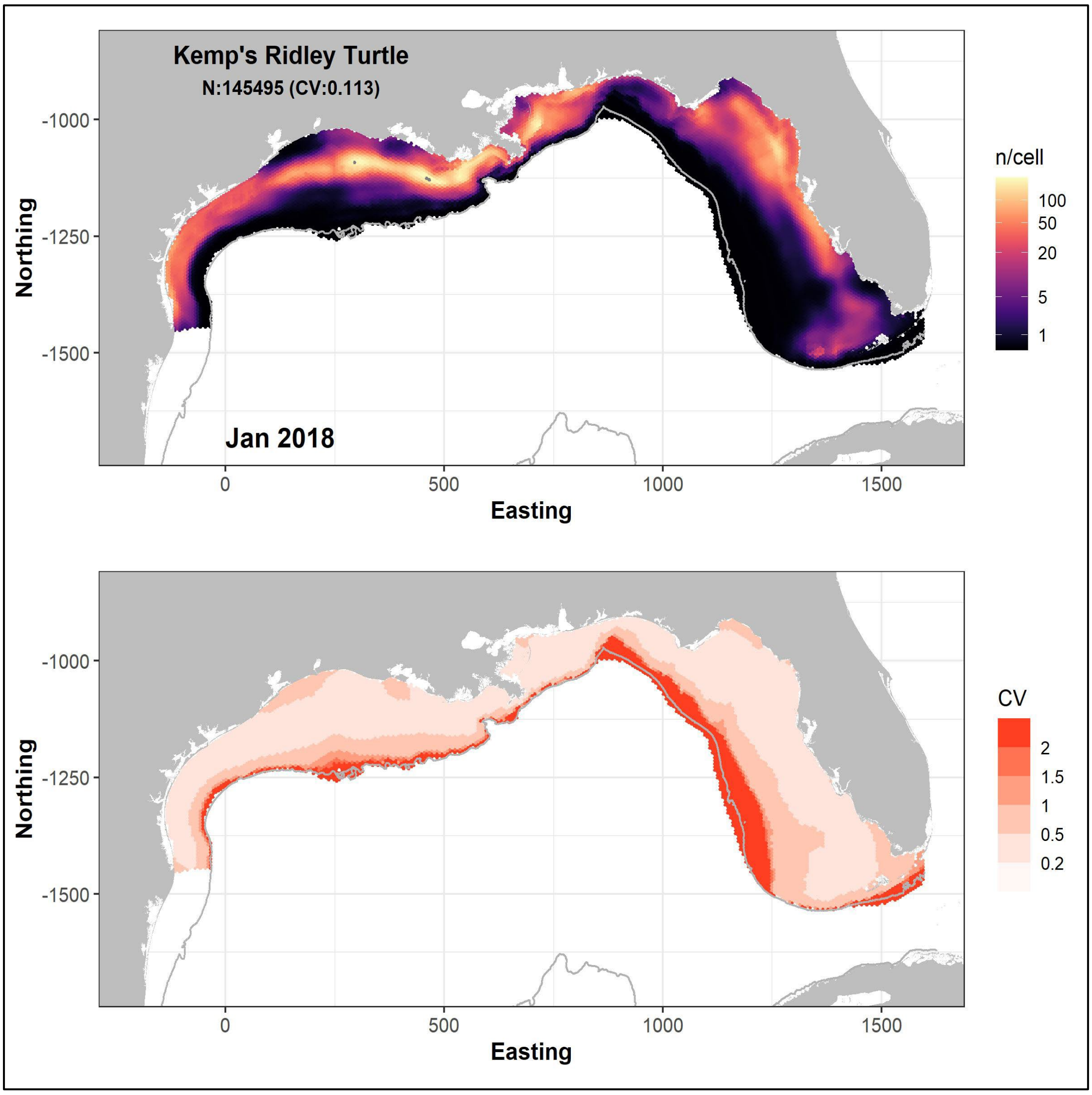

Figure D.3-14. Density model prediction for shelf Kemp's ridley turtles in the NGOM in January 2018.

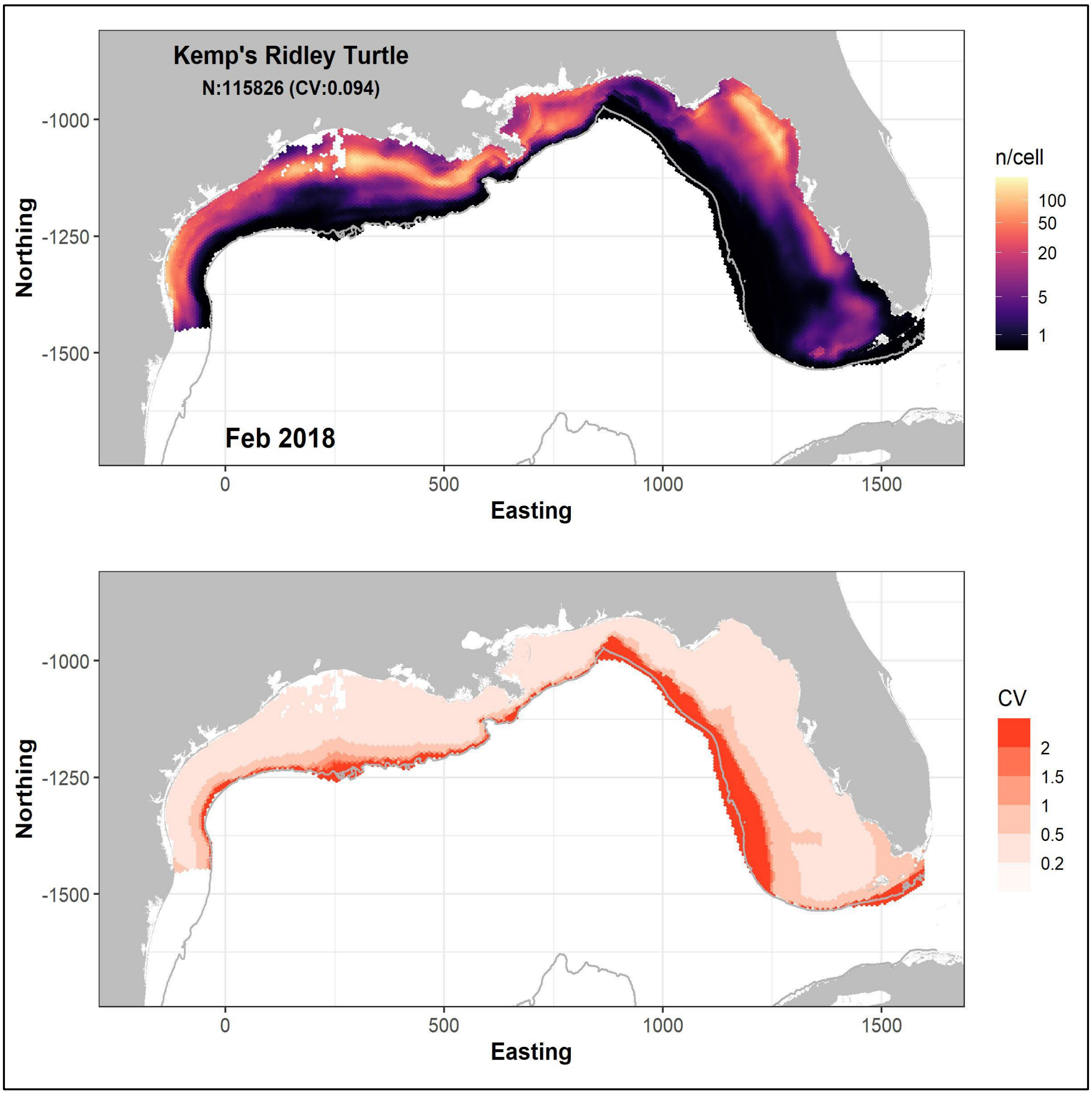

Figure D.3-15. Density model prediction for shelf Kemp's ridley turtles in the NGOM in February 2018.

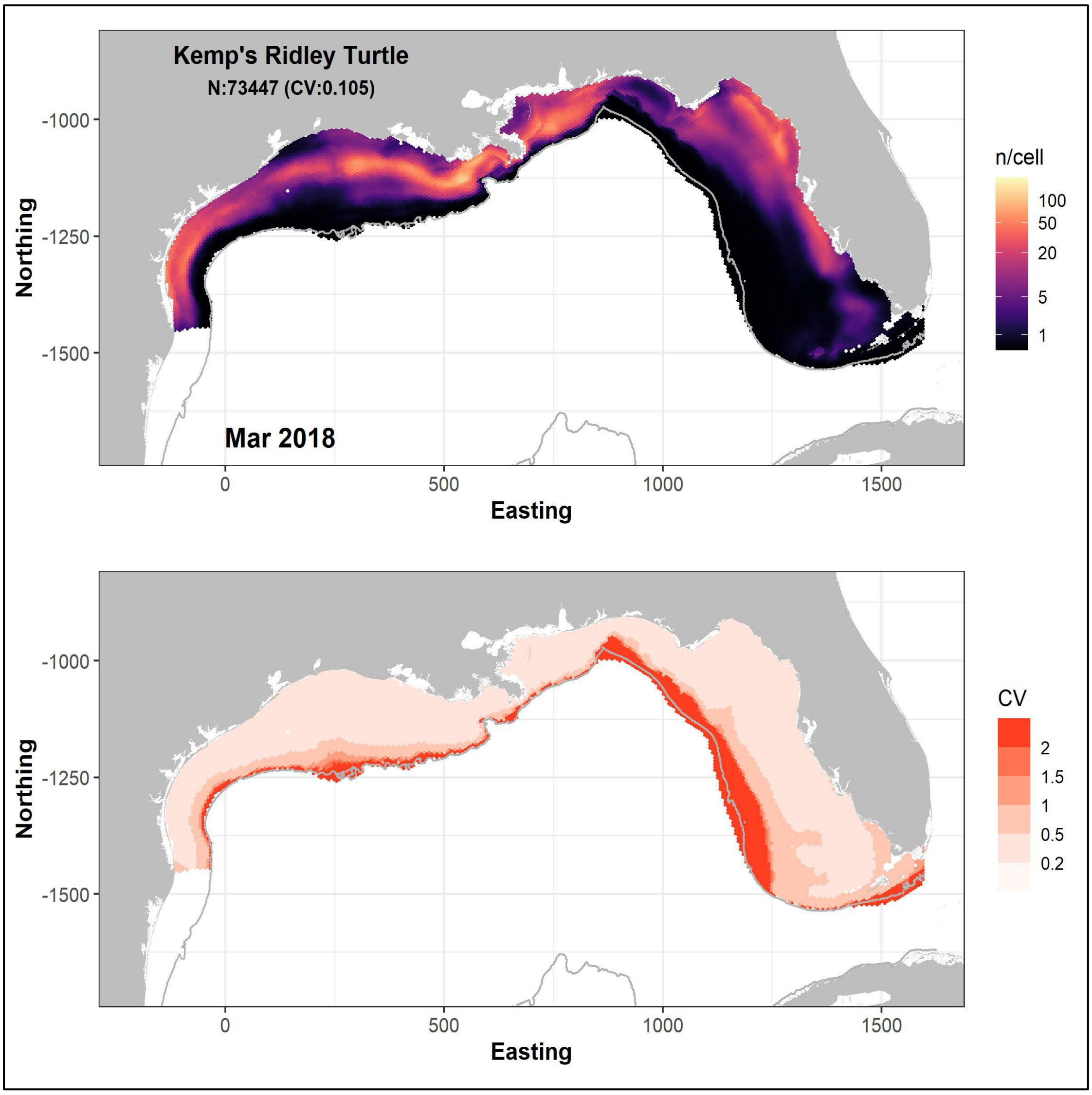

Figure D.3-16. Density model prediction for shelf Kemp's ridley turtles in the NGOM in March 2018.

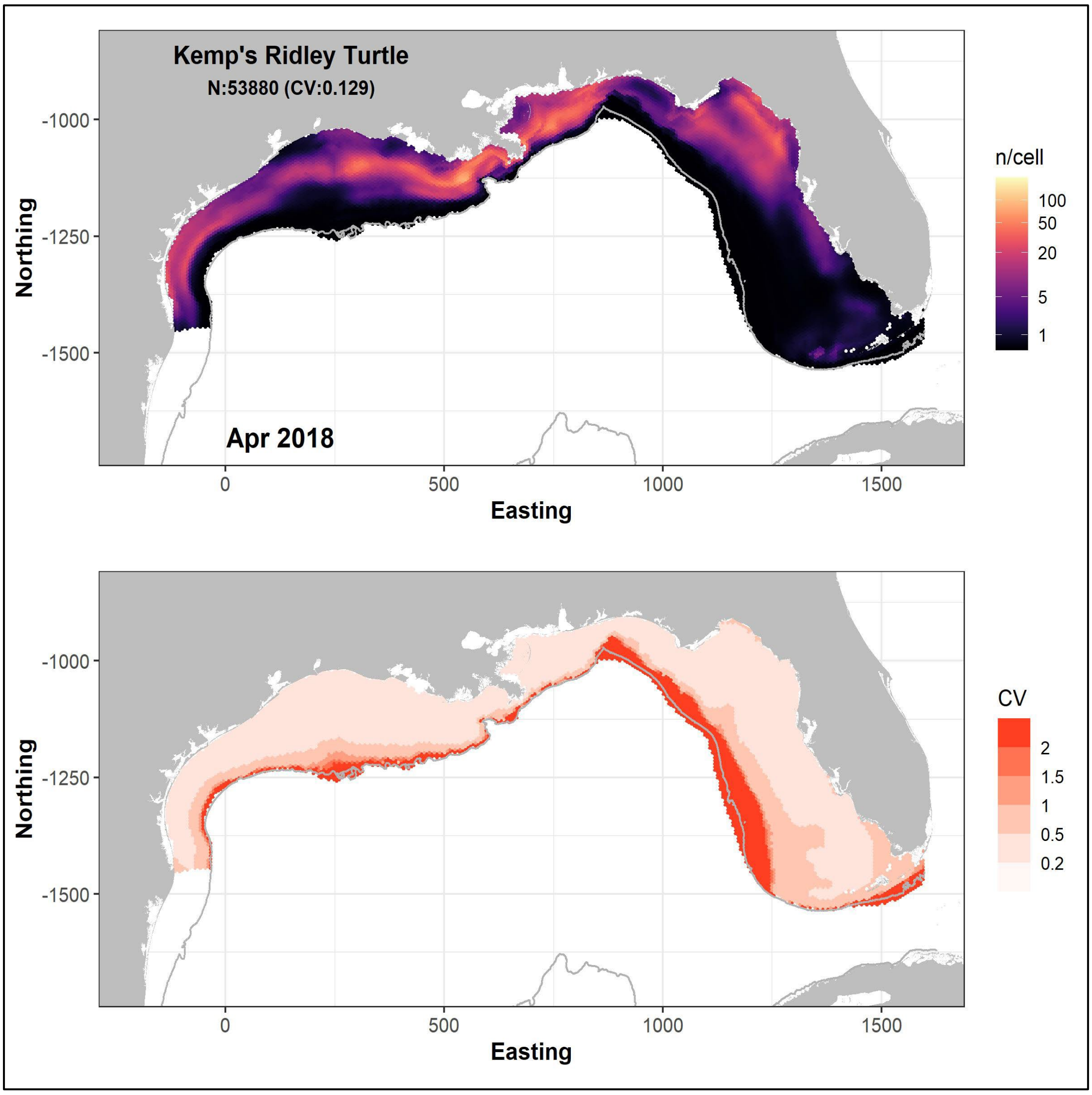

Figure D.3-17. Density model prediction for shelf Kemp's ridley turtles in the NGOM in April 2018.

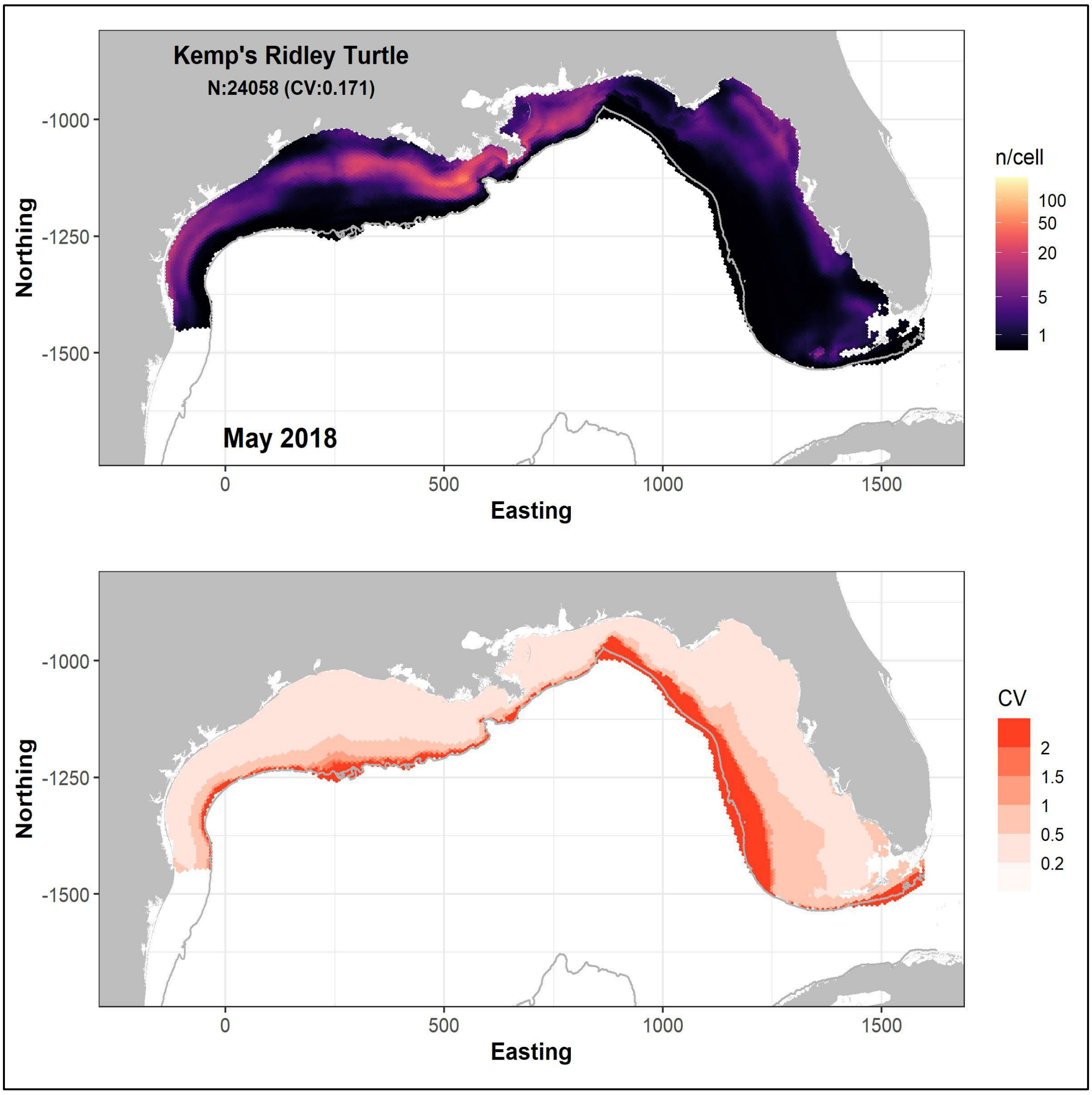

Figure D.3-18. Density model prediction for shelf Kemp's ridley turtles in the NGOM in May 2018.

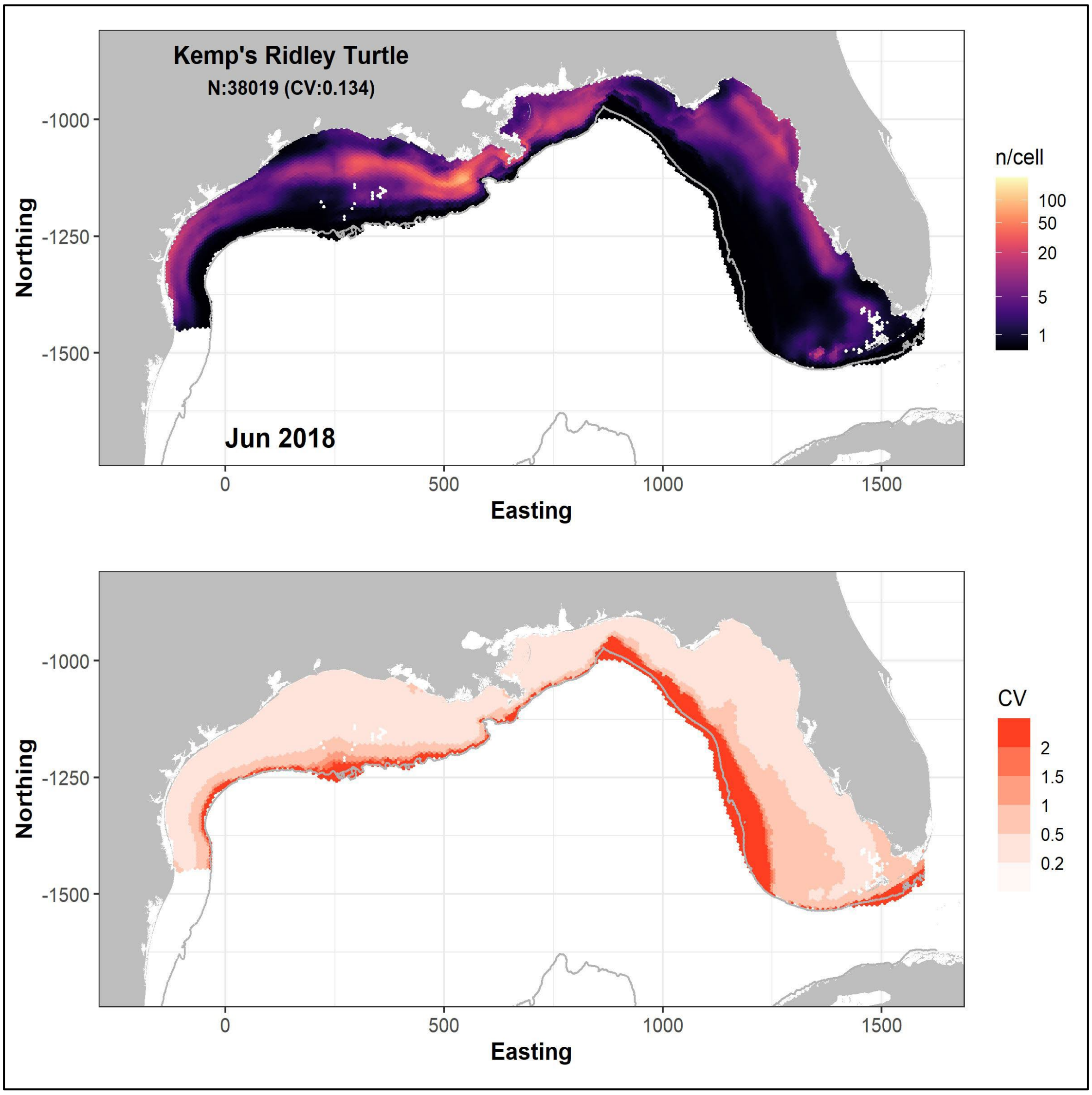

Figure D.3-19. Density model prediction for shelf Kemp's ridley turtles in the NGOM in June 2018.

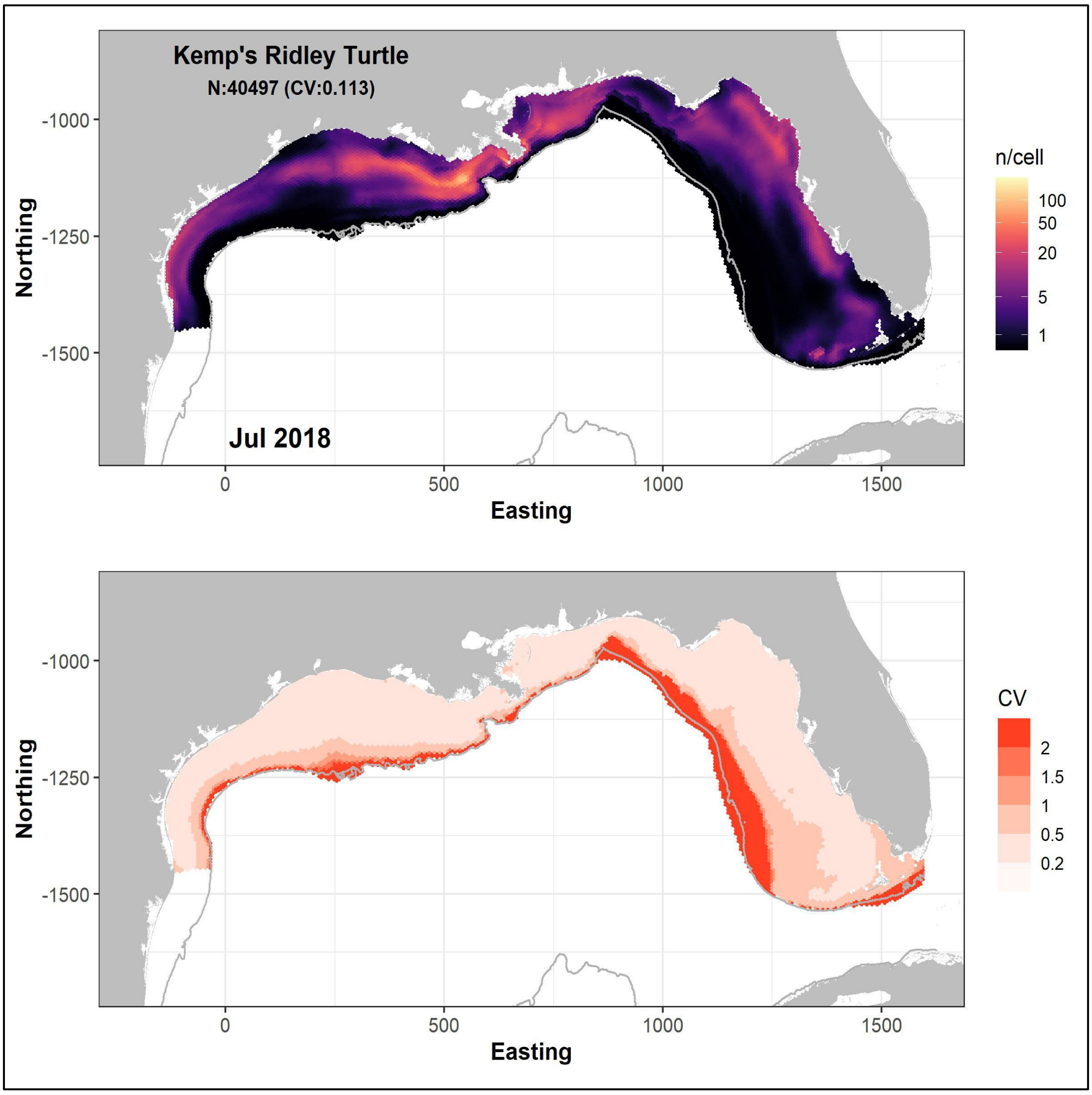

Figure D.3-20. Density model prediction for shelf Kemp's ridley turtles in the NGOM in July 2018.

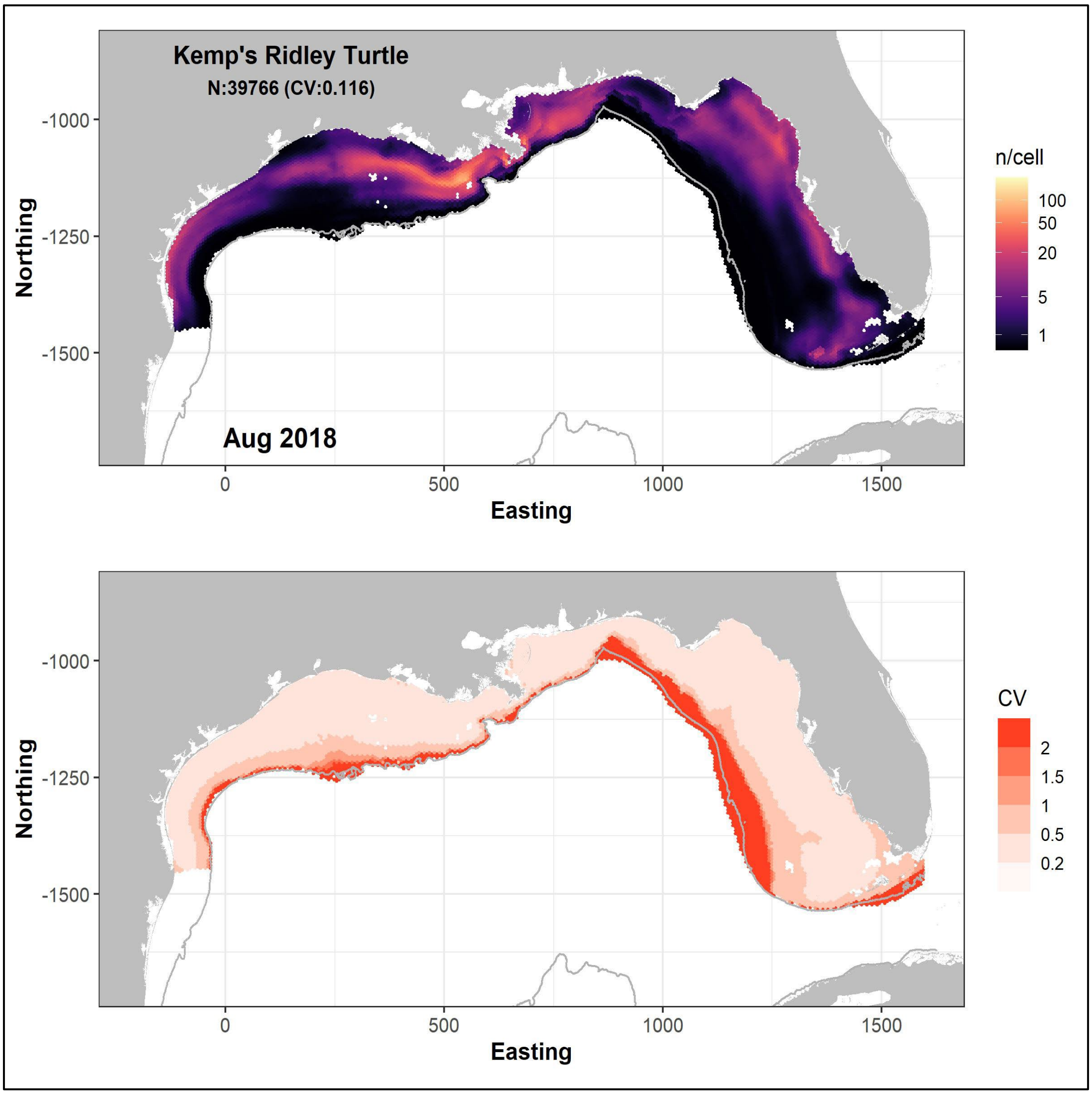

Figure D.3-21. Density model prediction for shelf Kemp's ridley turtles in the NGOM in August 2018.

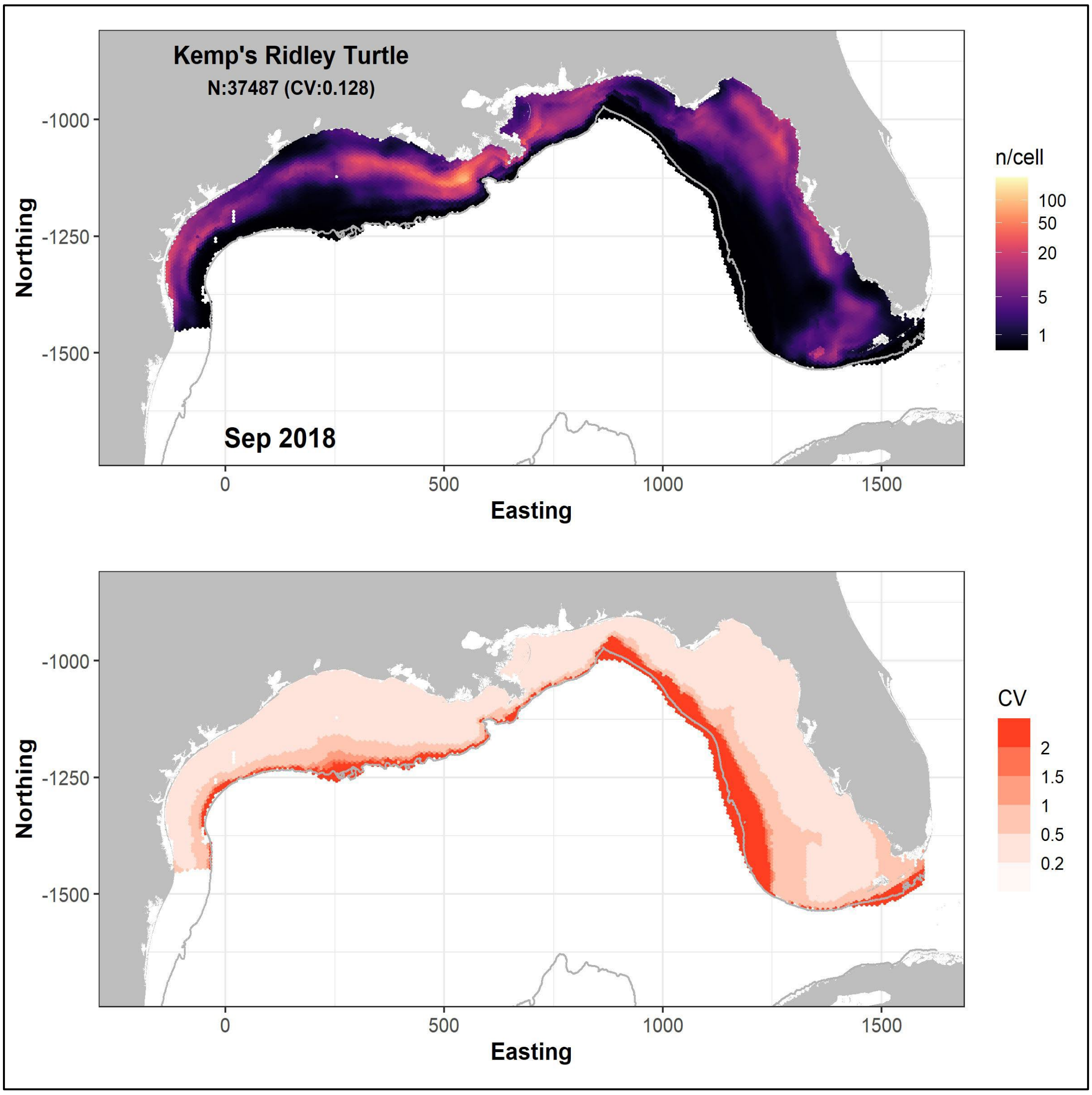

Figure D.3-22. Density model prediction for shelf Kemp's ridley turtles in the NGOM in September 2018.

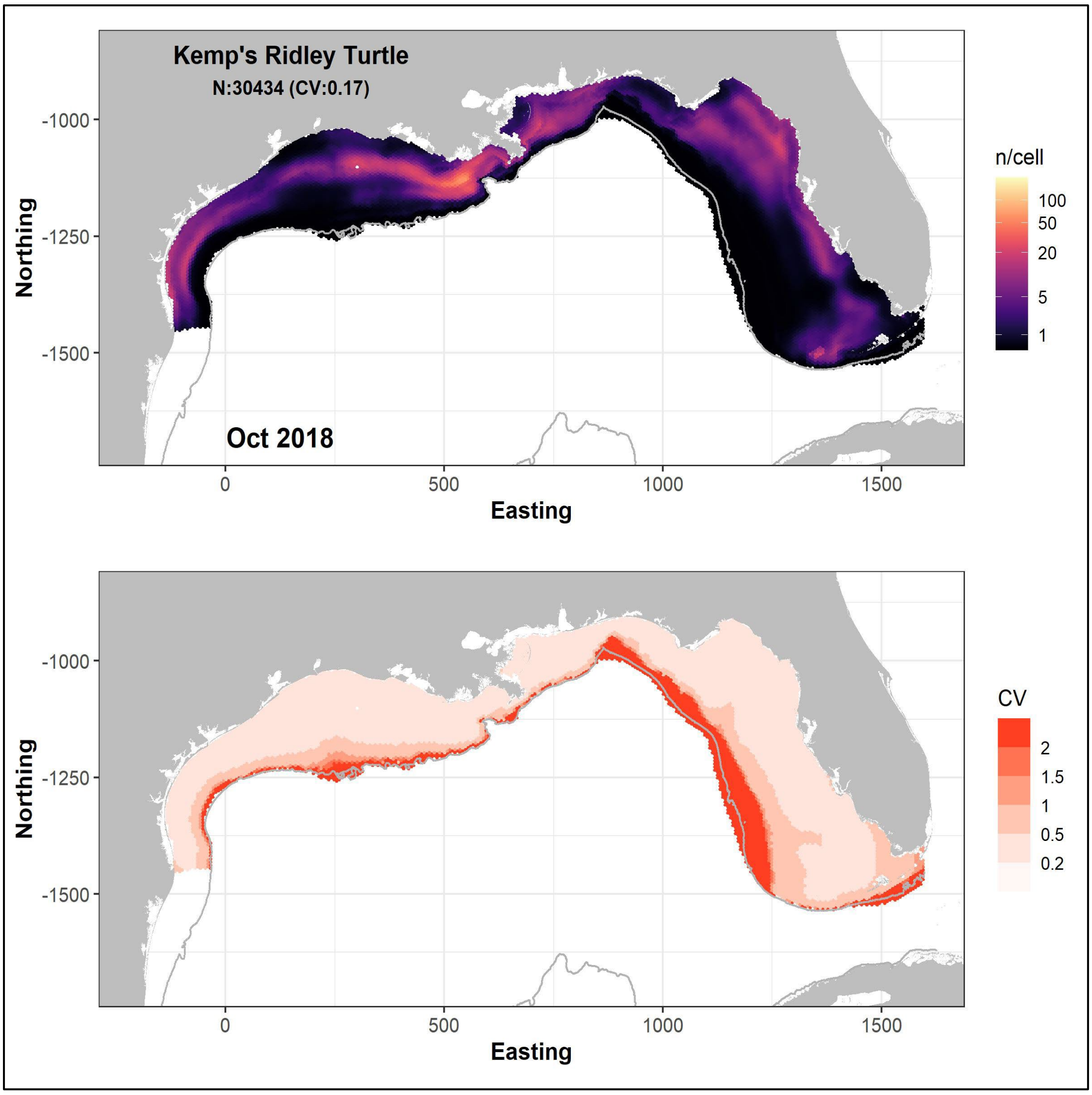

Figure D.3-23. Density model prediction for shelf Kemp's ridley turtles in the NGOM in October 2018.

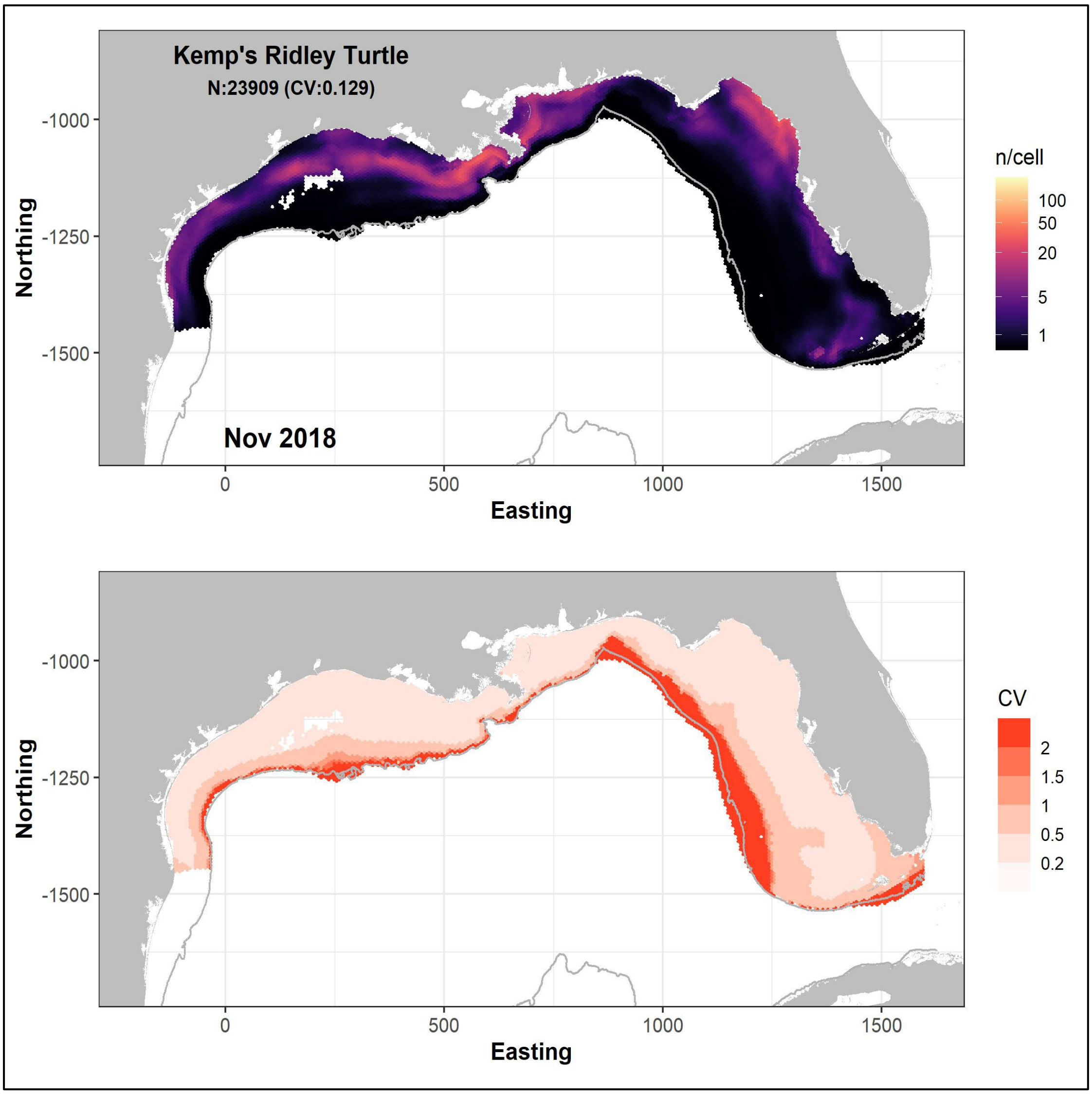

Figure D.3-24. Density model prediction for shelf Kemp's ridley turtles in the NGOM in November 2018.

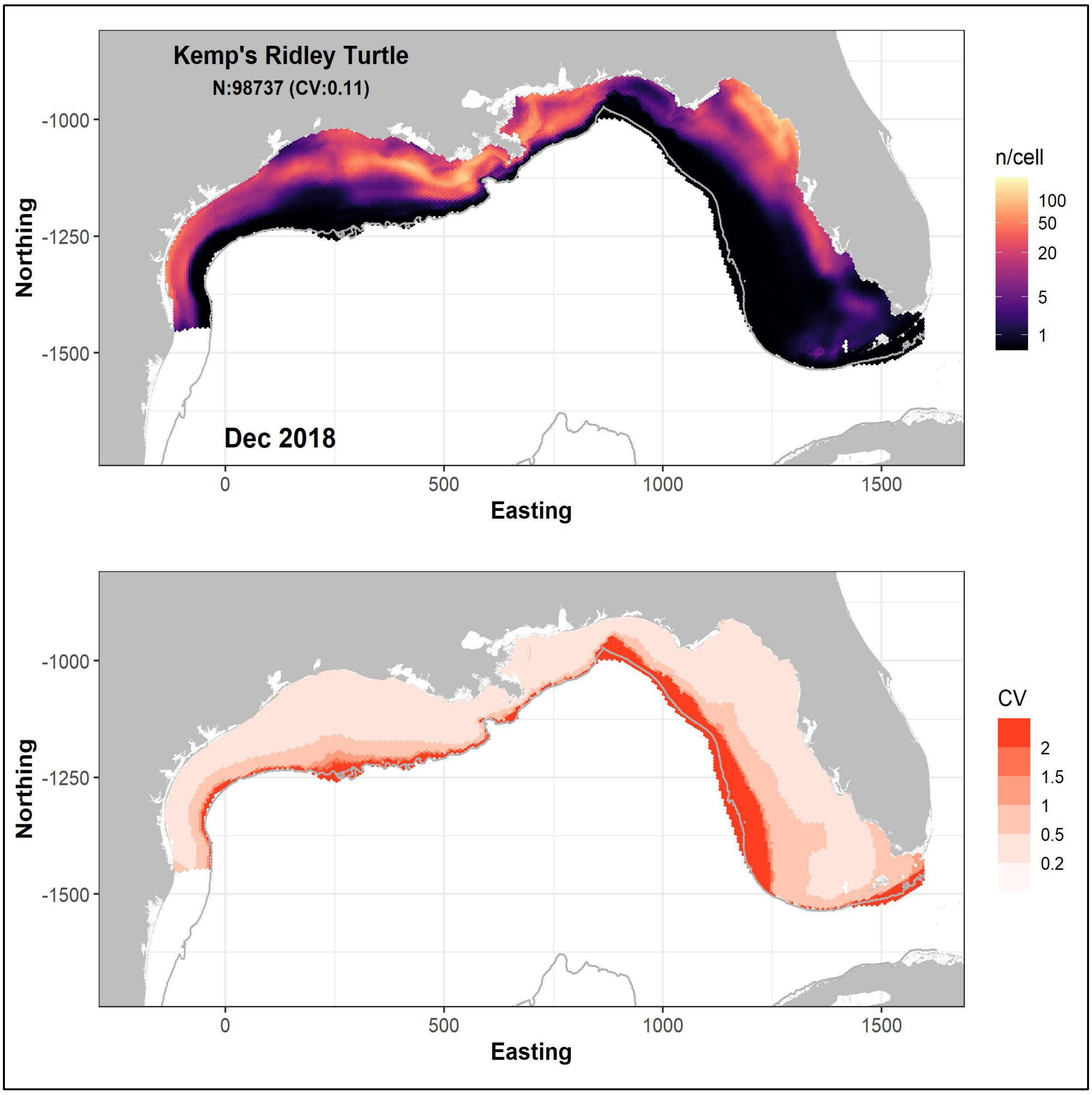

Figure D.3-25. Density model prediction for shelf Kemp's ridley turtles in the NGOM in December 2018.

D.3.5.2 Inclusion of Unidentified Turtles

Aside from leatherbacks, sea turtles are difficult to identify reliably from the air, and observers are trained to make positive identification to species only when they feel confident in their identification. In addition, turtles are often observed just below the water surface or diving, making reliable identification more challenging. As a result, many of the observed turtles during the aerial surveys were identified only as "hardshell turtles". Incorporating these unidentified observations into density estimates is essential to developing unbiased estimates. To properly apportion unidentified turtles among species, a SDM model was developed for hardshell turtles. The resulting density of hardshell turtles were partitioned among the identified species based upon the relative predicted density of each species in each spatial cell. Monthly density maps for Kemp's ridley turtles including both identified turtles and the proportion of unidentified turtles were generated (Figures D.3-26–D.3-37).

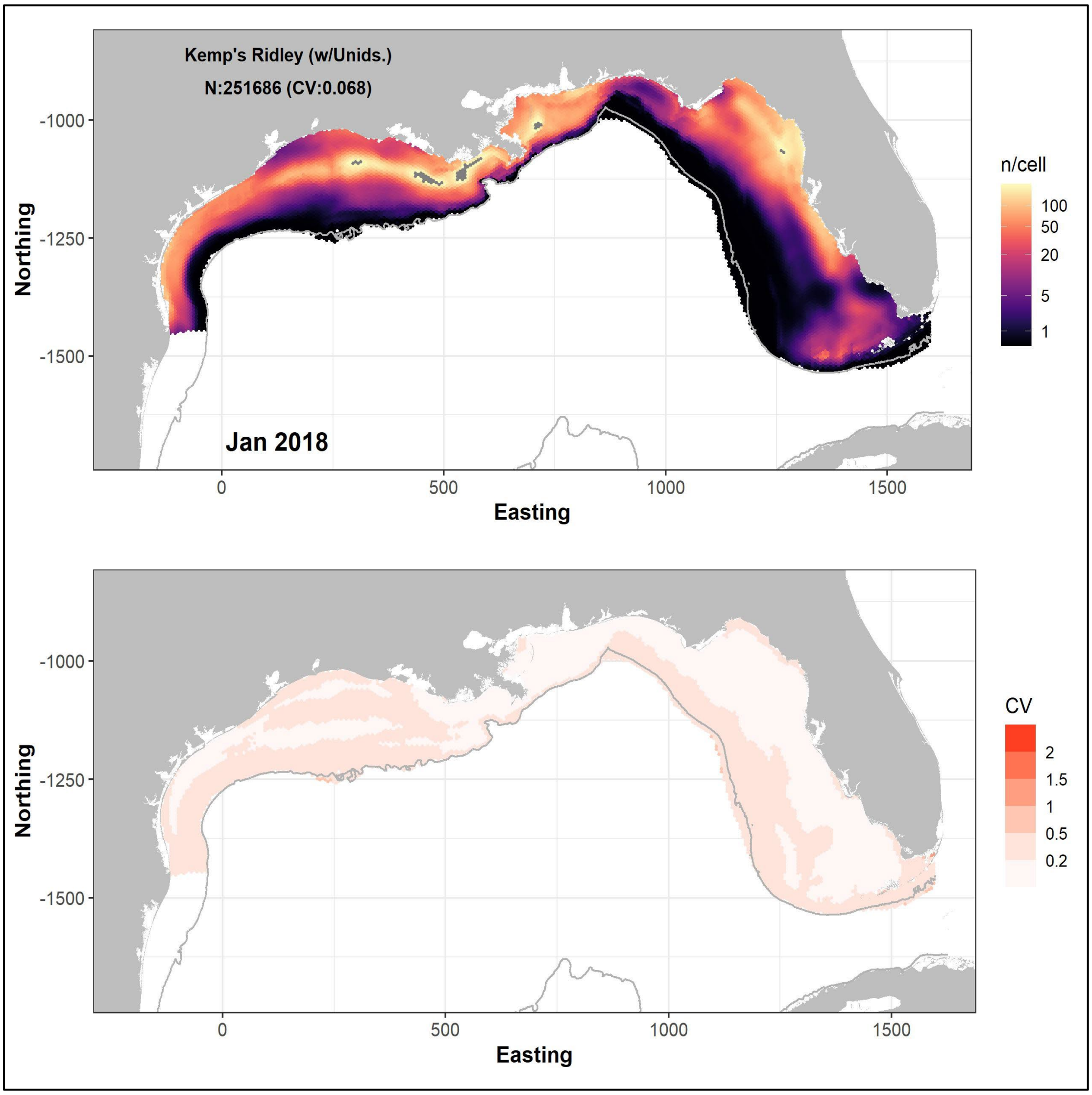

Figure D.3-26. Density model prediction for Kemp's ridley turtles including apportioned unidentified turtles in the NGOM in January 2018.

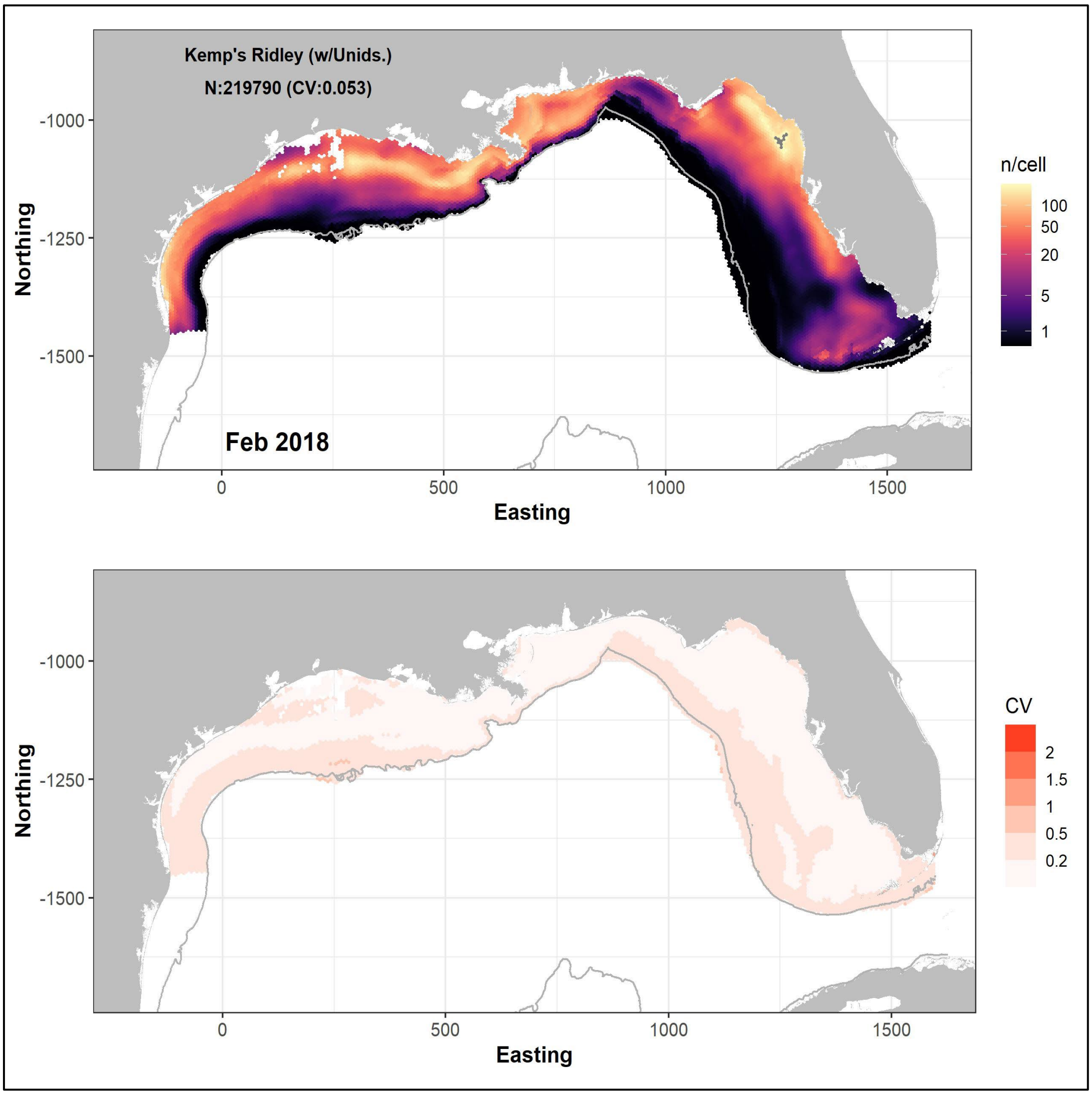

Figure D.3-27. Density model prediction for Kemp's ridley turtles including apportioned unidentified turtles in the NGOM in February 2018.

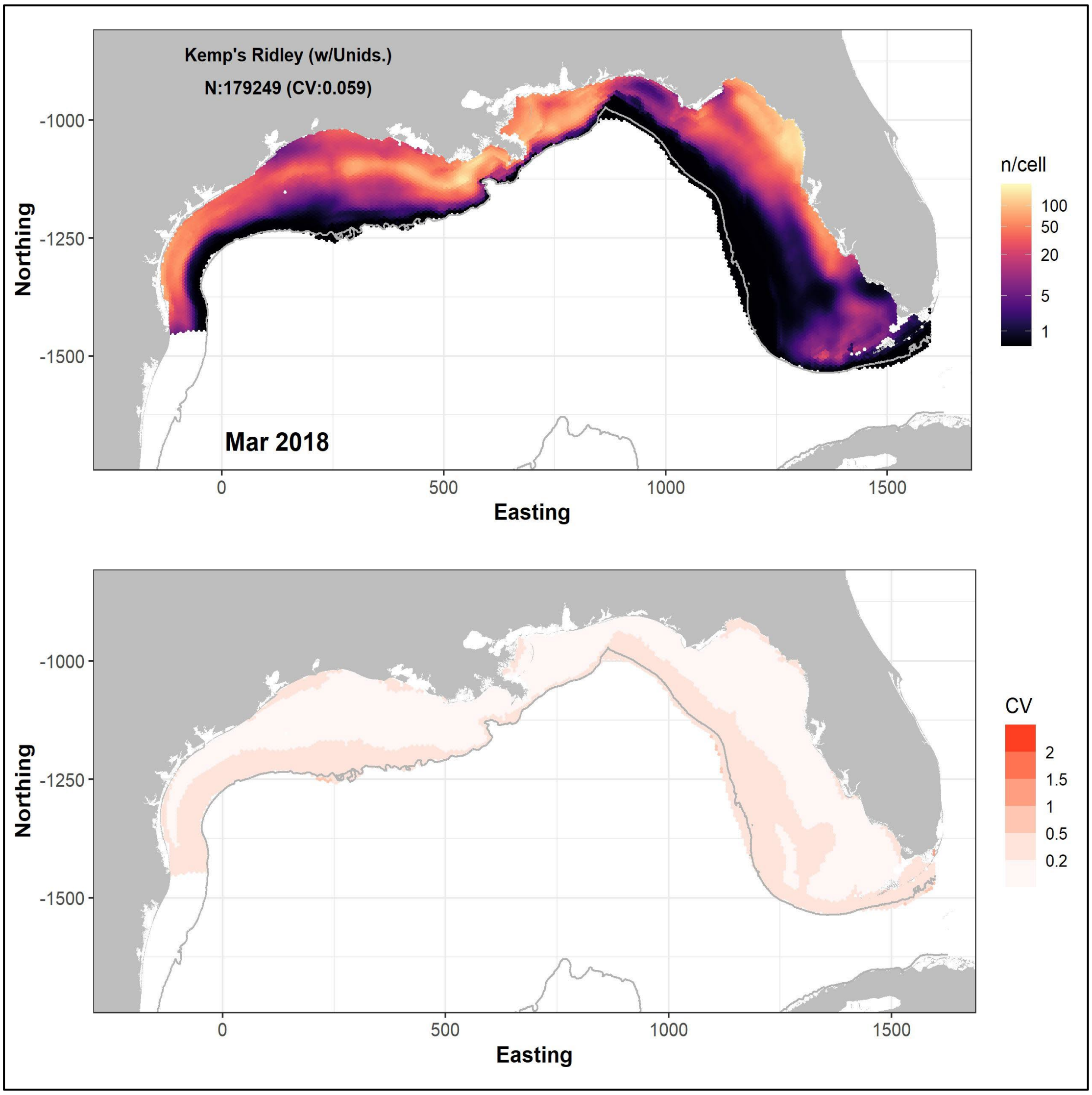

Figure D.3-28. Density model prediction for Kemp's ridley turtles including apportioned unidentified turtles in the NGOM in March 2018.

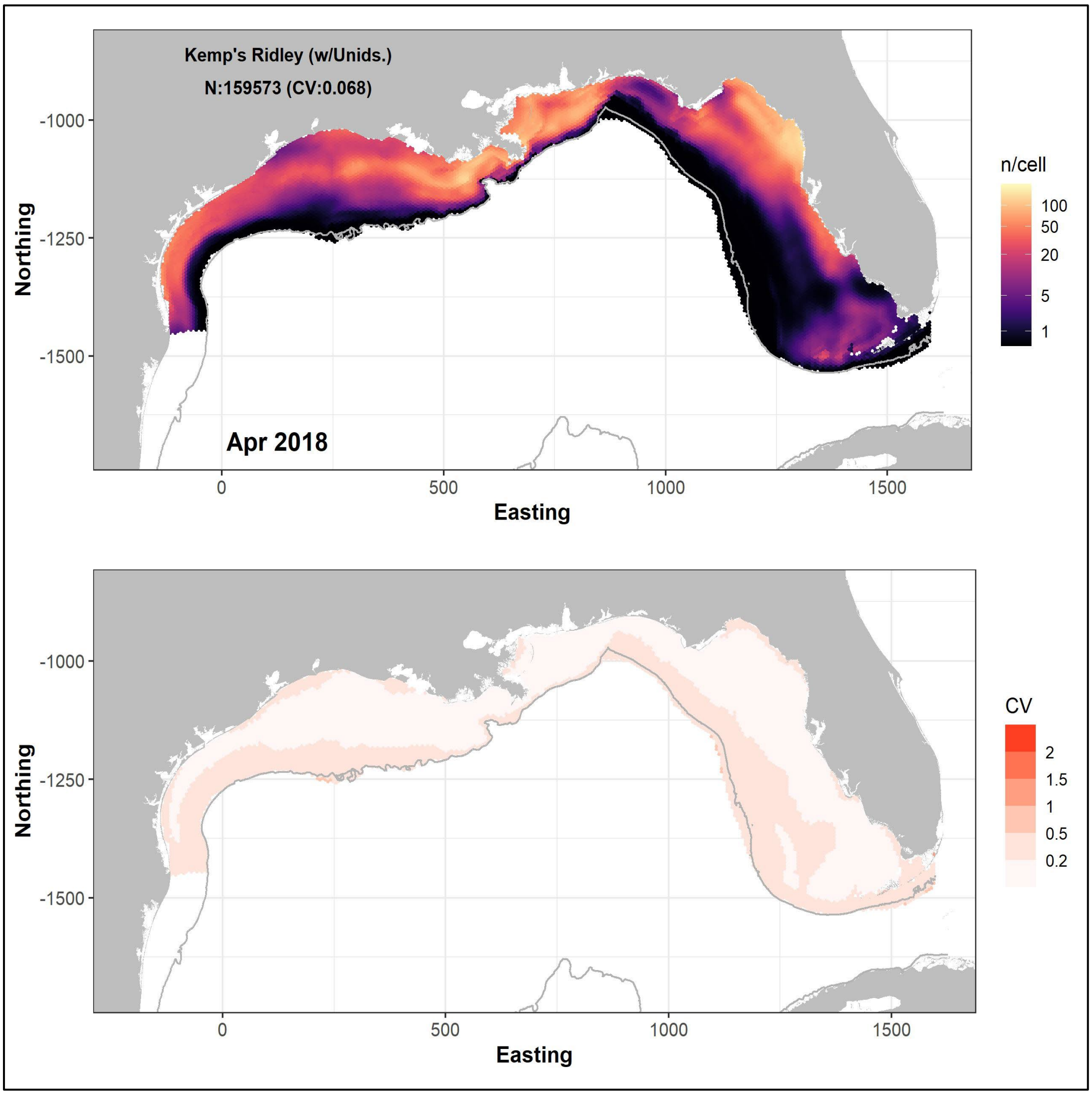

Figure D.3-29. Density model prediction for Kemp's ridley turtles including apportioned unidentified turtles in the NGOM in April 2018.

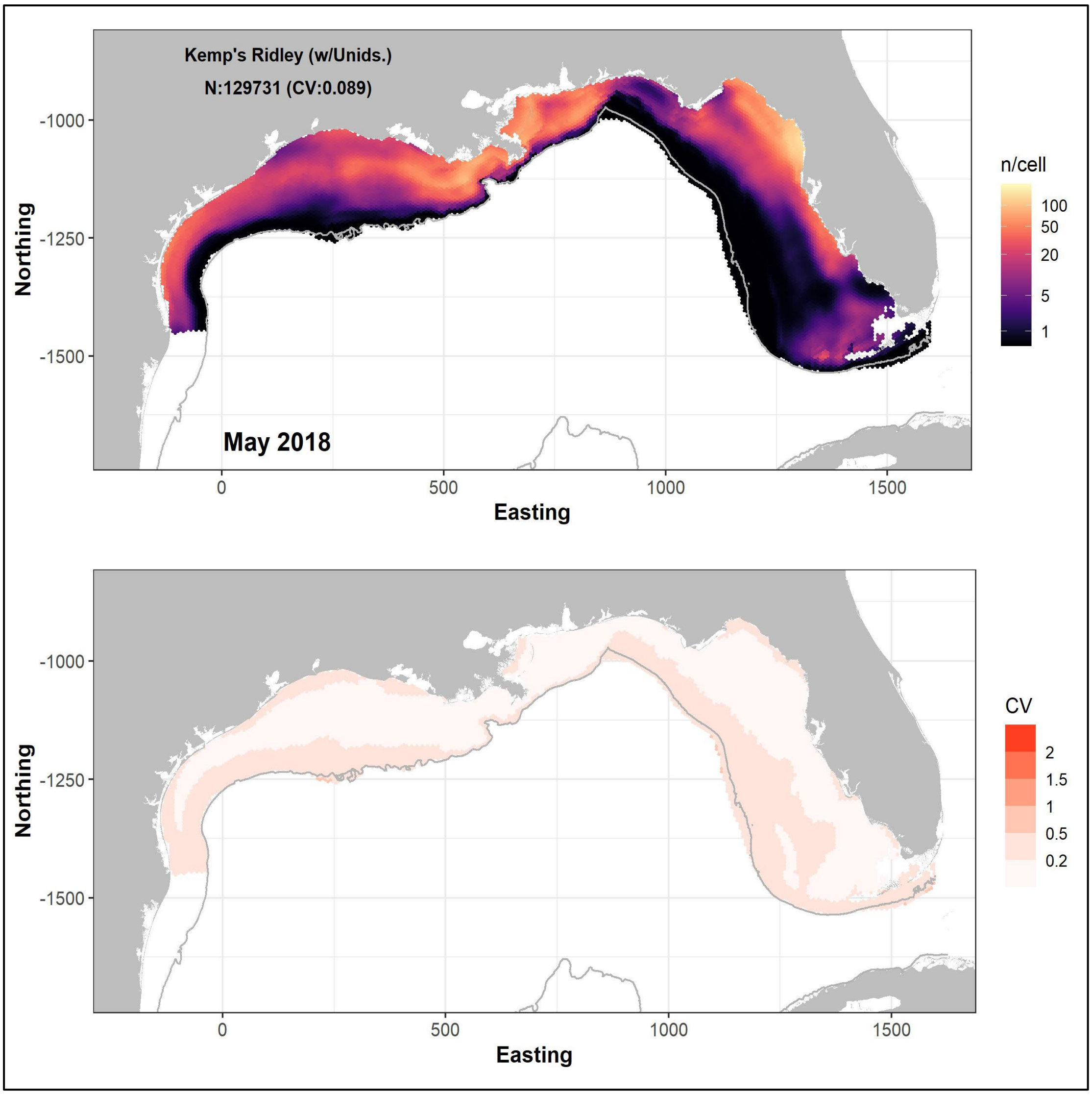

Figure D.3-30. Density model prediction for Kemp's ridley turtles including apportioned unidentified turtles in the NGOM in May 2018.

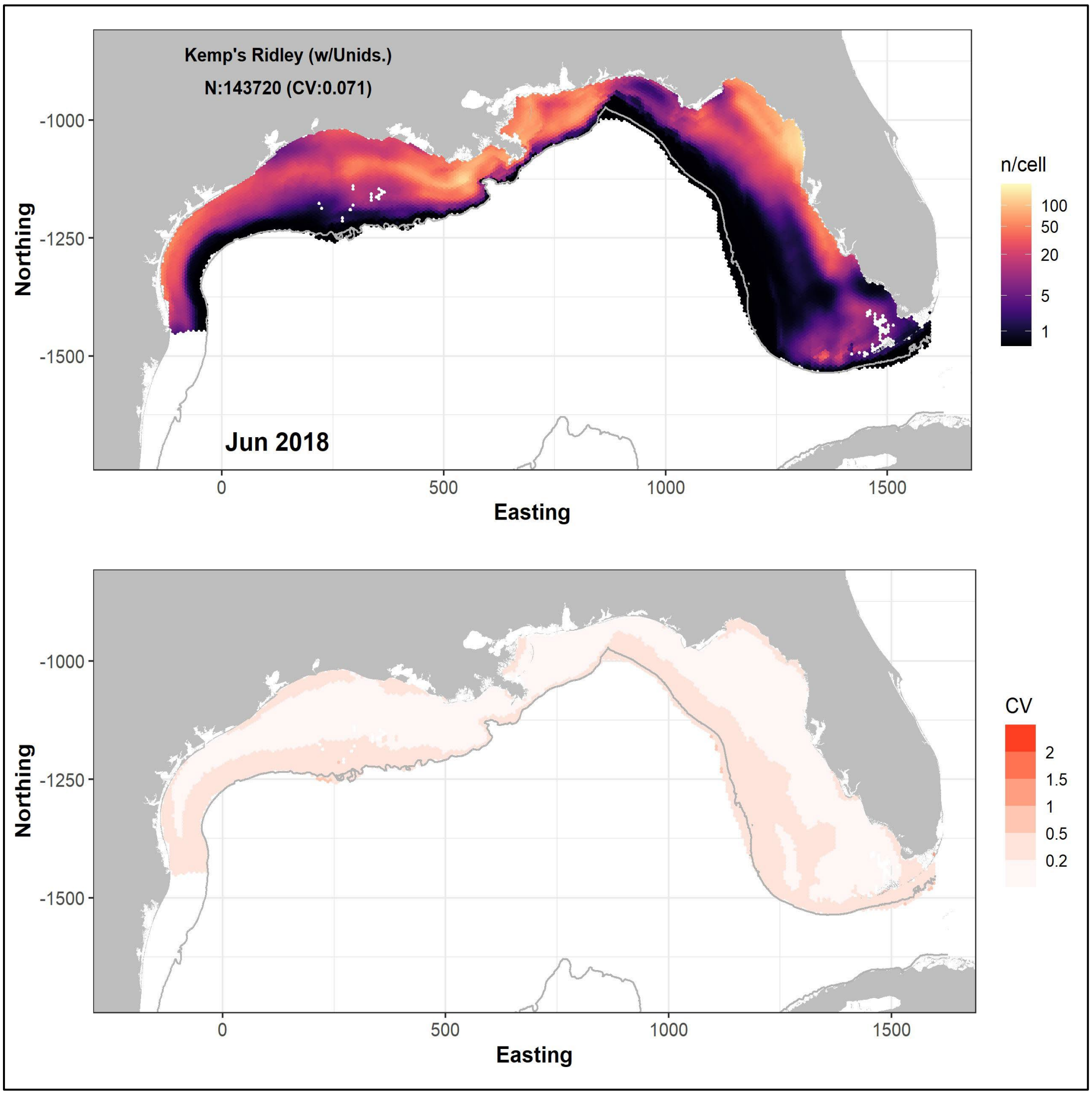

Figure D.3-31. Density model prediction for Kemp's ridley turtles including apportioned unidentified turtles in the NGOM in June 2018.

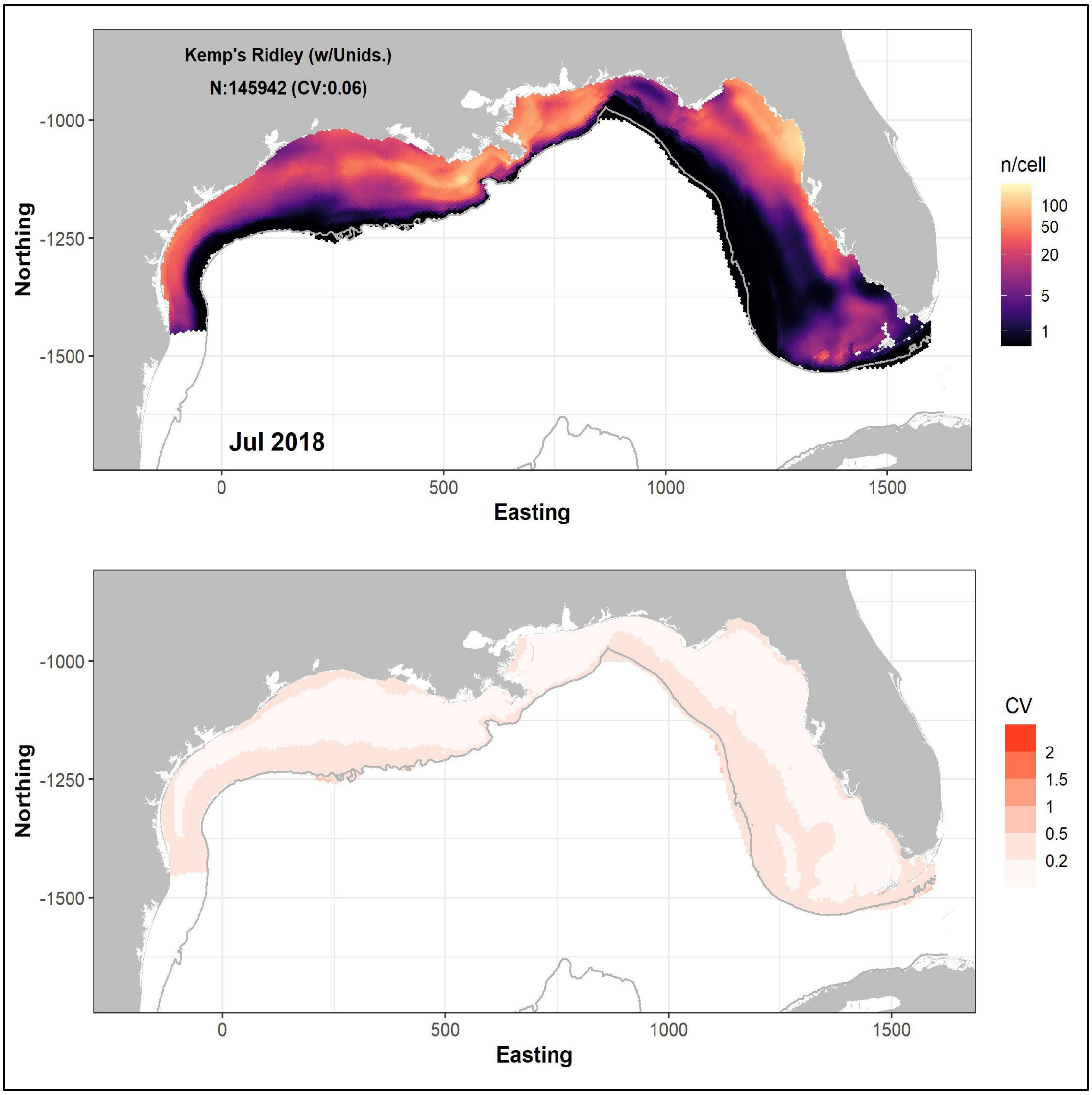

Figure D.3-32. Density model prediction for Kemp's ridley turtles including apportioned unidentified turtles in the NGOM in July 2018.

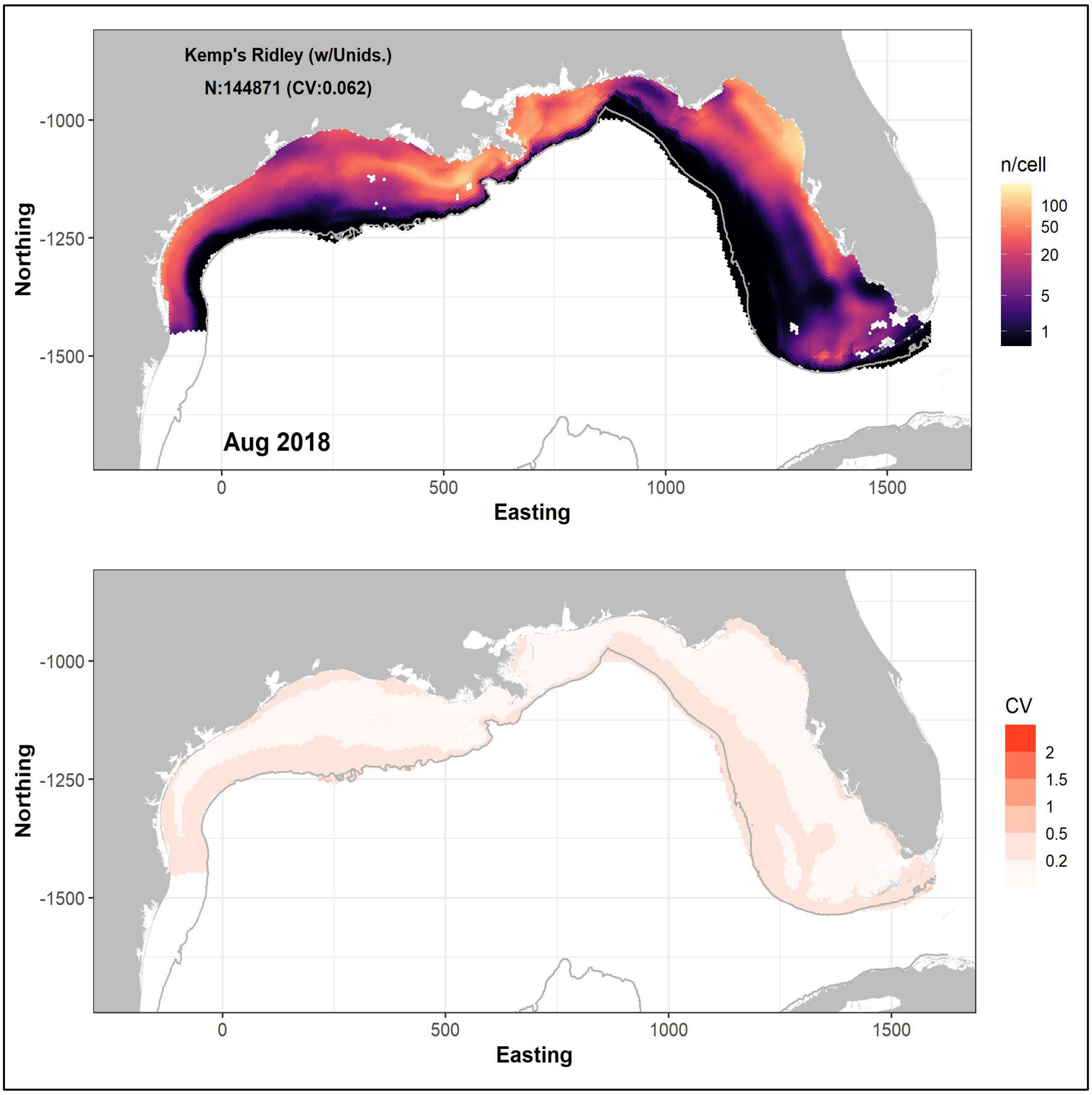

Figure D.3-33. Density model prediction for Kemp's ridley turtles including apportioned unidentified turtles in the NGOM in August 2018.

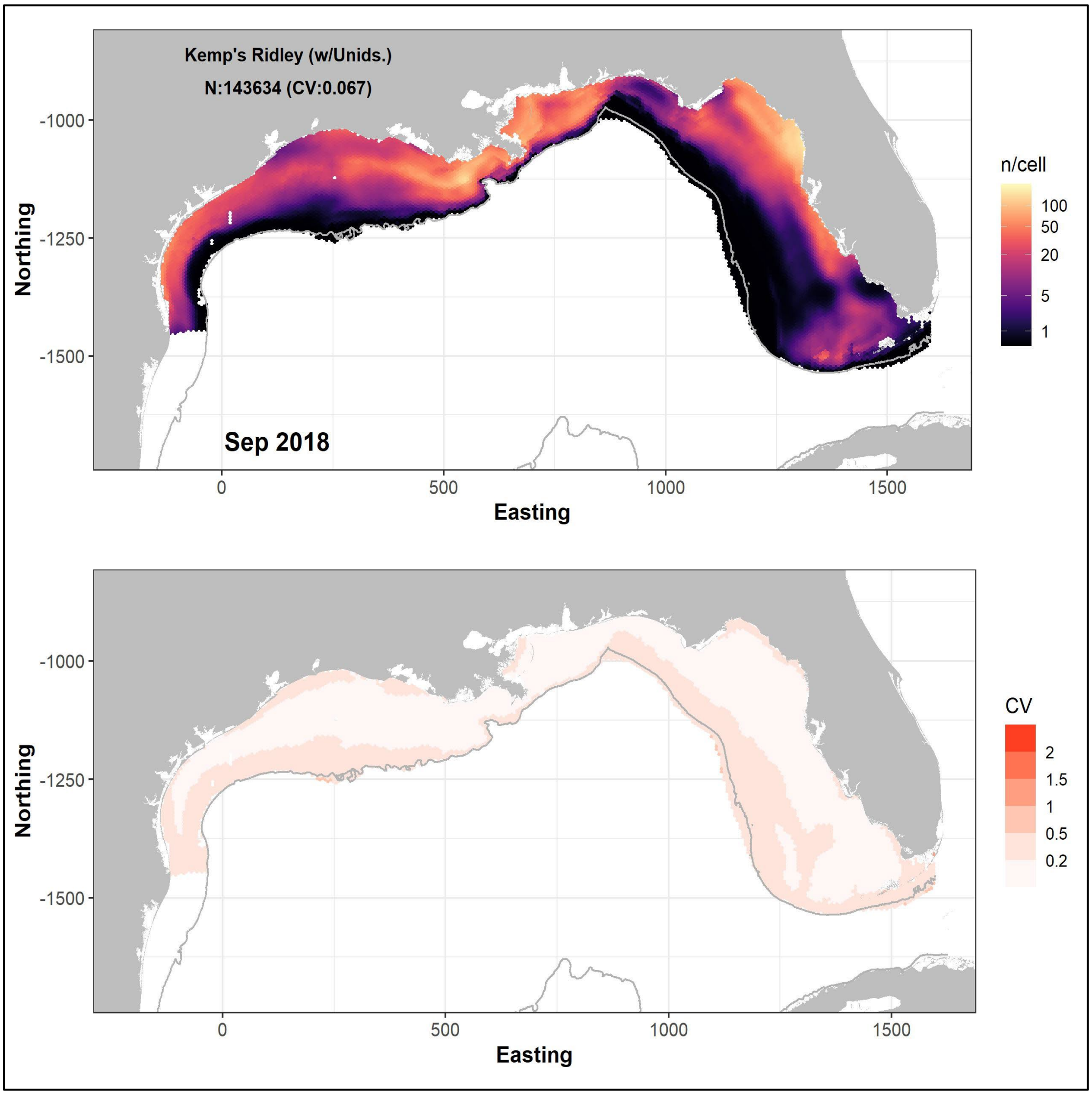

Figure D.3-34. Density model prediction for Kemp's ridley turtles including apportioned unidentified turtles in the NGOM in September 2018.

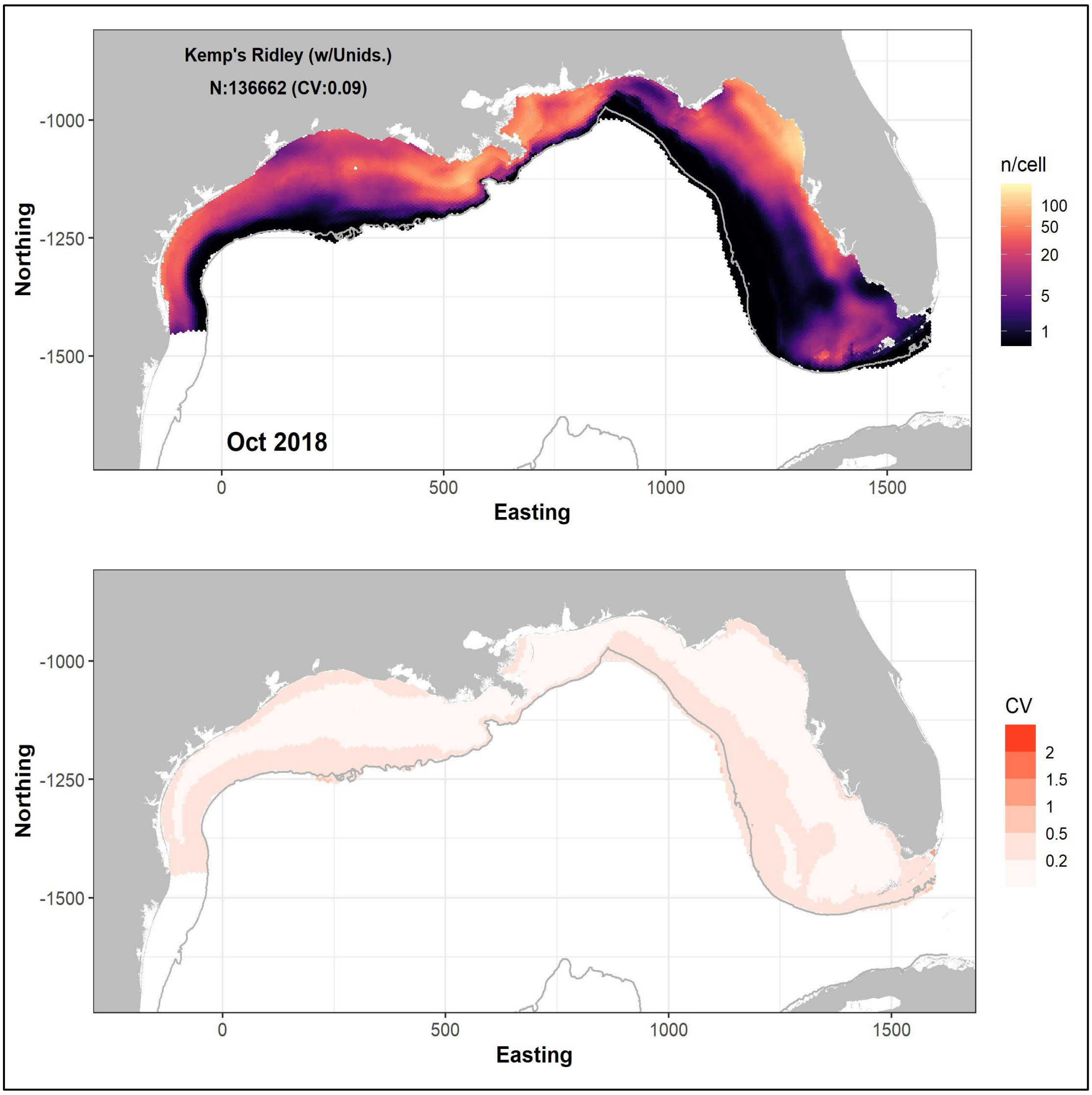

Figure D.3-35. Density model prediction for Kemp's ridley turtles including apportioned unidentified turtles in the NGOM in October 2018.

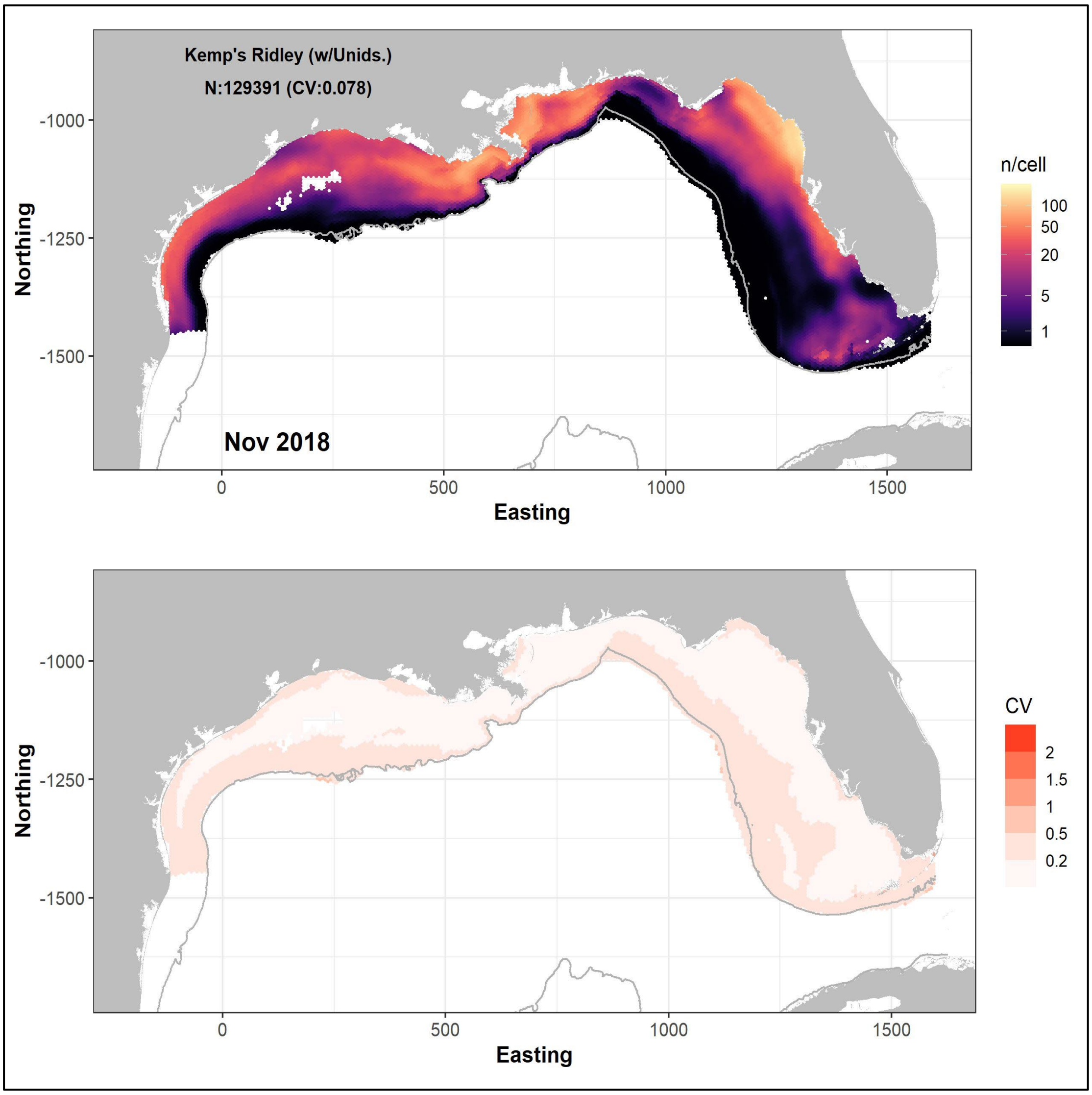

Figure D.3-36. Density model prediction for Kemp's ridley turtles including apportioned unidentified turtles in the NGOM in November 2018.

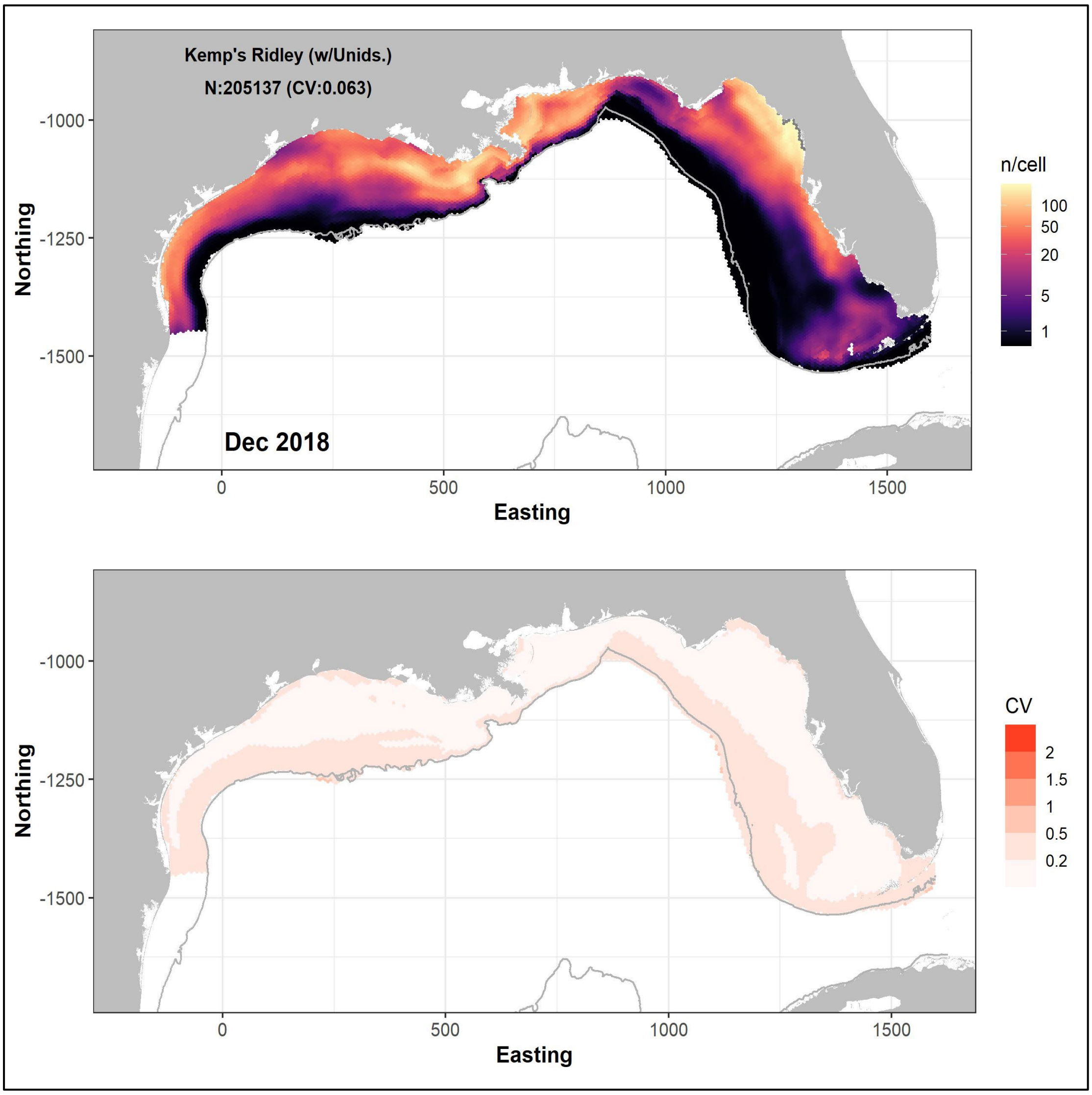

Figure D.3-37. Density model prediction for Kemp's ridley turtles including apportioned unidentified turtles in the NGOM in December 2018.

D.3.5.3 Projected Density throughout the Gulf of Mexico

While aerial survey effort was restricted to the NGOM, Kemp's ridley turtles occur throughout the northern and southern GOM. The projection of the resulting SDM beyond the NGOM assumes that species-habitat relationships are consistent, and it is unknown if this assumption is reliable. To evaluate the potential density of Kemp's ridley turtles outside of the US Exclusive Economic Zone (EEZ), the SDM was projected throughout the GOM. These results should be interpreted with caution given the extrapolation outside of the surveyed area (Figures D.3-38–D.3-49).

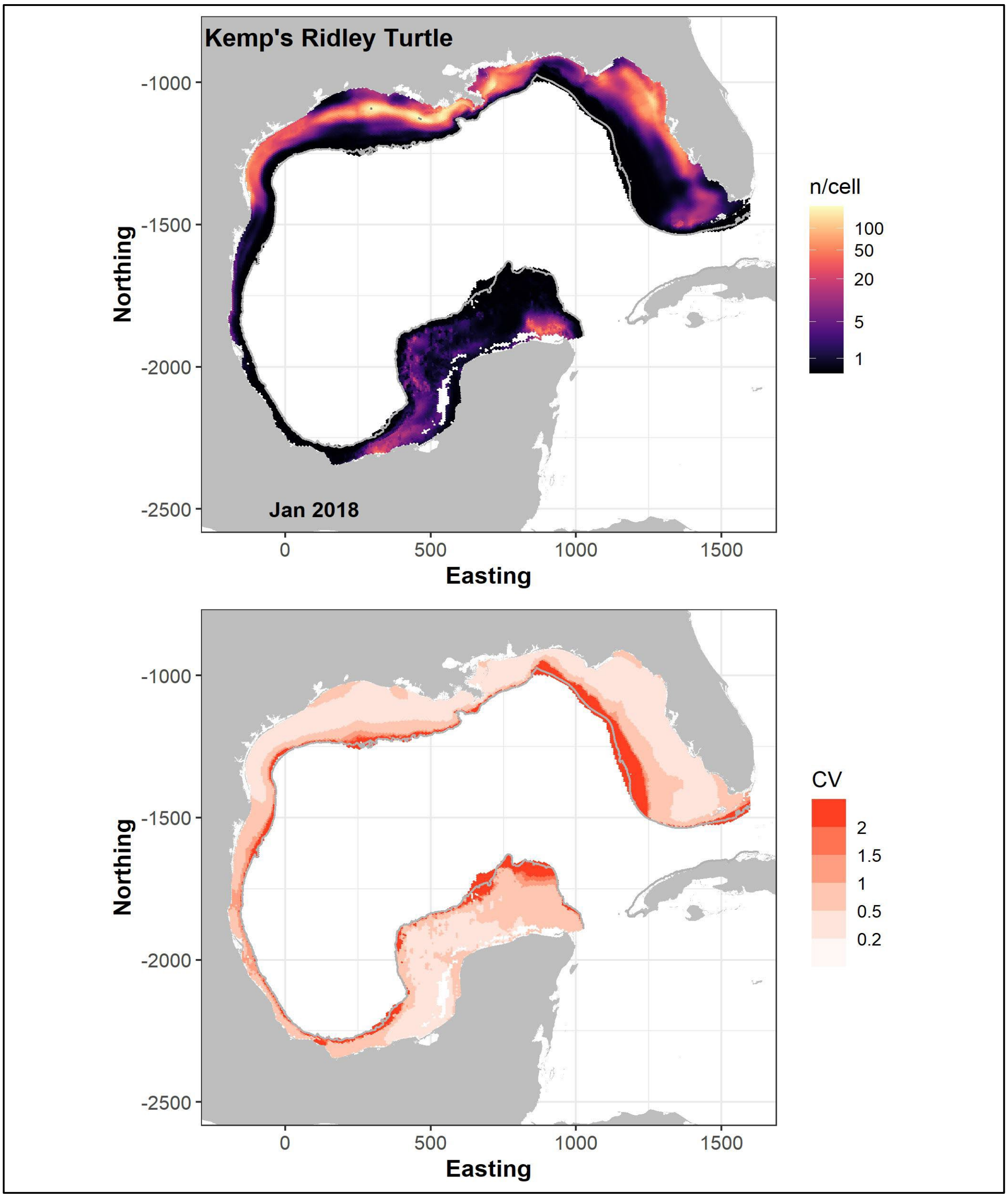

Figure D.3-38. Projected density model for shelf Kemp's ridley turtles in the entire GOM for January 2018.

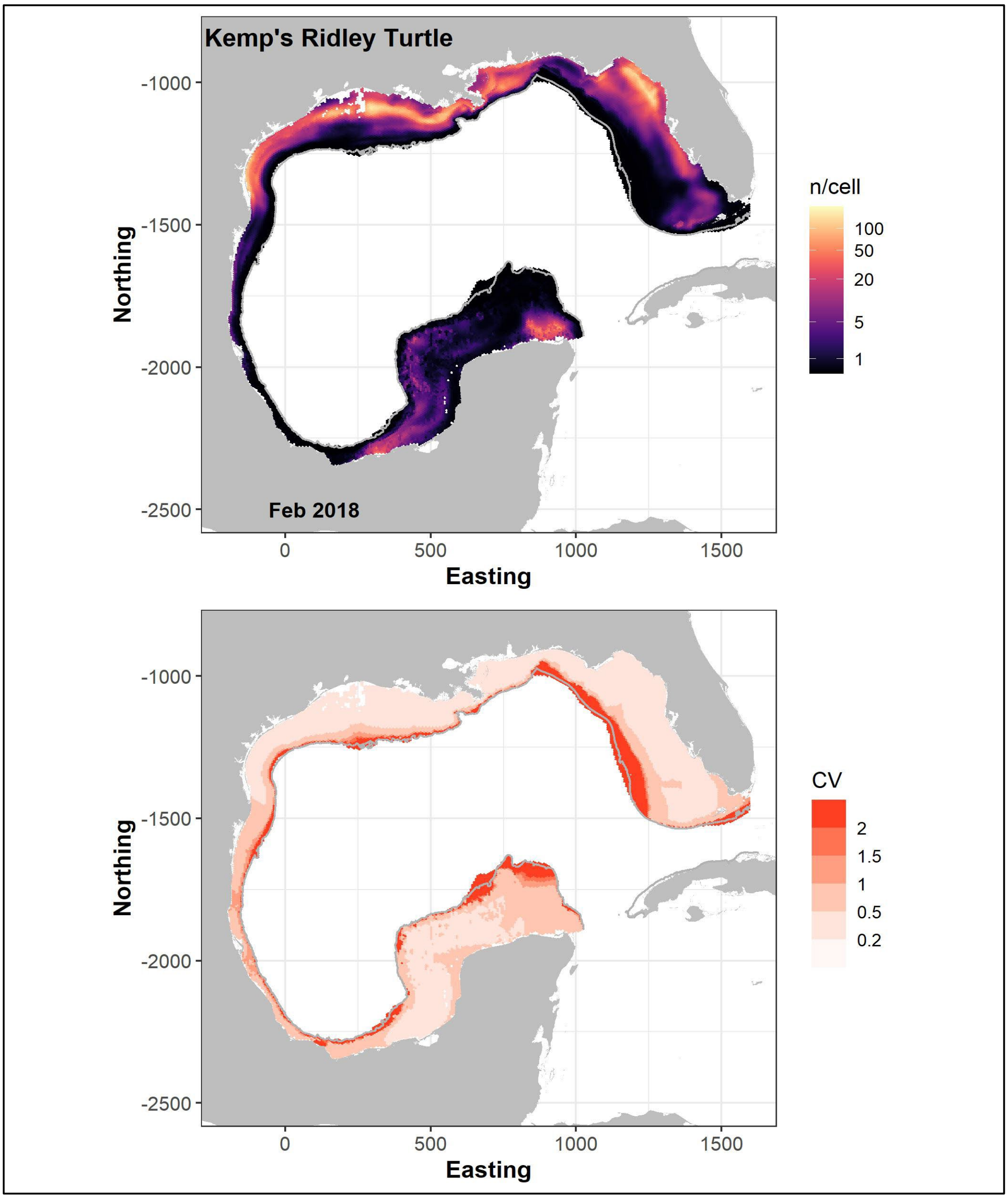

Figure D.3-39. Projected density model for shelf Kemp's ridley turtles in the entire GOM for February 2018.

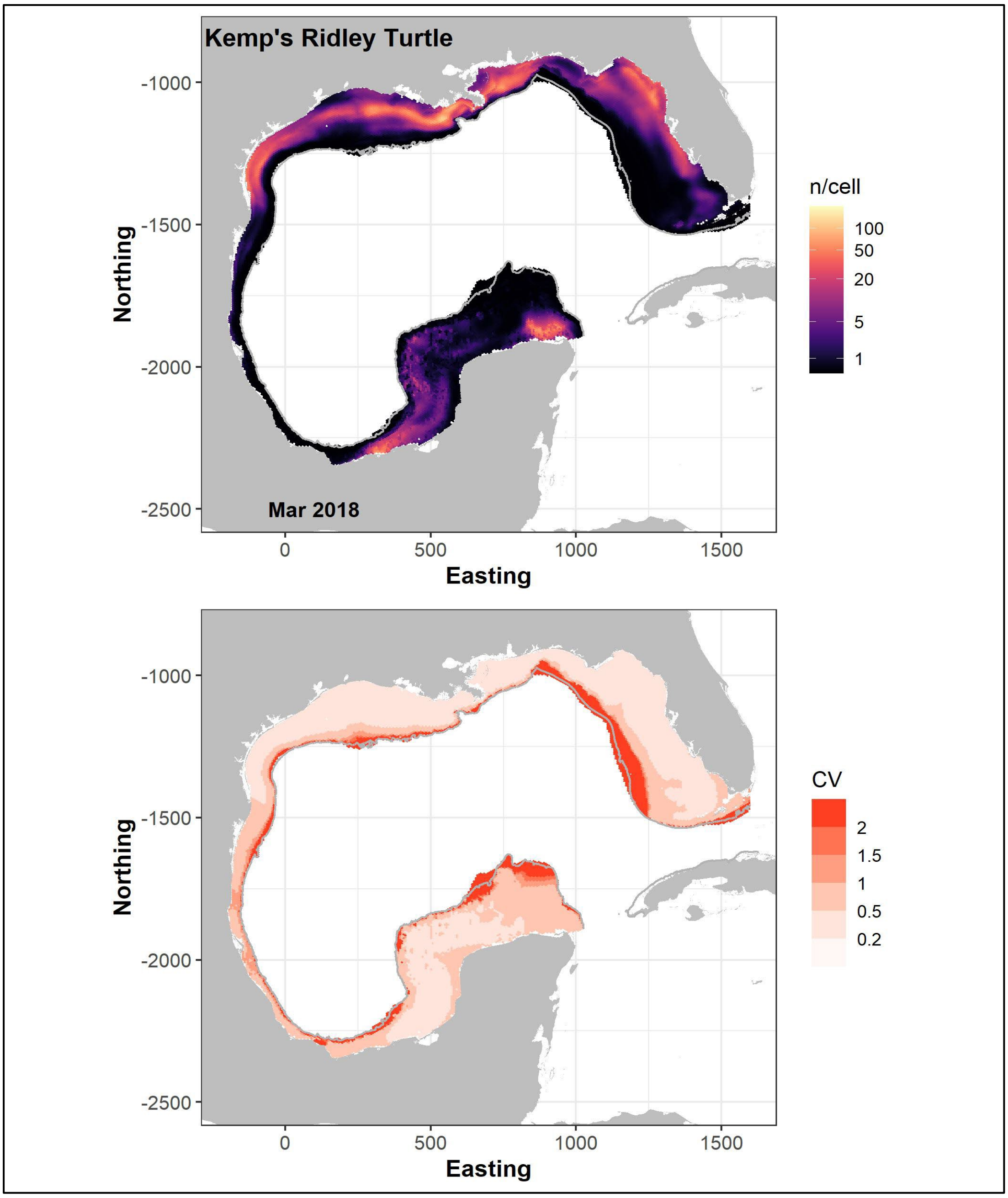

Figure D.3-40. Projected density model for shelf Kemp's ridley turtles in the entire GOM for March 2018.

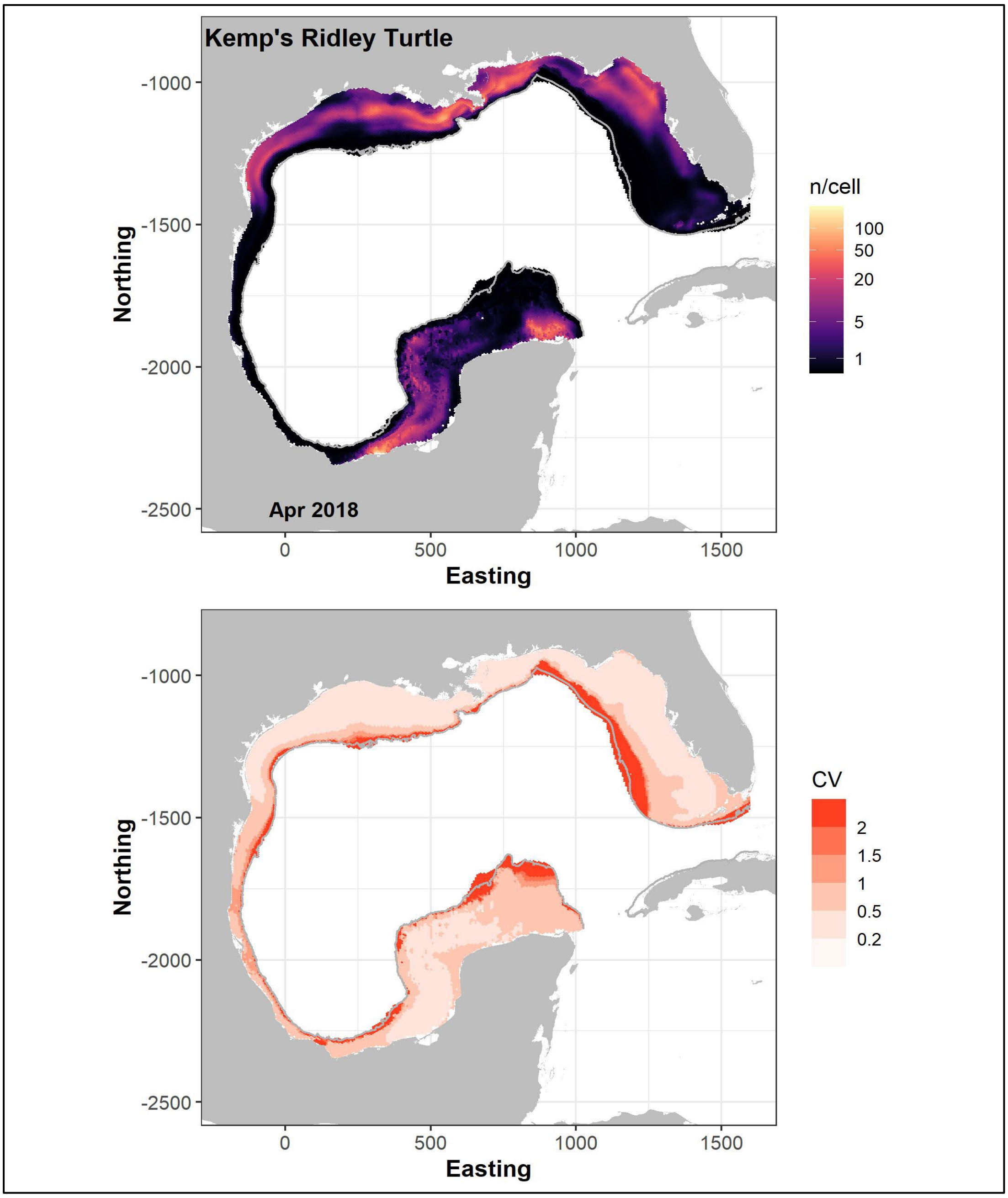

Figure D.3-41. Projected density model for shelf Kemp's ridley turtles in the entire GOM for April 2018.

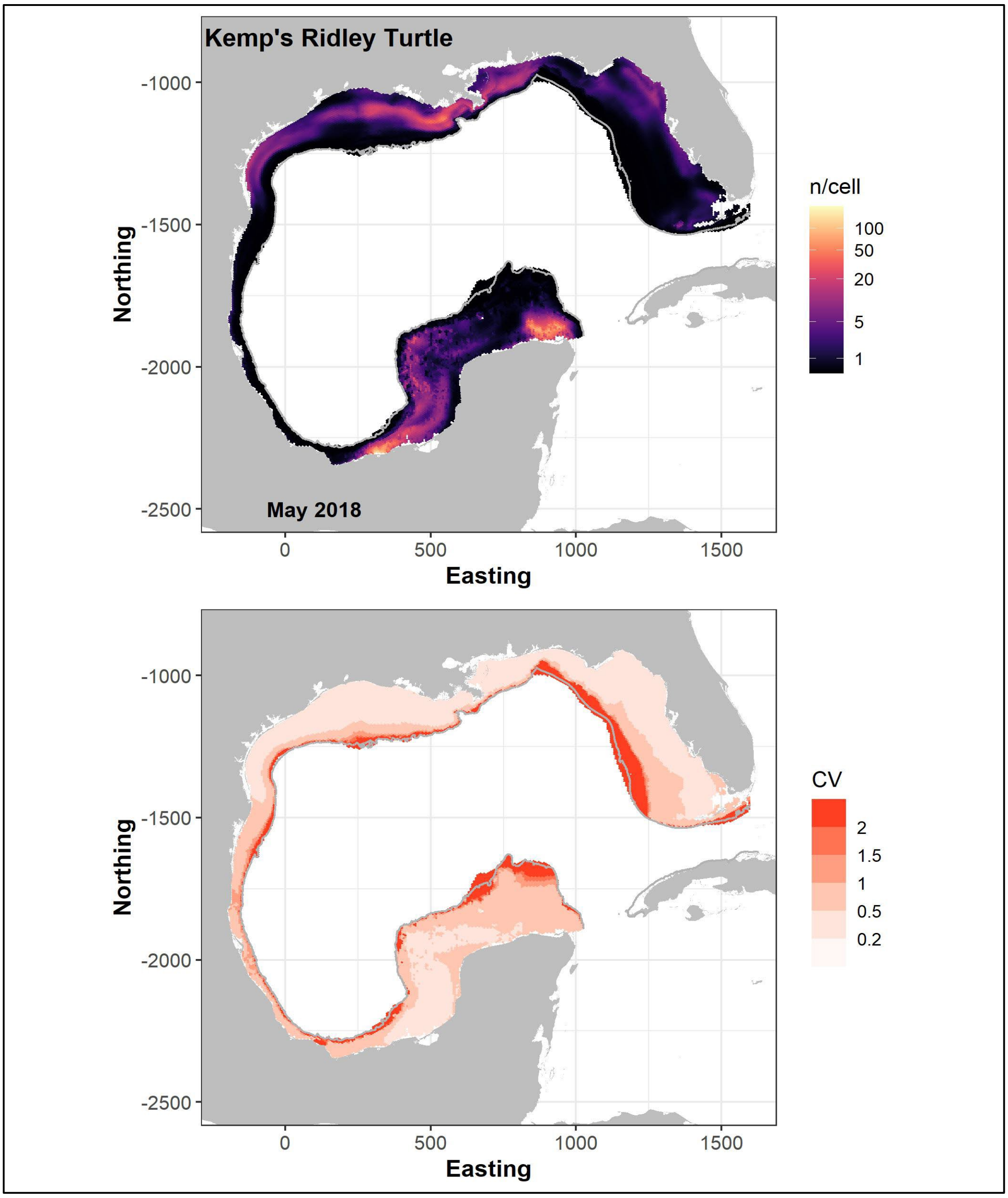

Figure D.3-42. Projected density model for shelf Kemp's ridley turtles in the entire GOM for May 2018.

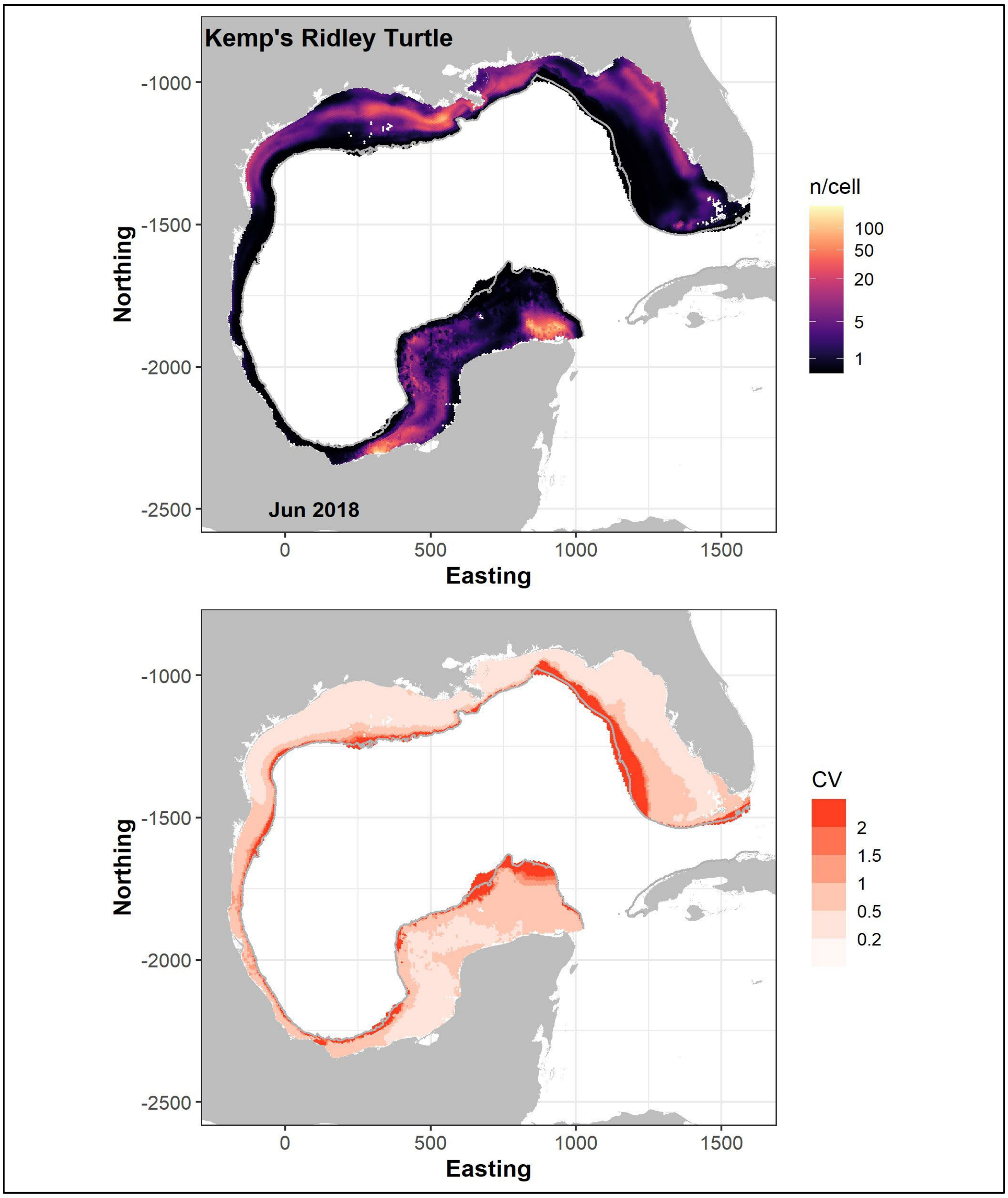

Figure D.3-43. Projected density model for shelf Kemp's ridley turtles in the entire GOM for June 2018.

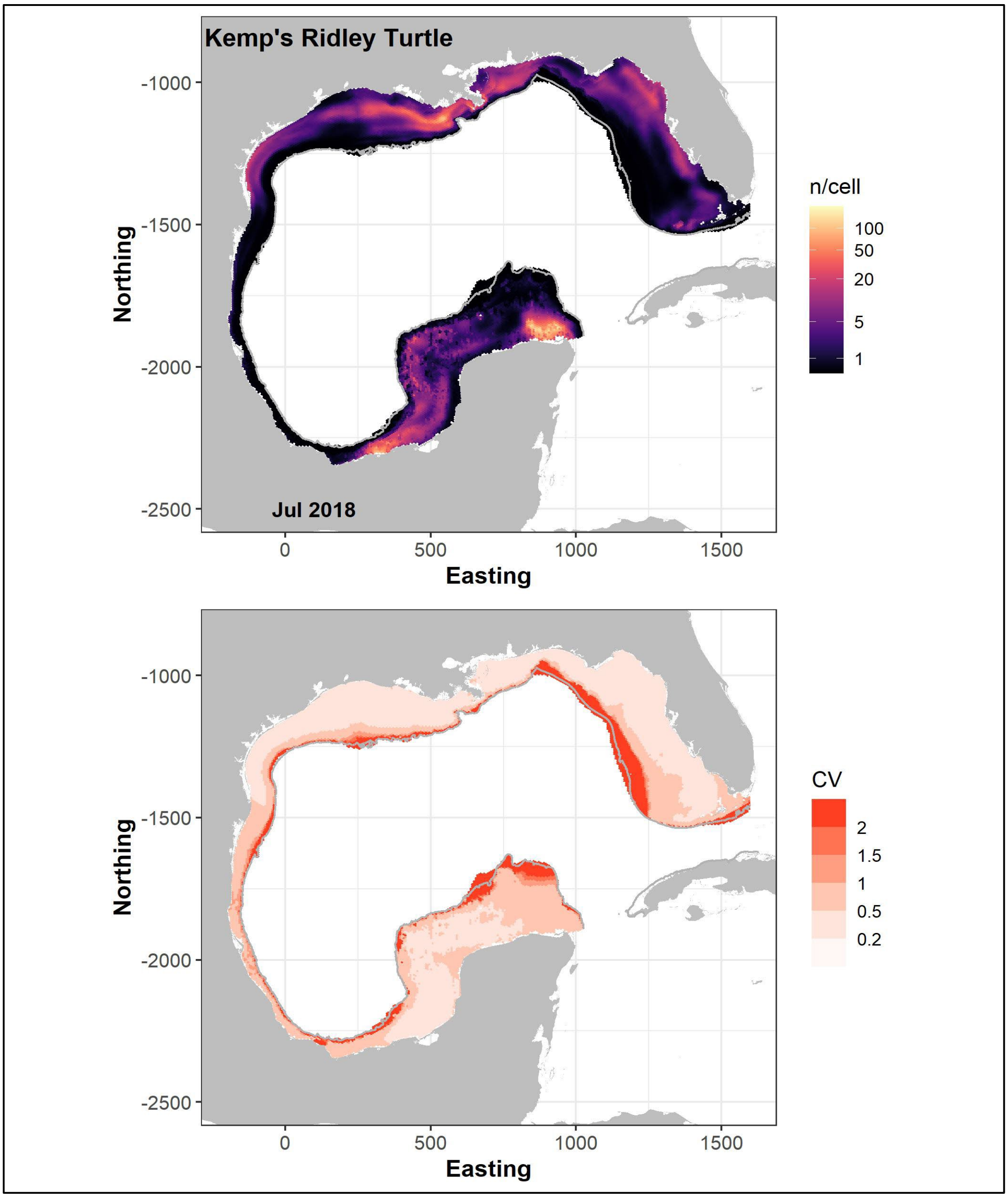

Figure D.3-44. Projected density model for shelf Kemp's ridley turtles in the entire GOM for July 2018.

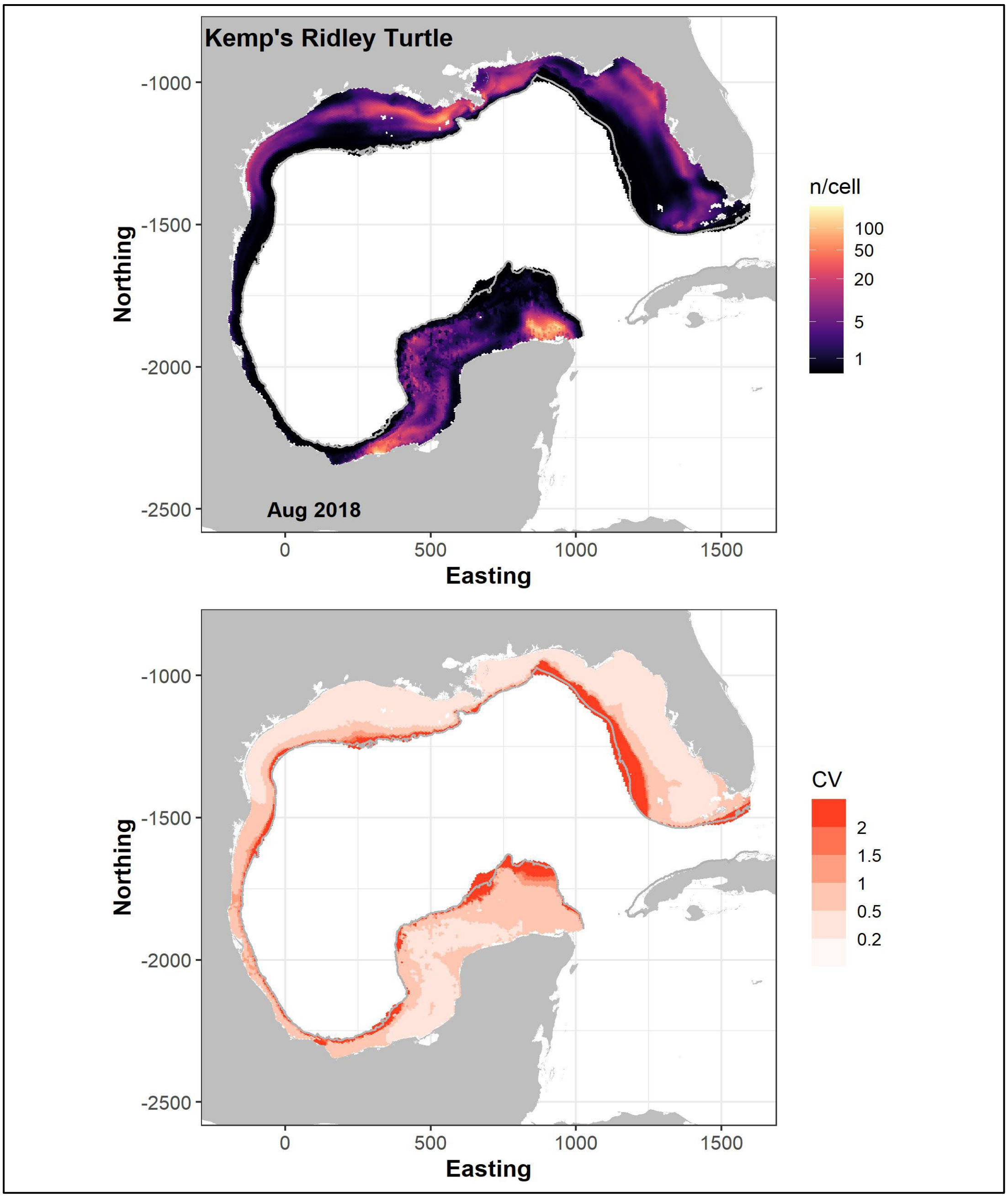

Figure D.3-45. Projected density model for shelf Kemp's ridley turtles in the entire GOM for August 2018.

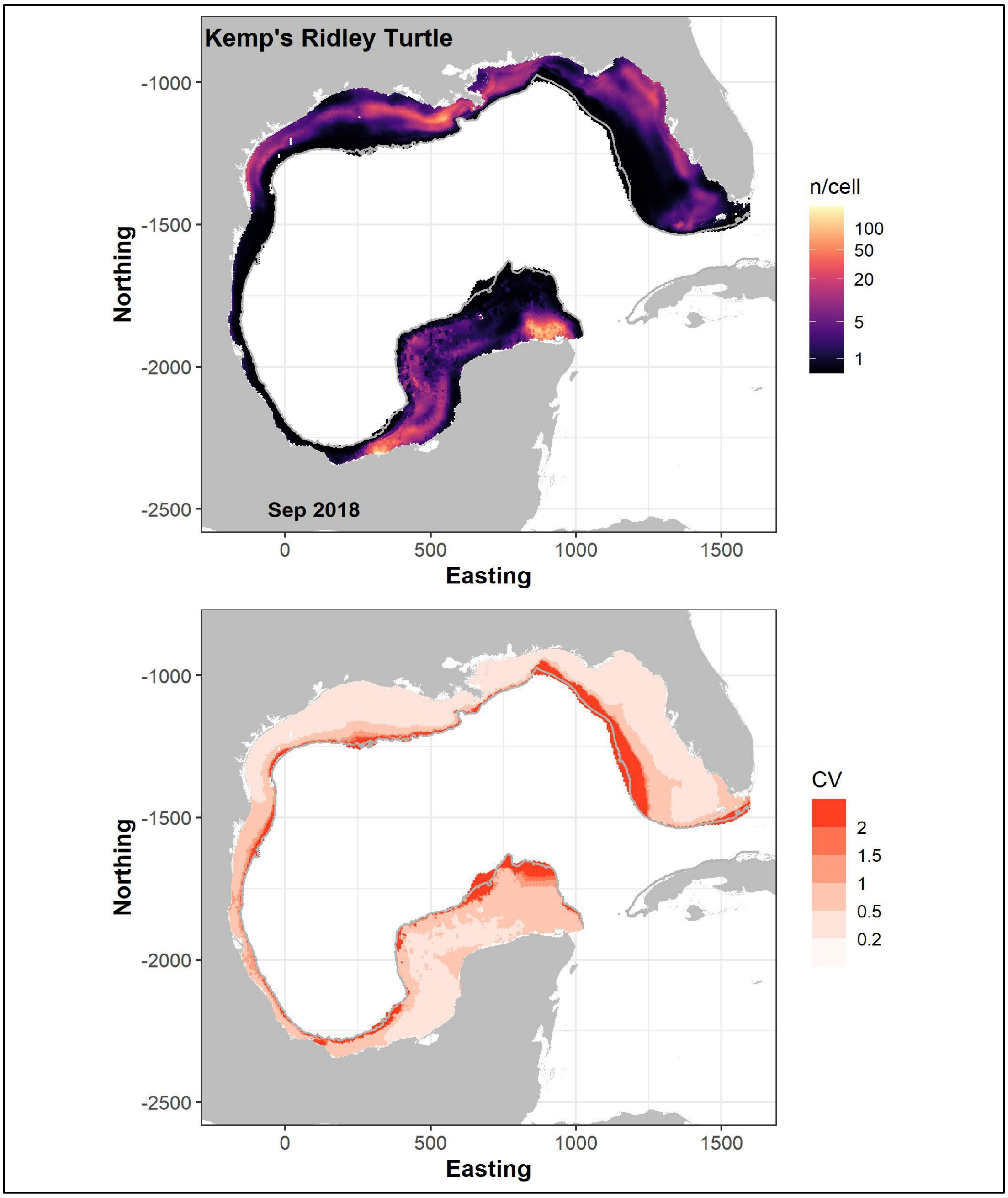

Figure D.3-46. Projected density model for shelf Kemp's ridley turtles in the entire GOM for September 2018.

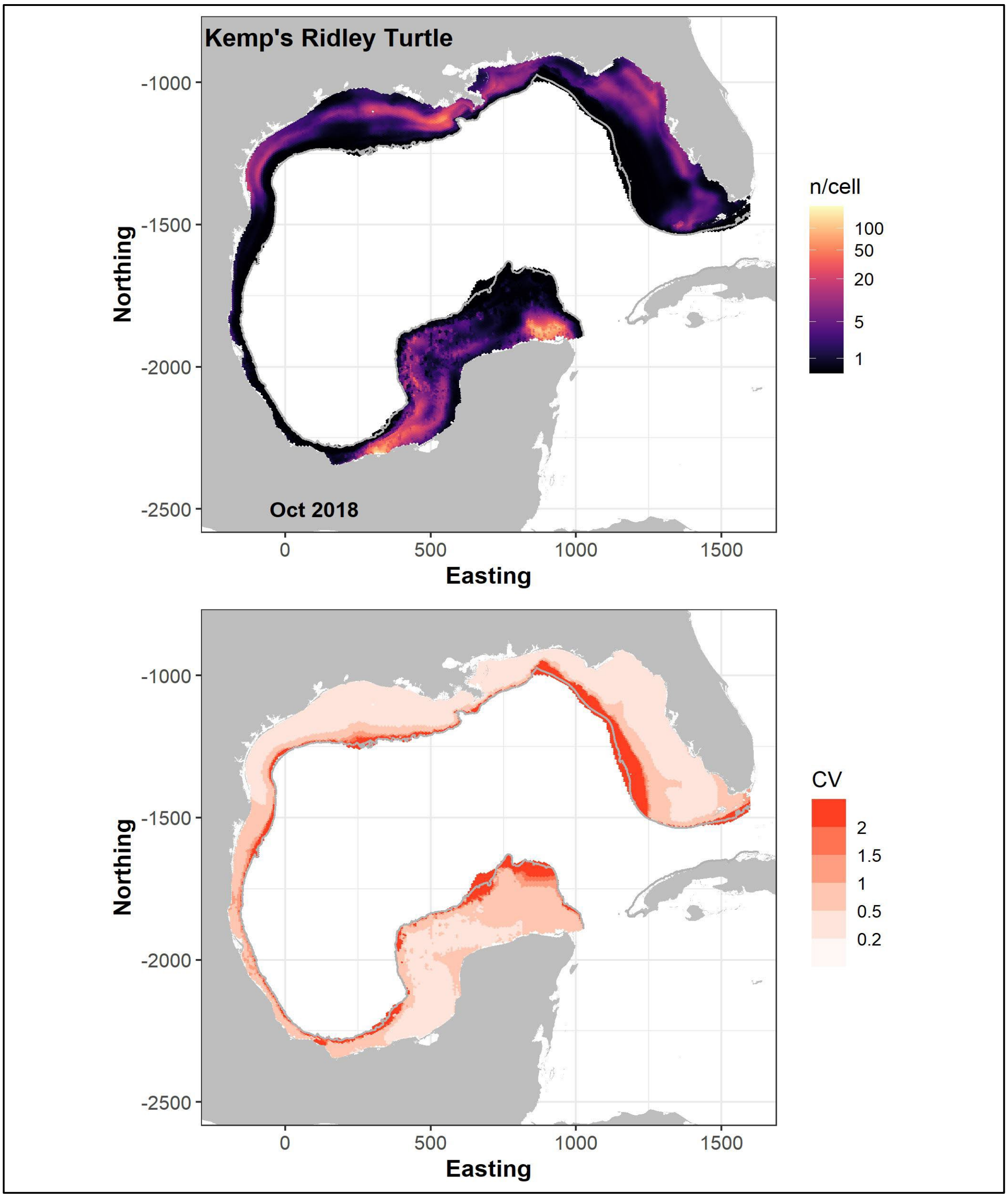

Figure D.3-47. Projected density model for shelf Kemp's ridley turtles in the entire GOM for October 2018.

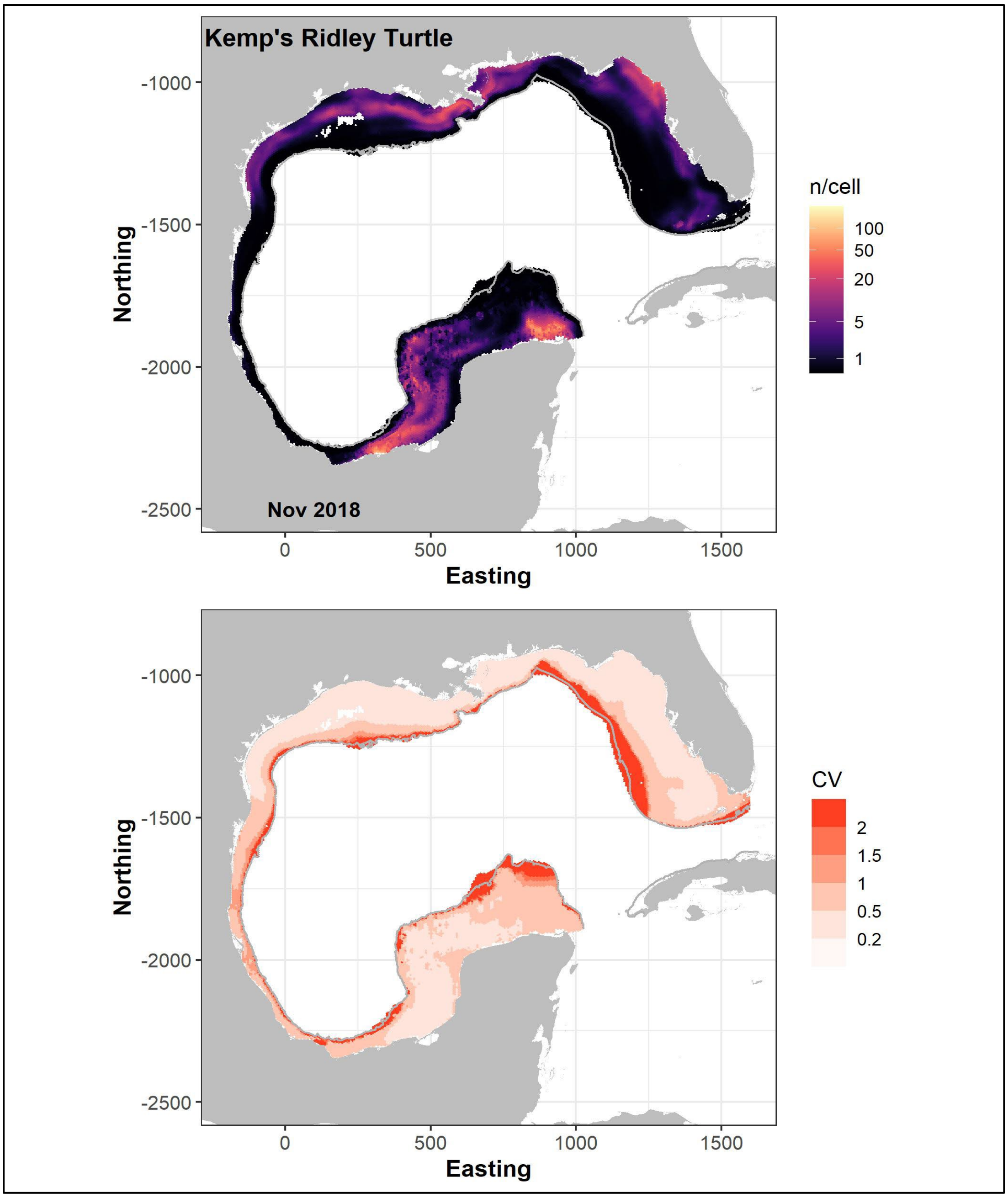

Figure D.3-48. Projected density model for shelf Kemp's ridley turtles in the entire GOM for November 2018.

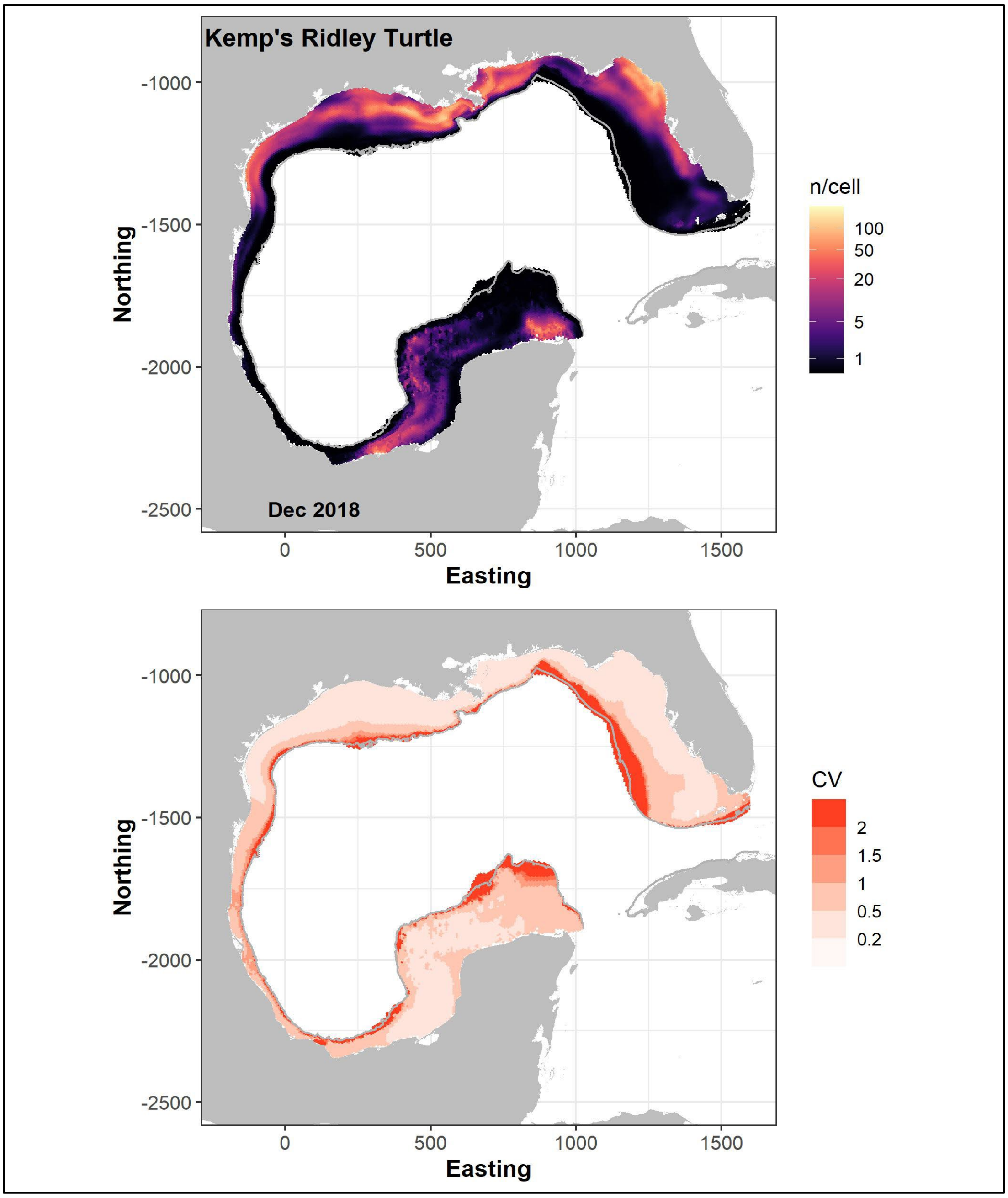

Figure D.3-49. Projected density model for shelf Kemp's ridley turtles in the entire GOM for December 2018.

D.3.5.4 Average Monthly Density: 2015–2019

Prediction maps were generated using monthly environmental parameters for the period of 2015–2019. The posterior distribution of the GAM parameters was sampled 1,000 times to generate a distribution of model coefficients that reflect the statistical uncertainty in the parameter estimation. Predictions of animal density were generated for each month in the 2015–2019 period based on each of these 1,000 parameter sets. In this way, both inter-annual variability in environmental conditions and model uncertainty were included in the resulting samples. The monthly predictions were examined to identify sampled parameters that generated extreme predicted densities, and these extreme values

were excluded from the bootstrap sample before variance estimation. These extreme values, associated with density predictions many orders of magnitude higher than the observed median, reflect projection of the model predictions into poorly sampled parameter space. It was not necessary to trim the bootstrap iterations for Kemp's ridley turtles. The resulting distribution of realizations was used to summarize predicted average densities by month and to calculate metrics of uncertainty. The average monthly abundance for Kemp's ridley turtles in US waters is shown in Table D.3-5 (Figures D.3-50–D.3-61).

Table D.3-5. Monthly average abundance of Kemp's ridley turtles in US shelf waters 2015–2019

Month	Abundance	CV
January	236,751	0.237
February	273,633	0.211
March	174,408	0.147
April	80,354	0.287
May	48,398	0.141
June	74,393	0.125
July	84,391	0.107
August	83,607	0.092
September	77,299	0.108
October	57,196	0.148
November	57,969	0.213
December	144,825	0.292

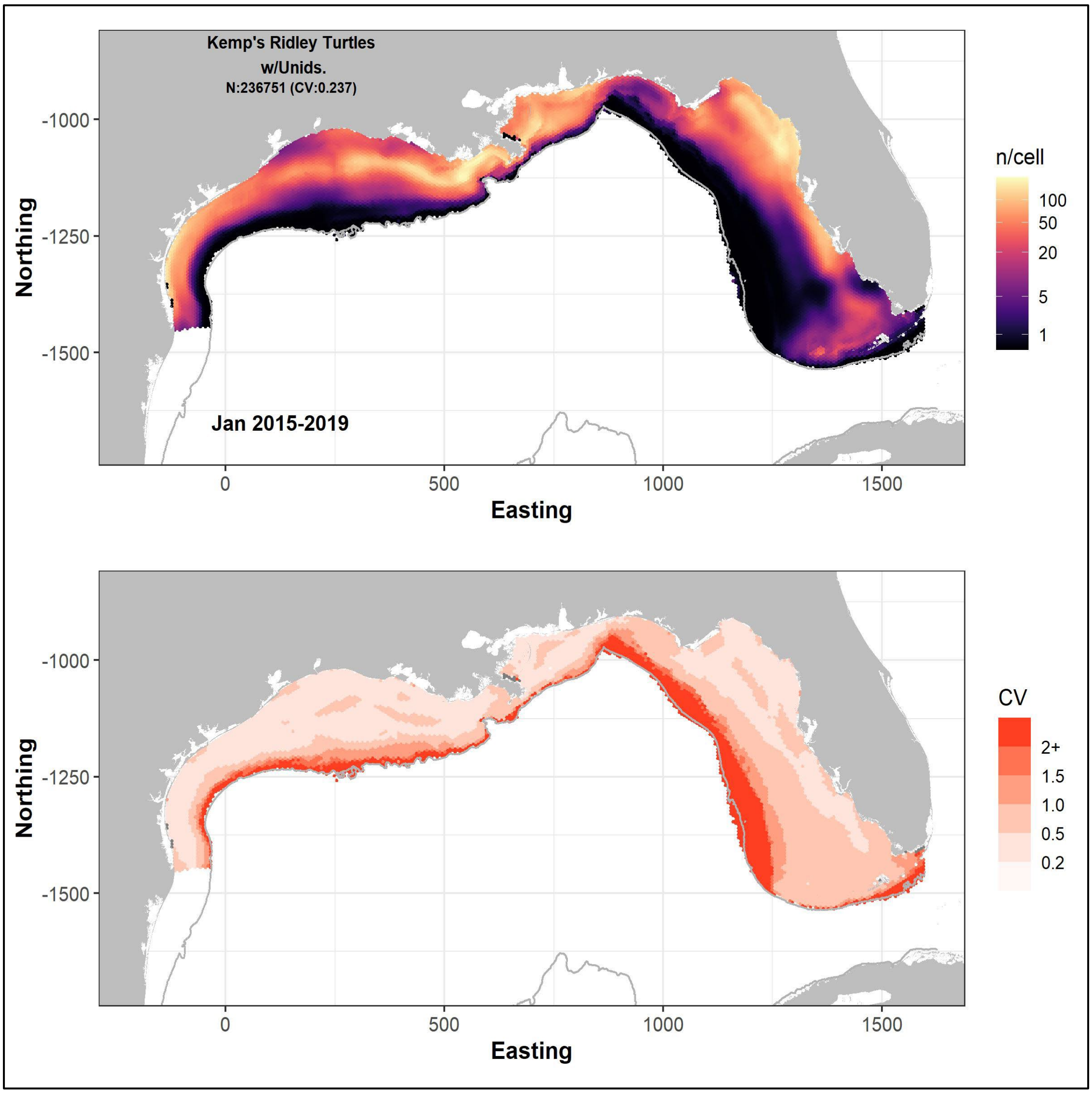

Figure D.3-50. Density model prediction for shelf Kemp's ridley turtles in the NGOM for the months of January 2015–2019.

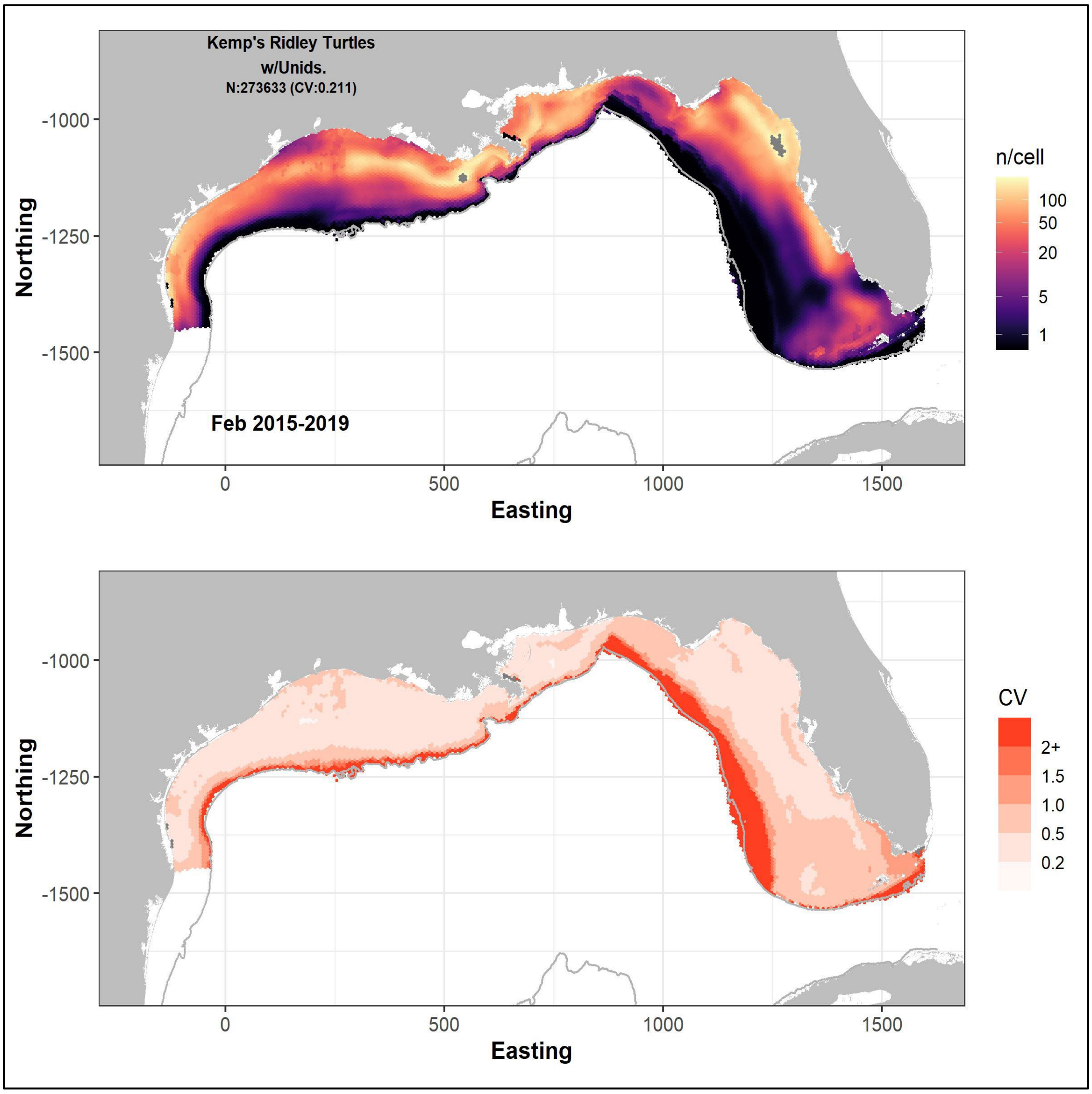

Figure D.3-51. Density model prediction for shelf Kemp's ridley turtles in the NGOM for the months of February 2015–2019.

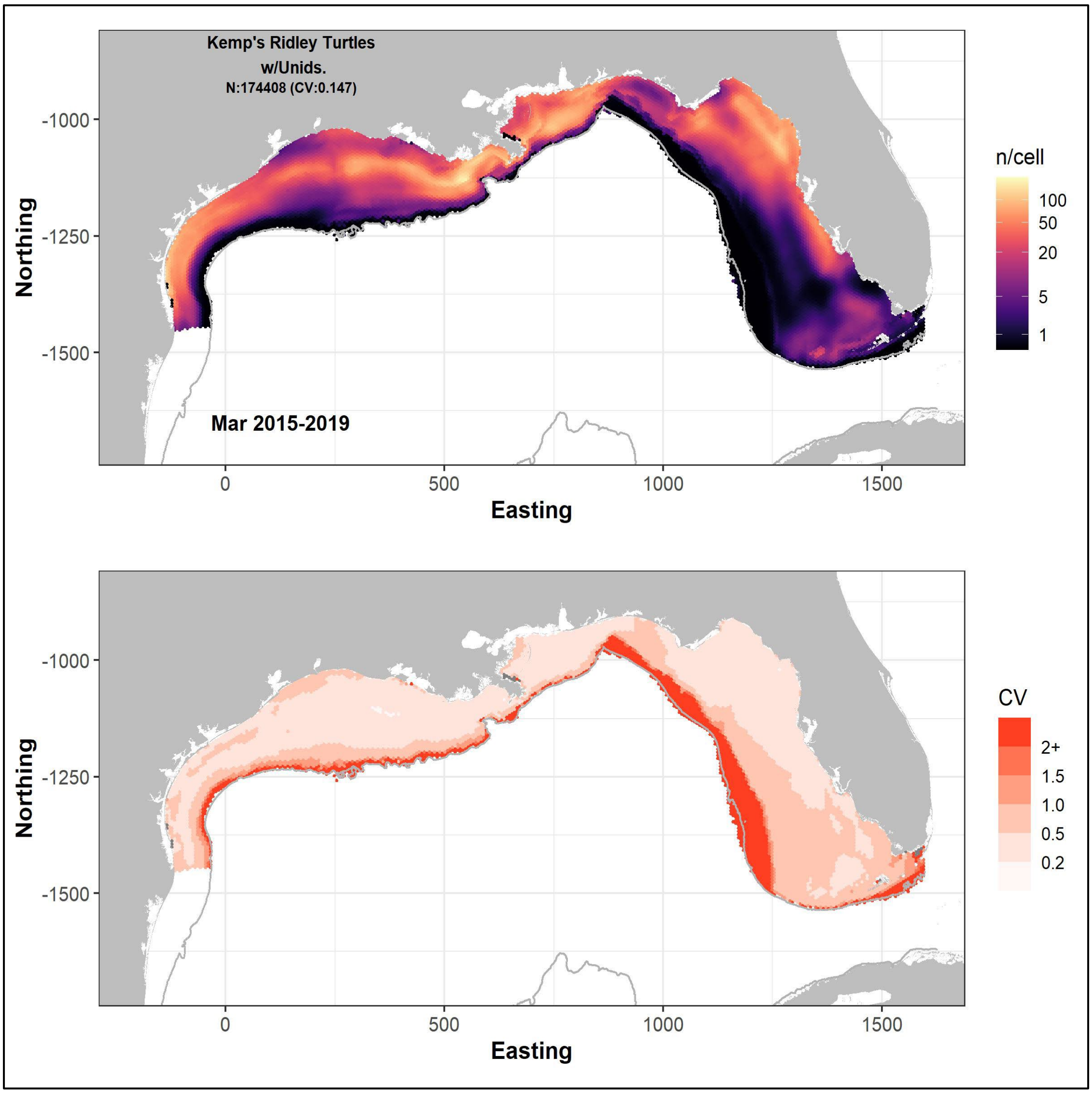

Figure D.3-52. Density model prediction for shelf Kemp's ridley turtles in the NGOM for the months of March 2015–2019.

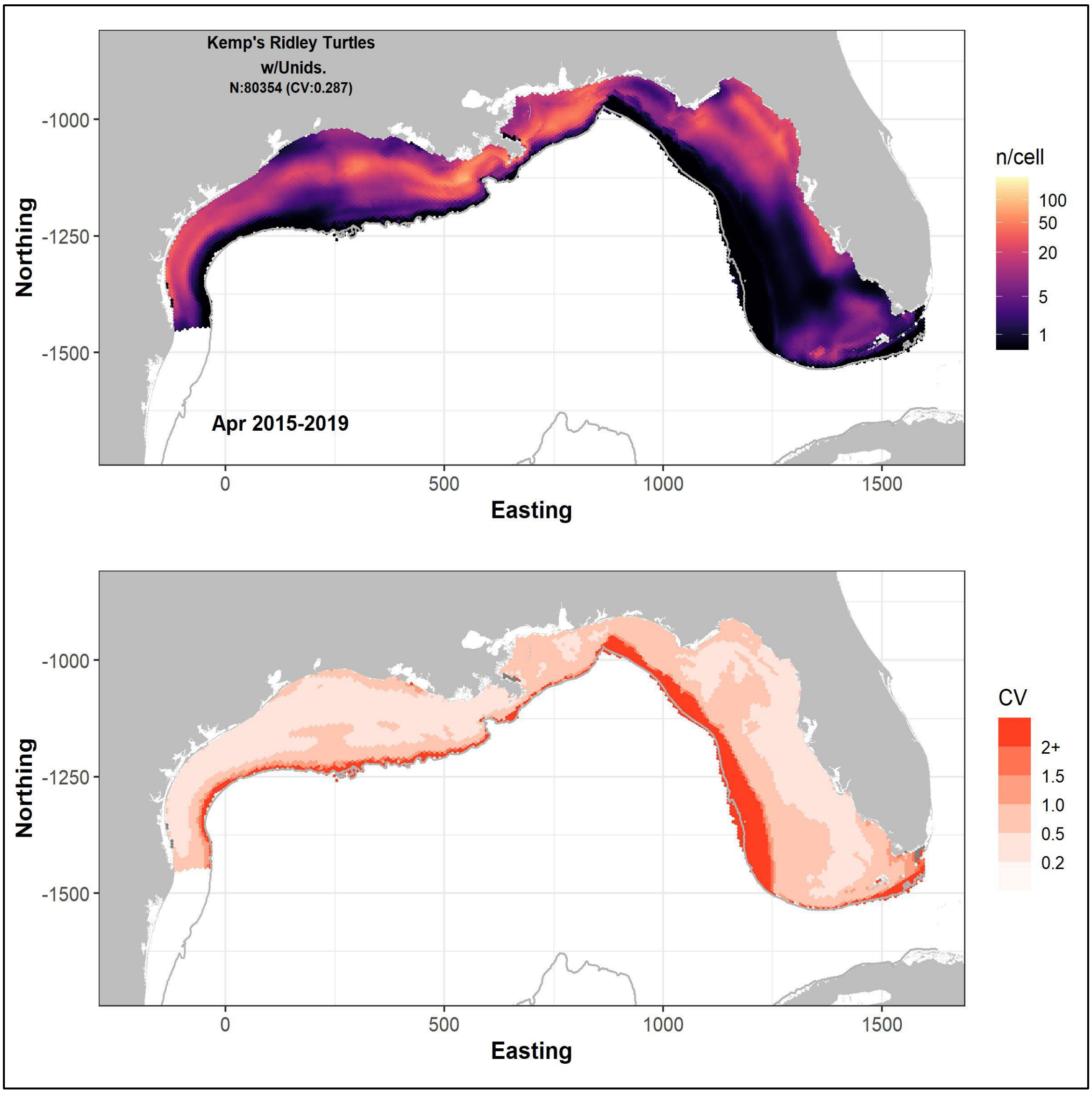

Figure D.3-53. Density model prediction for shelf Kemp's ridley turtles in the NGOM for the months of April 2015–2019.

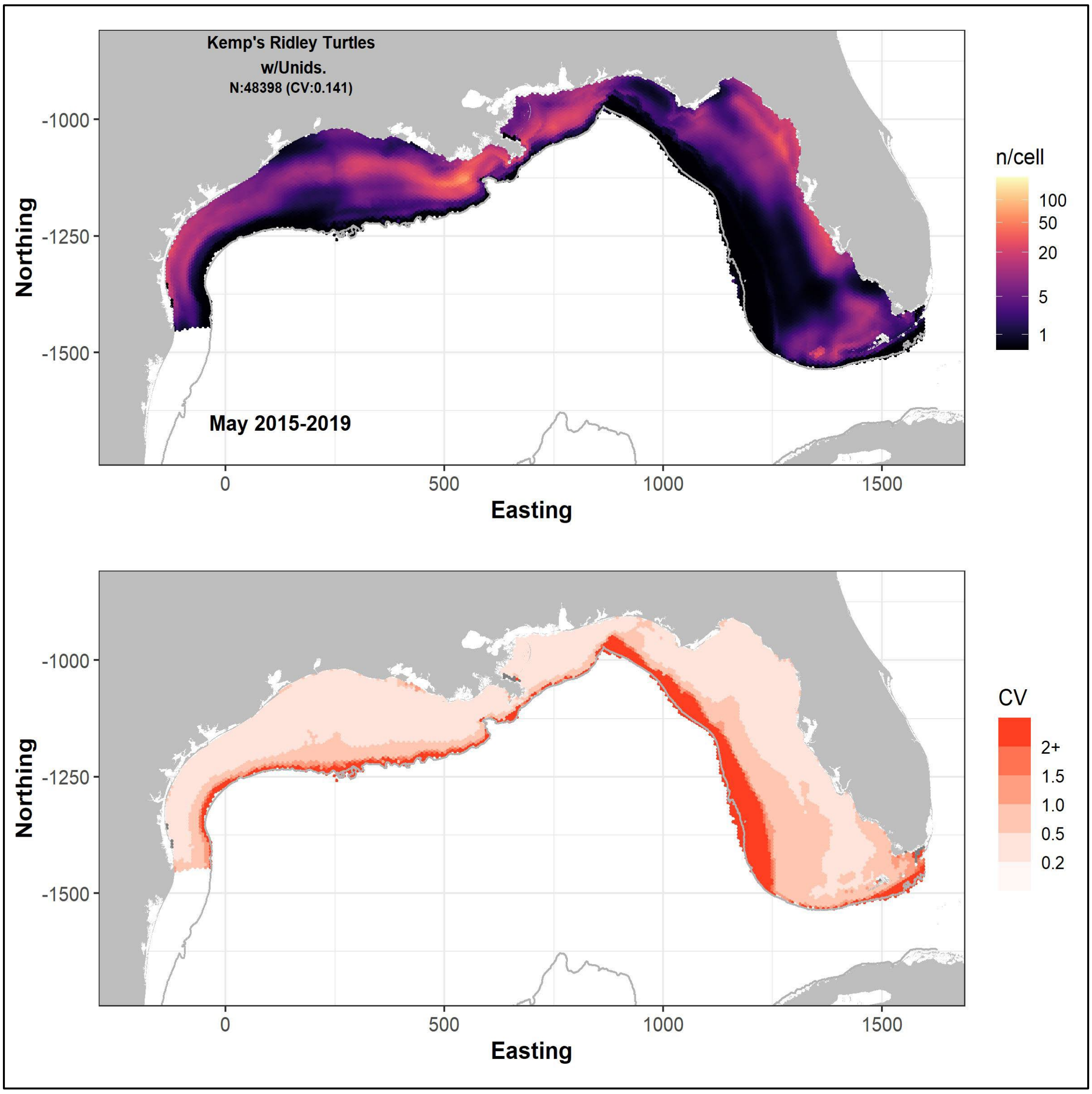

Figure D.3-54. Density model prediction for shelf Kemp's ridley turtles in the NGOM for the months of May 2015–2019.

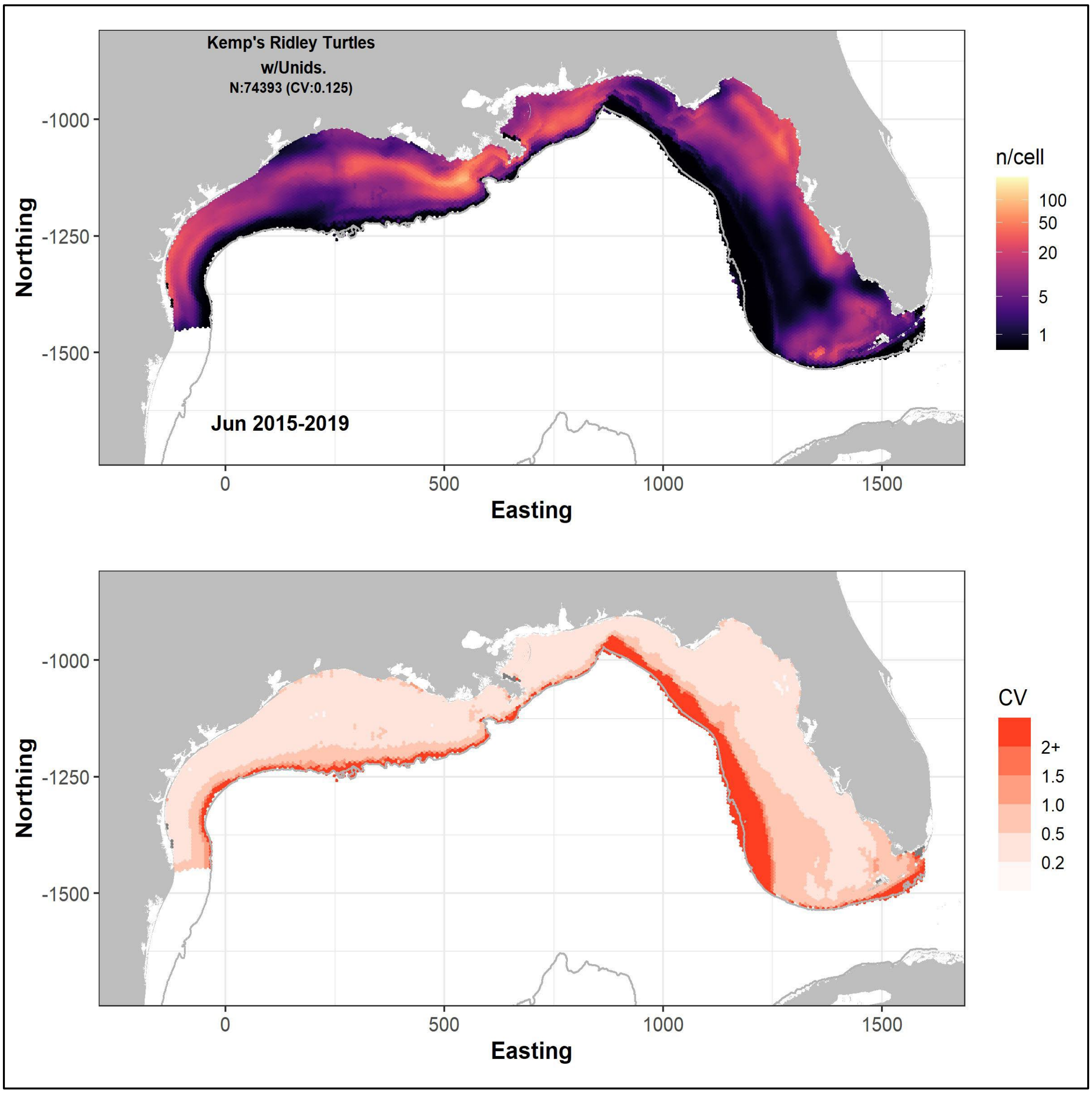

Figure D.3-55. Density model prediction for shelf Kemp's ridley turtles in the NGOM for the months of June 2015–2019.

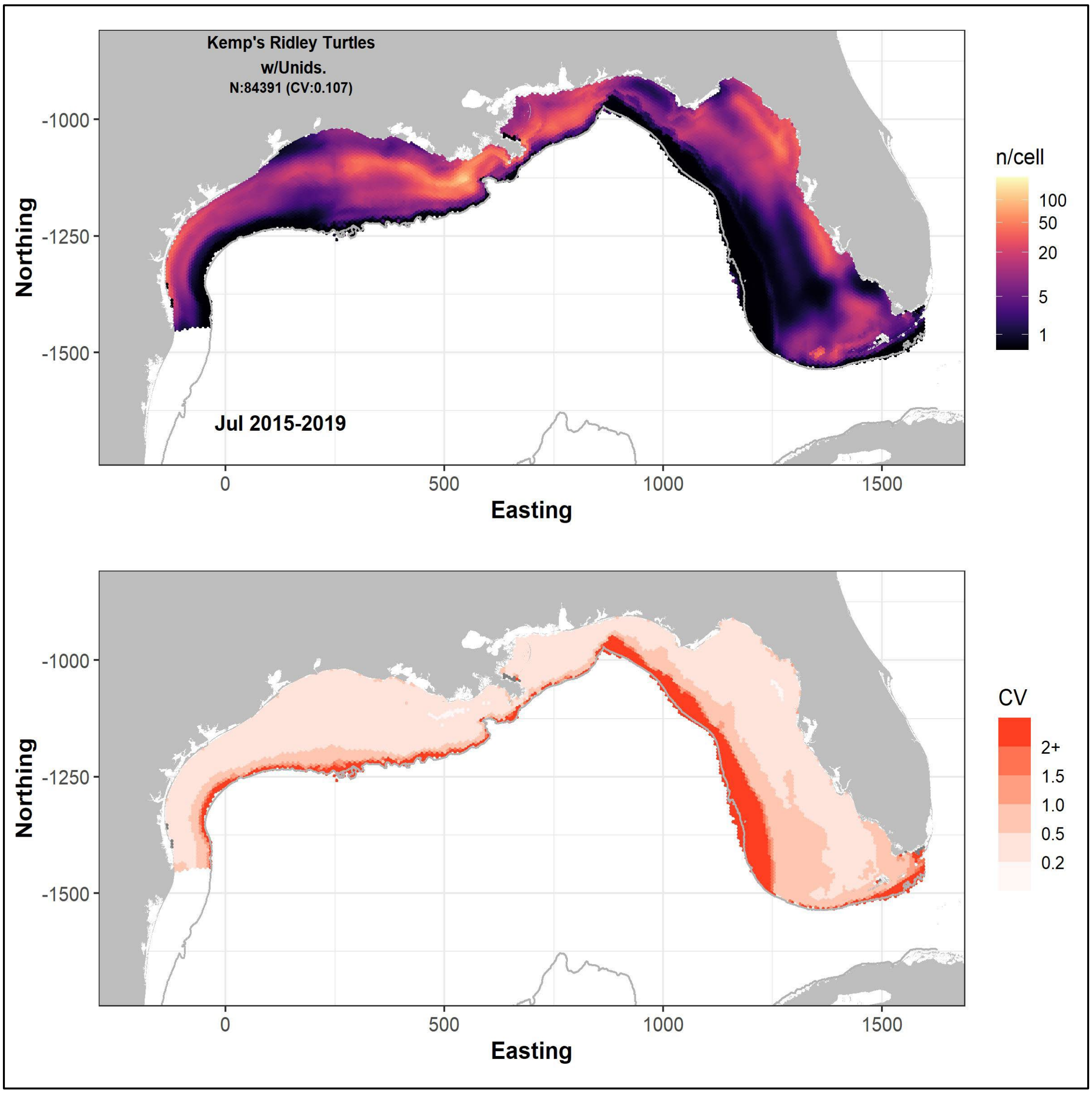

Figure D.3-56. Density model prediction for shelf Kemp's ridley turtles in the NGOM for the months of July 2015–2019.

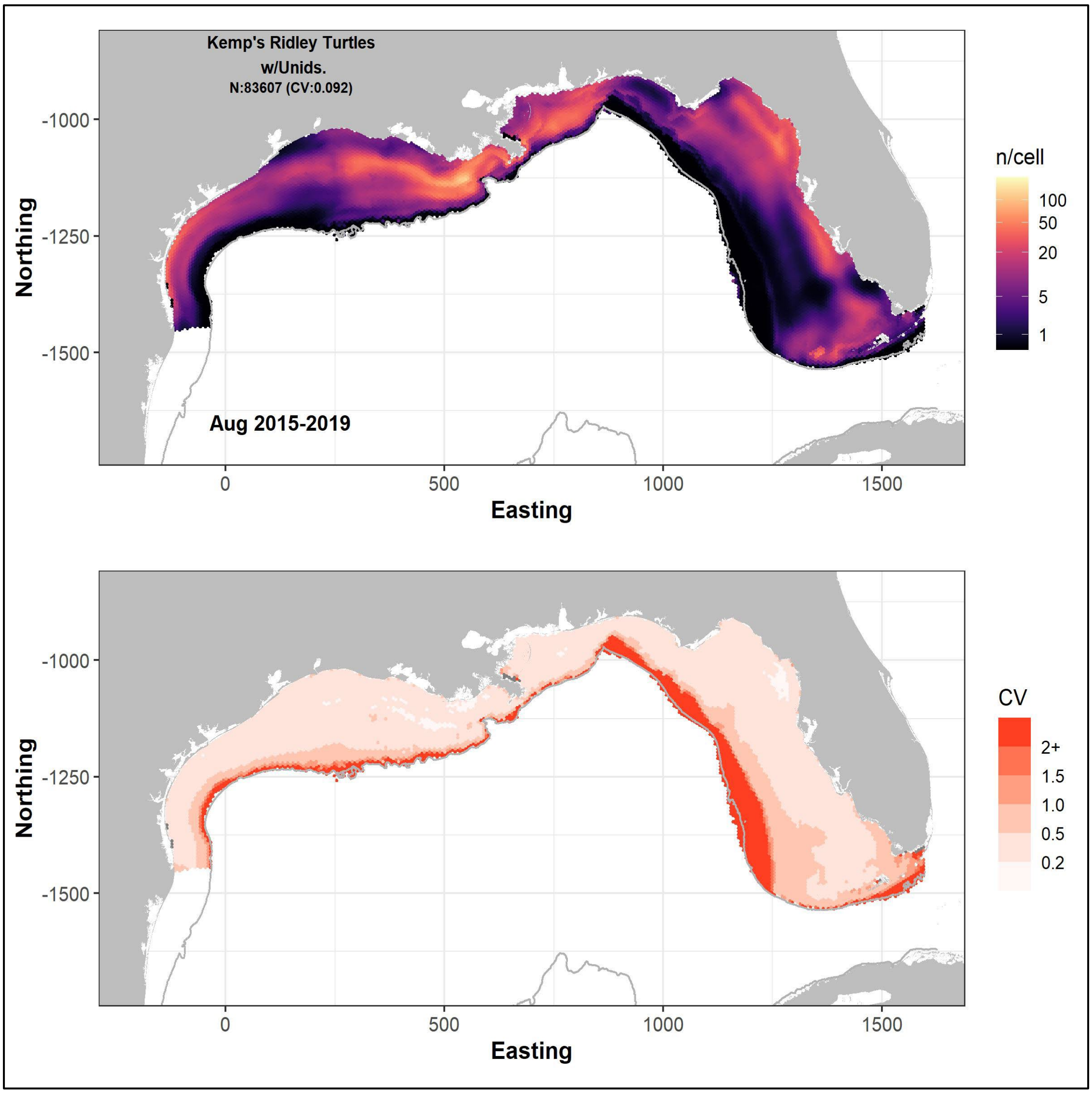

Figure D.3-57. Density model prediction for shelf Kemp's ridley turtles in the NGOM for the months of August 2015–2019.

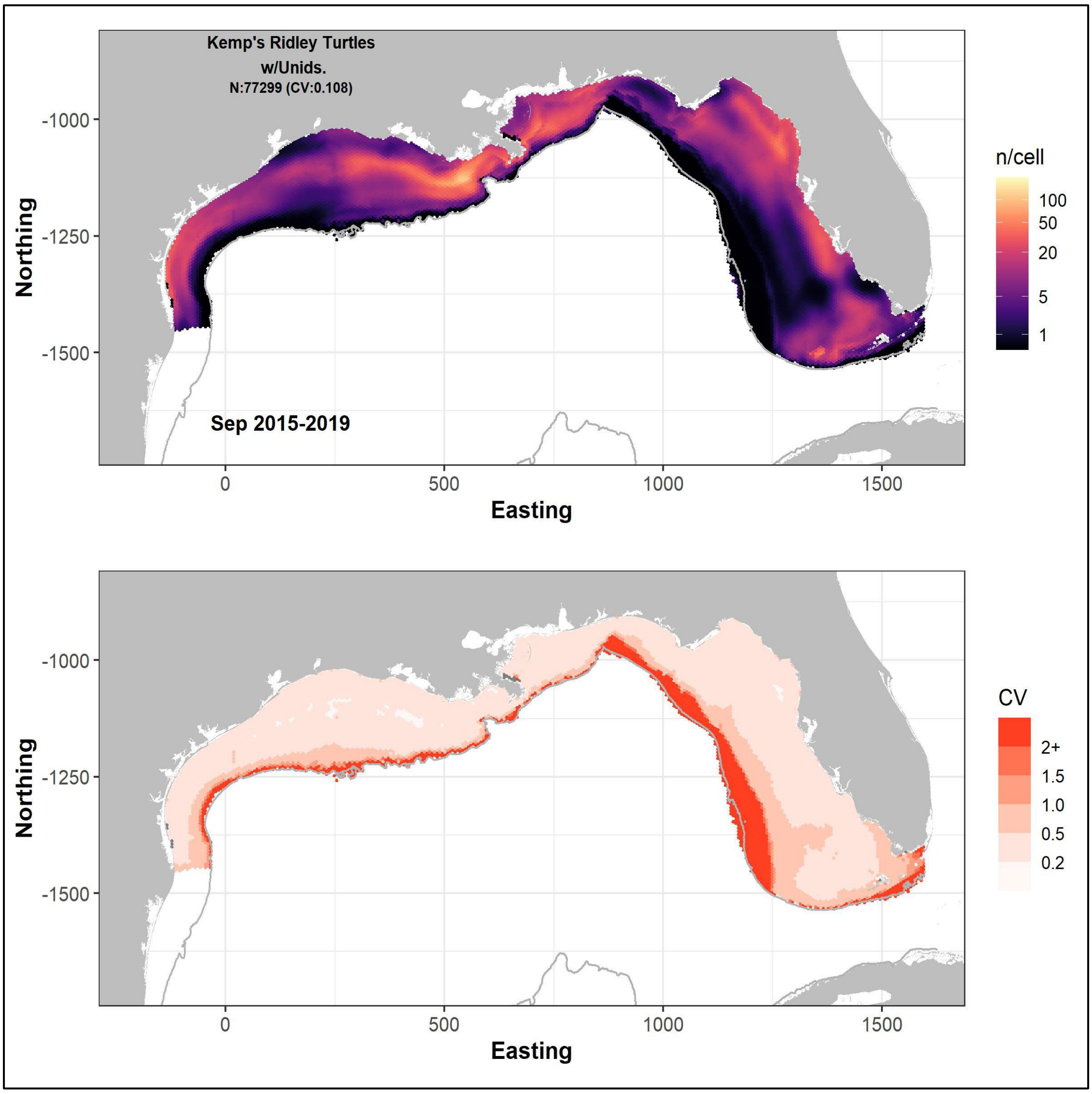

Figure D.3-58. Density model prediction for shelf Kemp's ridley turtles in the NGOM for the months of September 2015–2019.

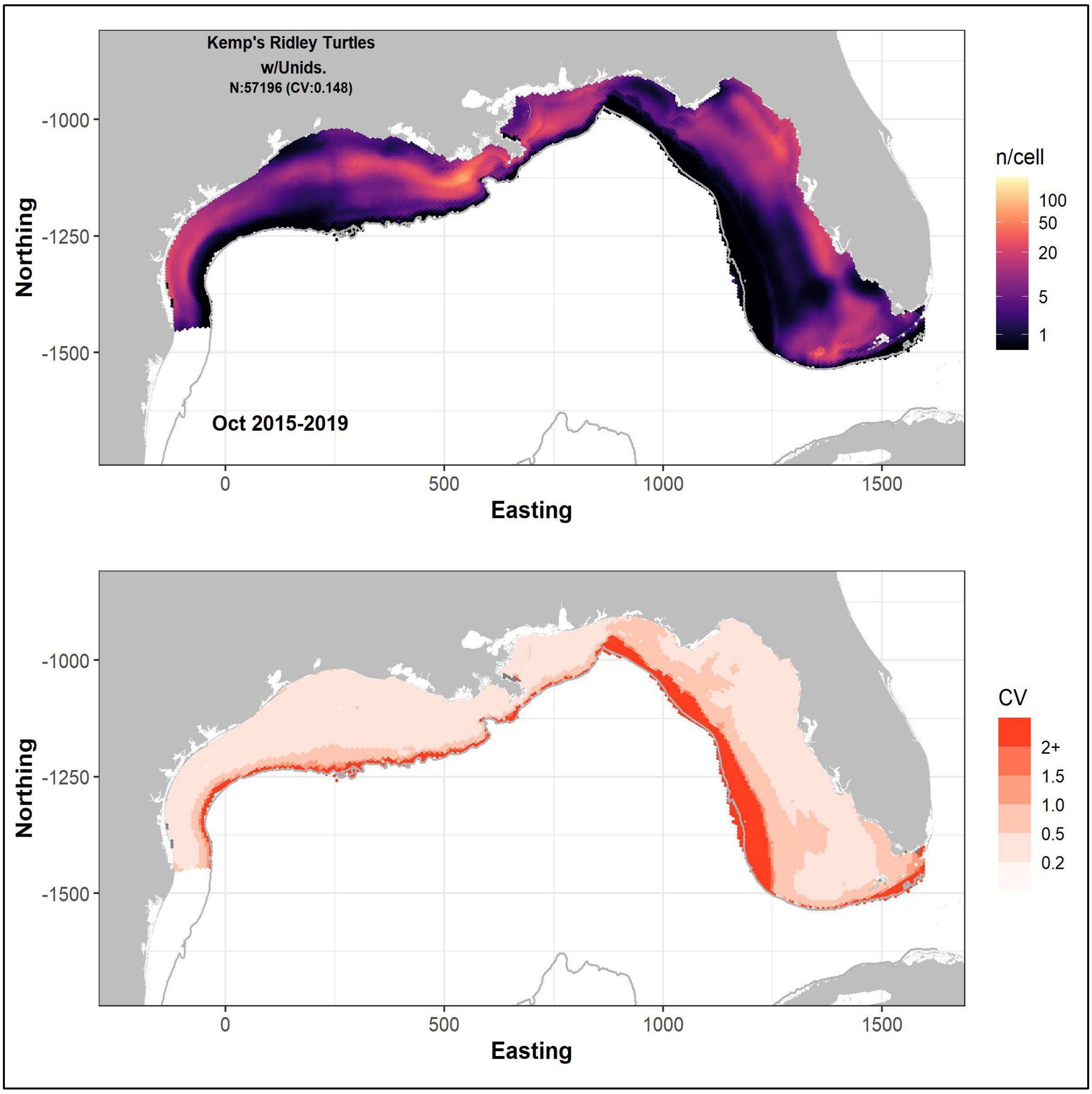

Figure D.3-59. Density model prediction for shelf Kemp's ridley turtles in the NGOM for the months of October 2015–2019.

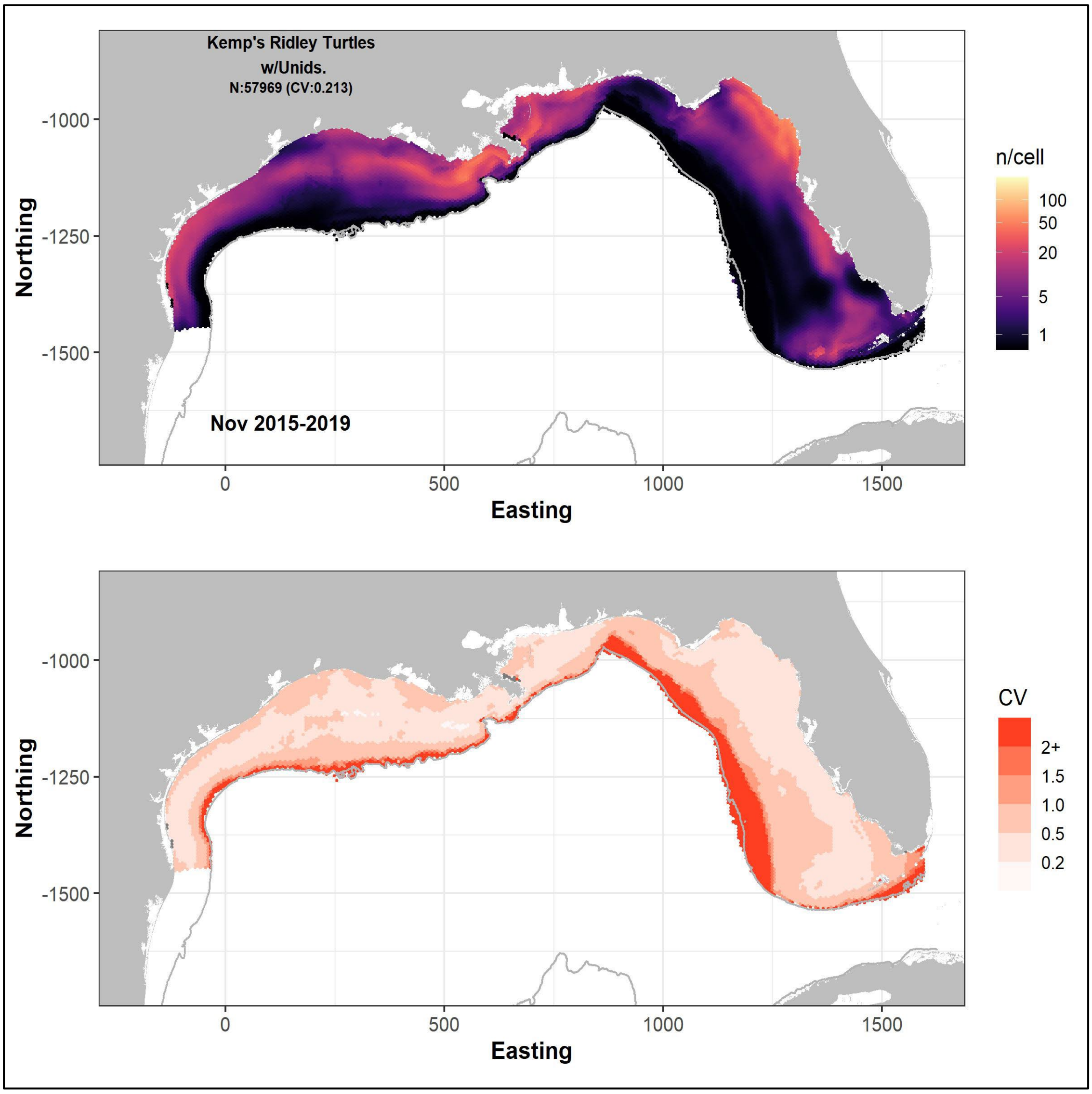

Figure D.3-60. Density model prediction for shelf Kemp's ridley turtles in the NGOM for the months of November 2015–2019.

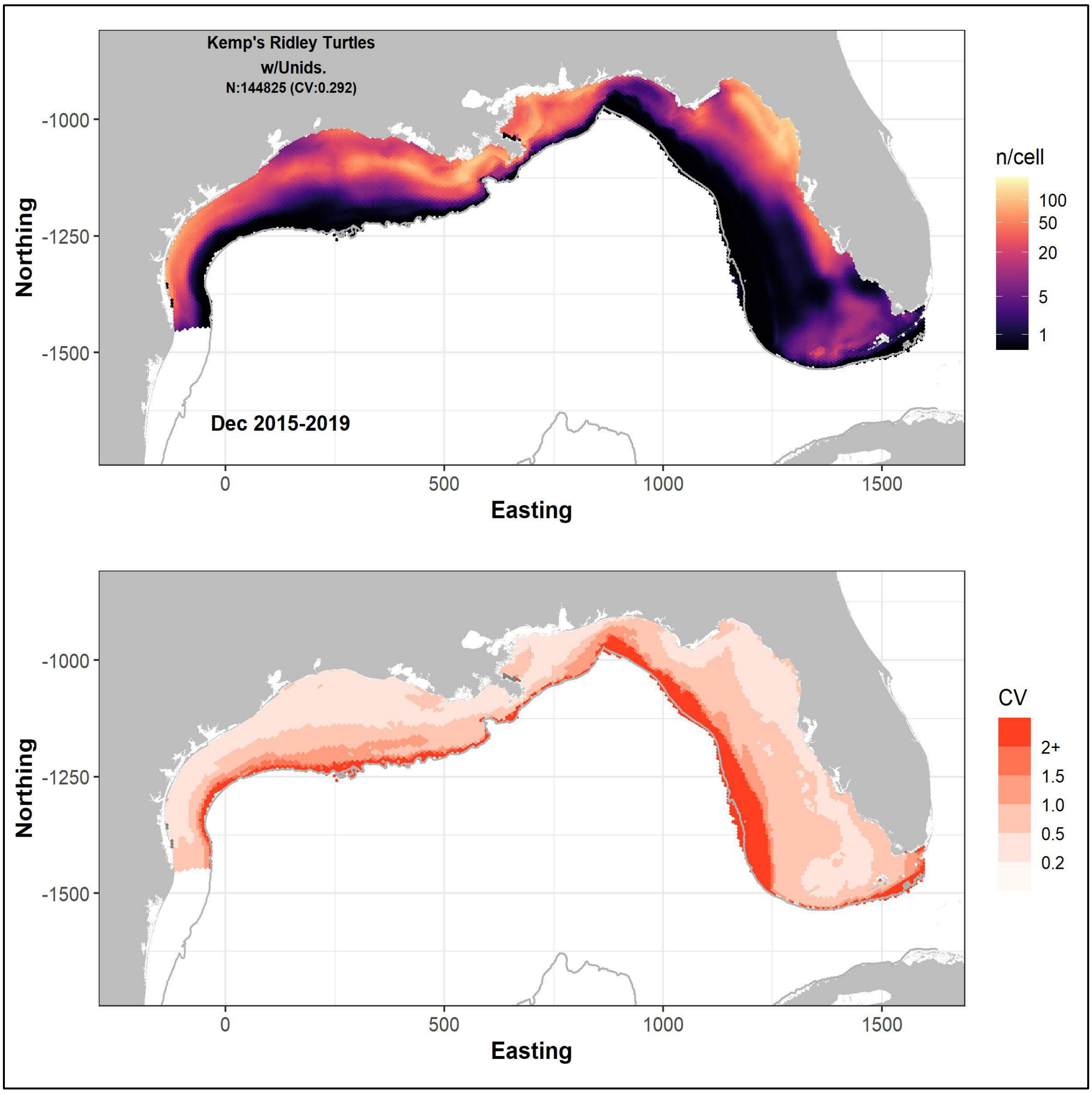

Figure D.3-61. Density model prediction for shelf Kemp's ridley turtles in the NGOM for the months of December 2015–2019.

The density models for Kemp's ridley turtles were summarized seasonally (Winter: Dec–Feb, Spring: Mar–May, Summer: Jun–Aug, Fall: Sep–Nov) and by Bureau of Ocean Energy Management (BOEM) planning area to generate abundance and coefficients of variation (CV) that reflect uncertainty in both model parameters and interannual variation in environmental conditions for each area (Table D.3-6).

Table D.3-6. Seasonal abundance (CV) of Kemp's ridley turtles in US shelf waters during 2015–2019 for BOEM planning areas

Season	Eastern	Central	Western
Winter	66,091 (0.41)	71,570 (0.35)	26,813 (0.36)
Spring	29,736 (0.57)	36,141 (0.56)	14,893 (0.67)
Summer	25,054 (0.15)	31,015 (0.16)	9,176 (0.2)
Fall	20,777 (0.24)	22,168 (0.27)	7,705 (0.21)

D.3.5.5 Gulf-Wide Average Monthly Density: 2015–2019

Prediction maps were generated using monthly environmental parameters for the period of 2015–2019 extrapolating the model for Kemp's ridley turtles throughout the GOM. As noted above, these extrapolations should be treated with caution given the potential for changing species-environment relationships in unsampled areas (Figures D.3-62–D.3-73).

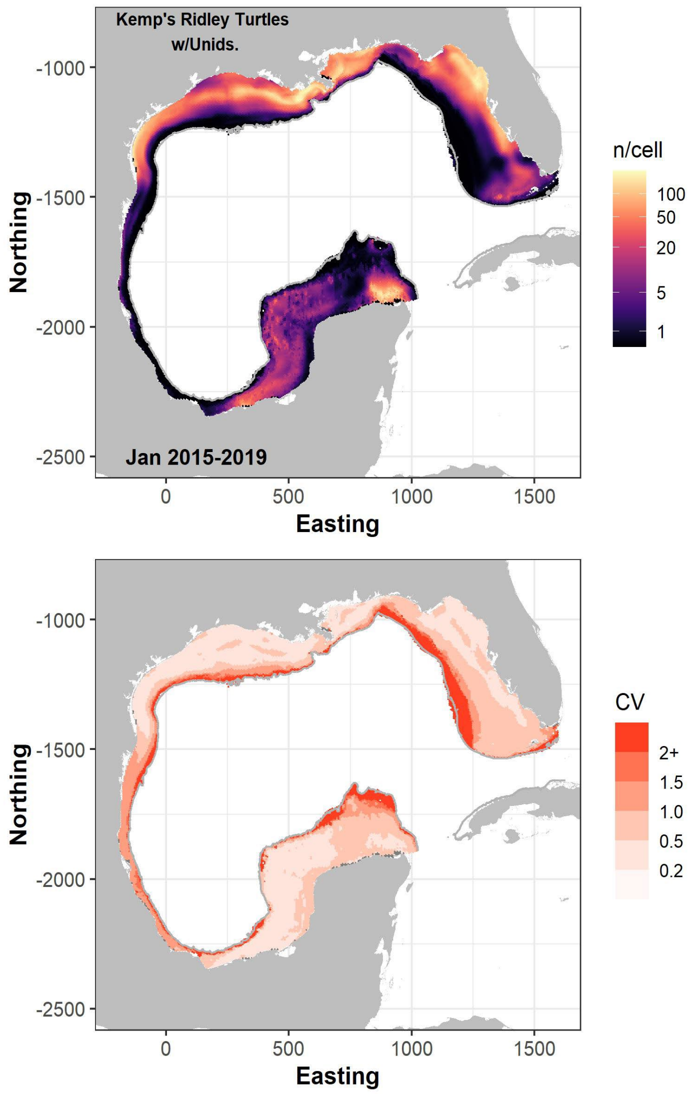

Figure D.3-62. Projected density model for shelf Kemp's ridley turtles in the entire GOM for the months of January 2015–2019.

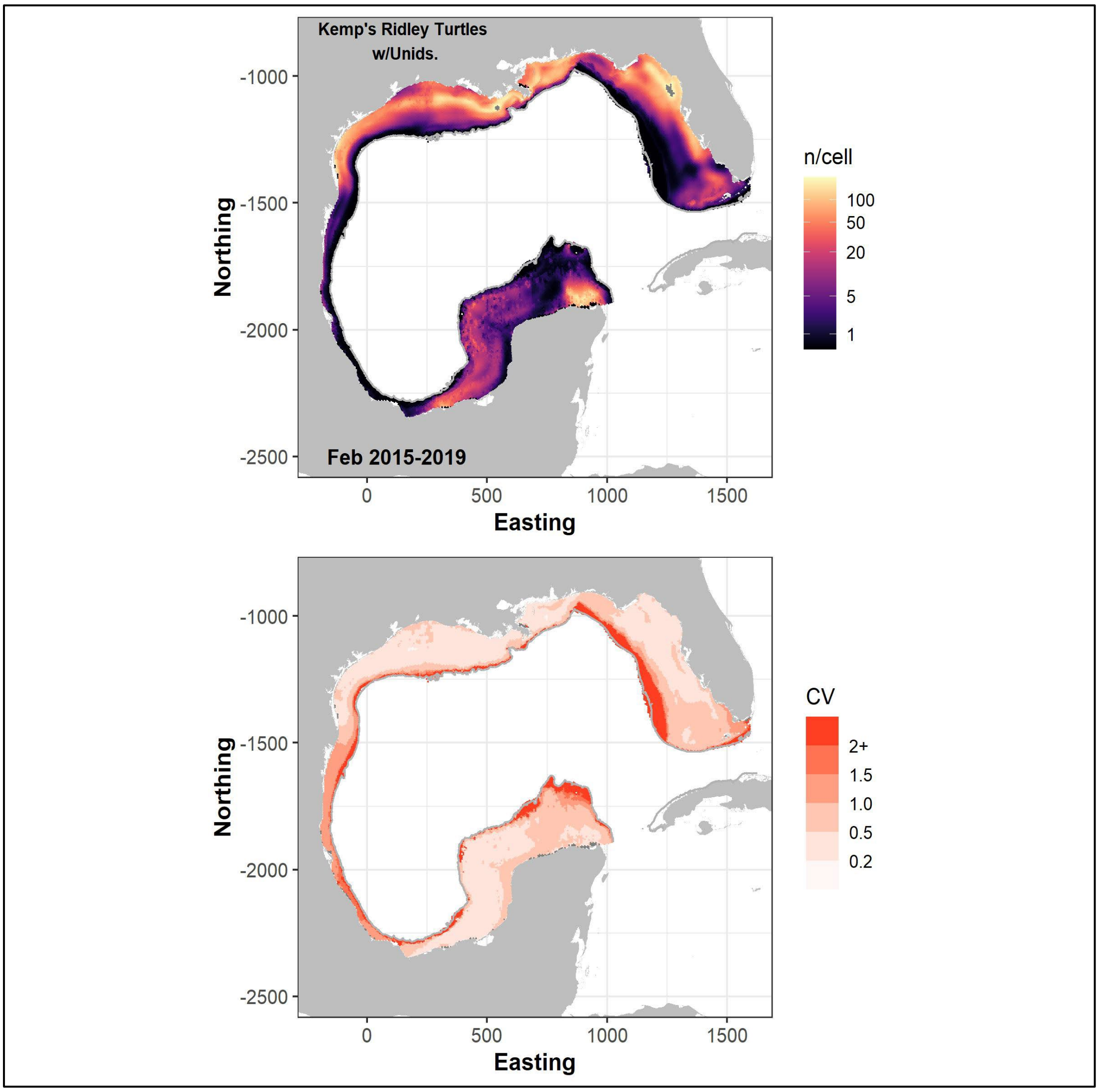

Figure D.3-63. Projected density model for shelf Kemp's ridley turtles in the entire GOM for the months of February 2015–2019.

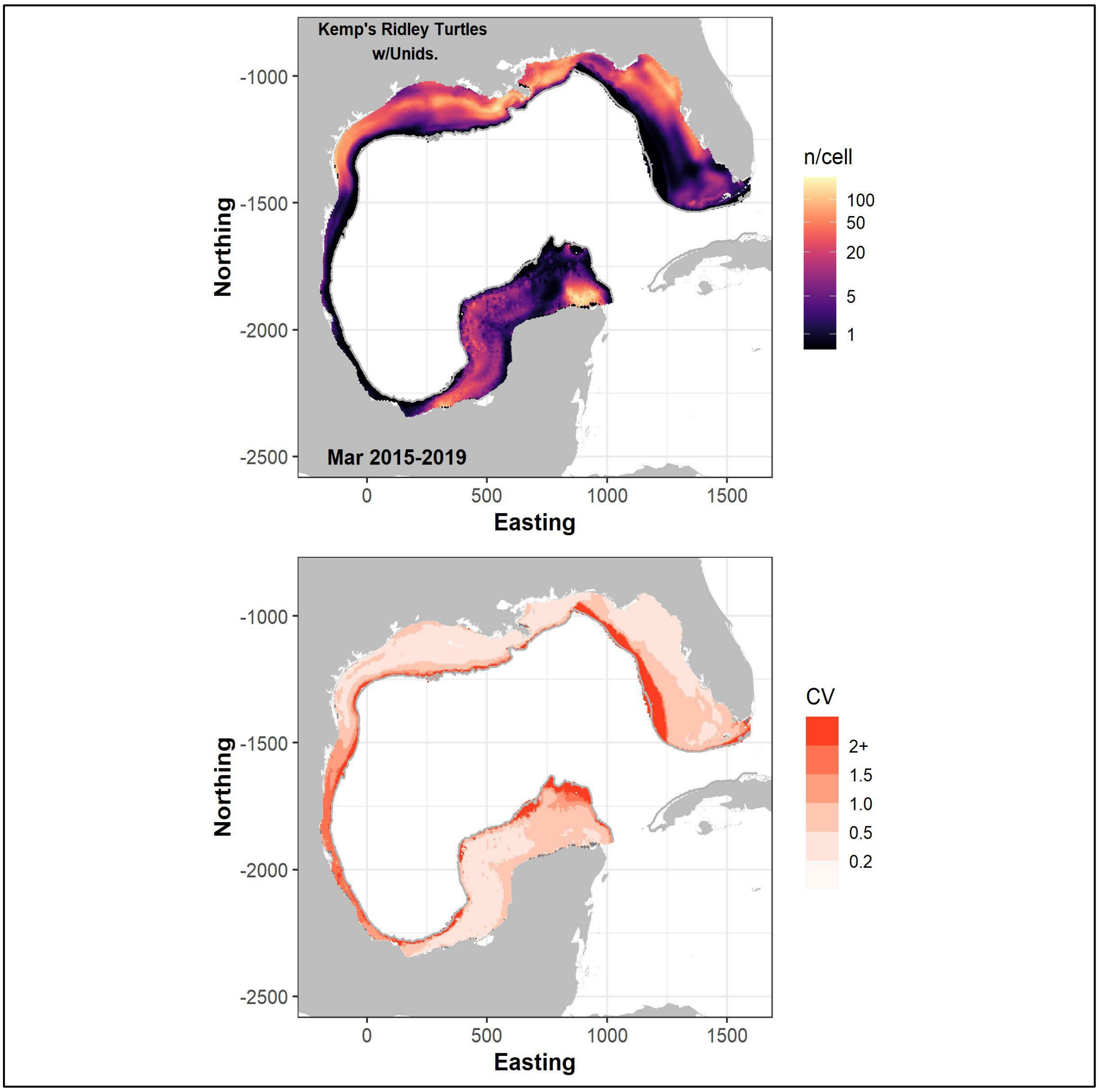

Figure D.3-64. Projected density model for shelf Kemp's ridley turtles in the entire GOM for the months of March 2015–2019.

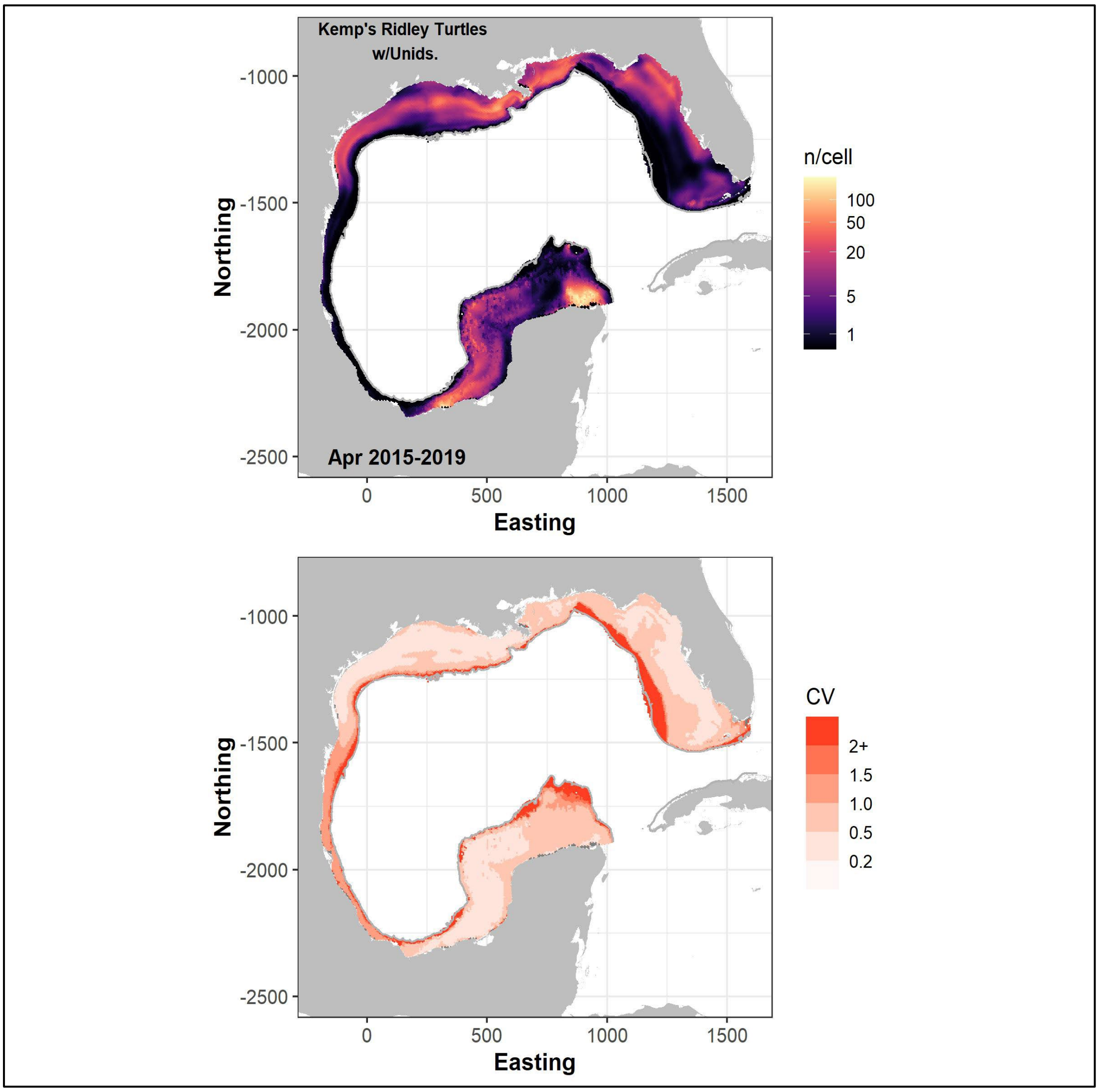

Figure D.3-65. Projected density model for shelf Kemp's ridley turtles in the entire GOM for the months of April 2015–2019.

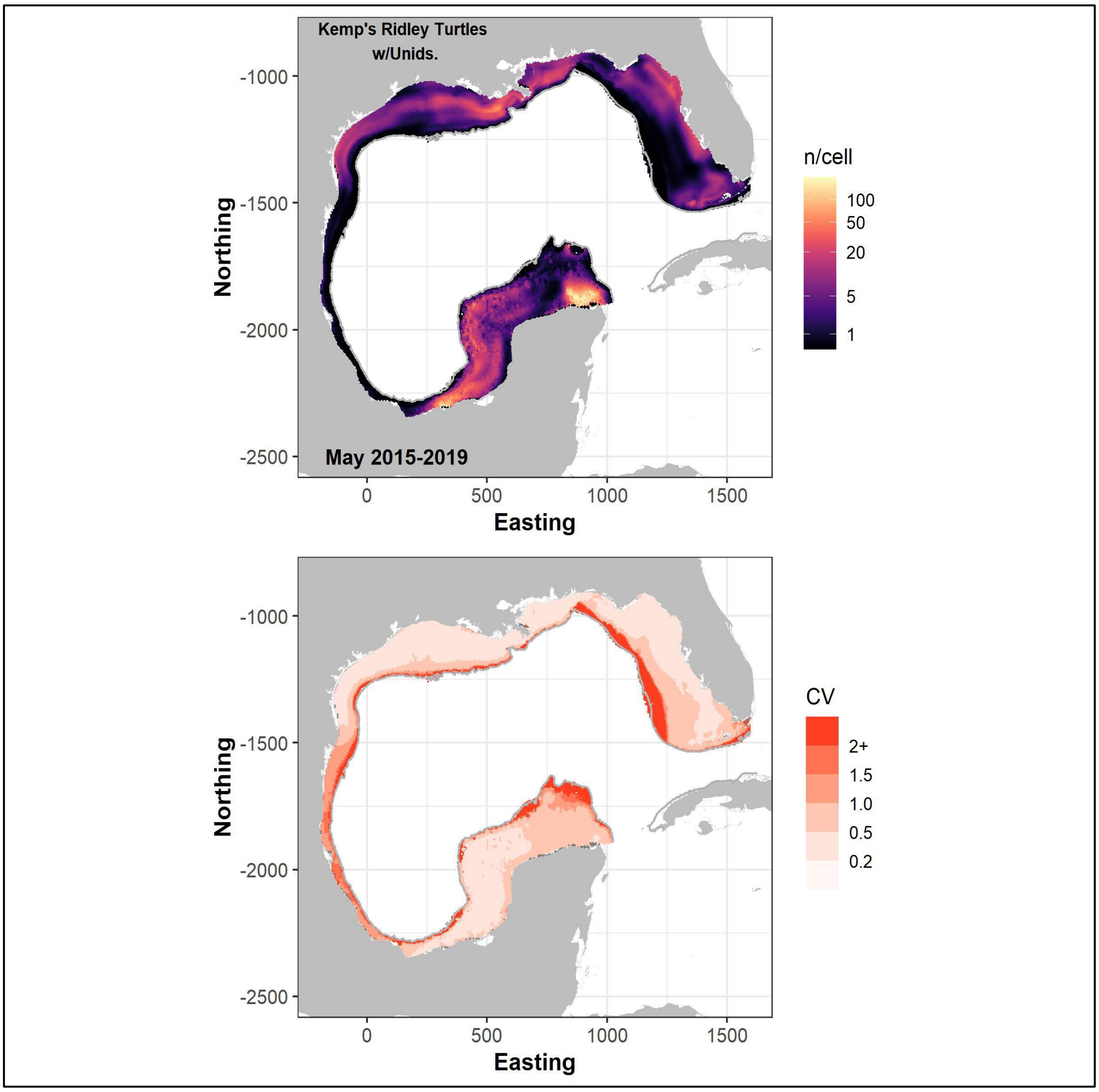

Figure D.3-66. Projected density model for shelf Kemp's ridley turtles in the entire GOM for the months of May 2015–2019.

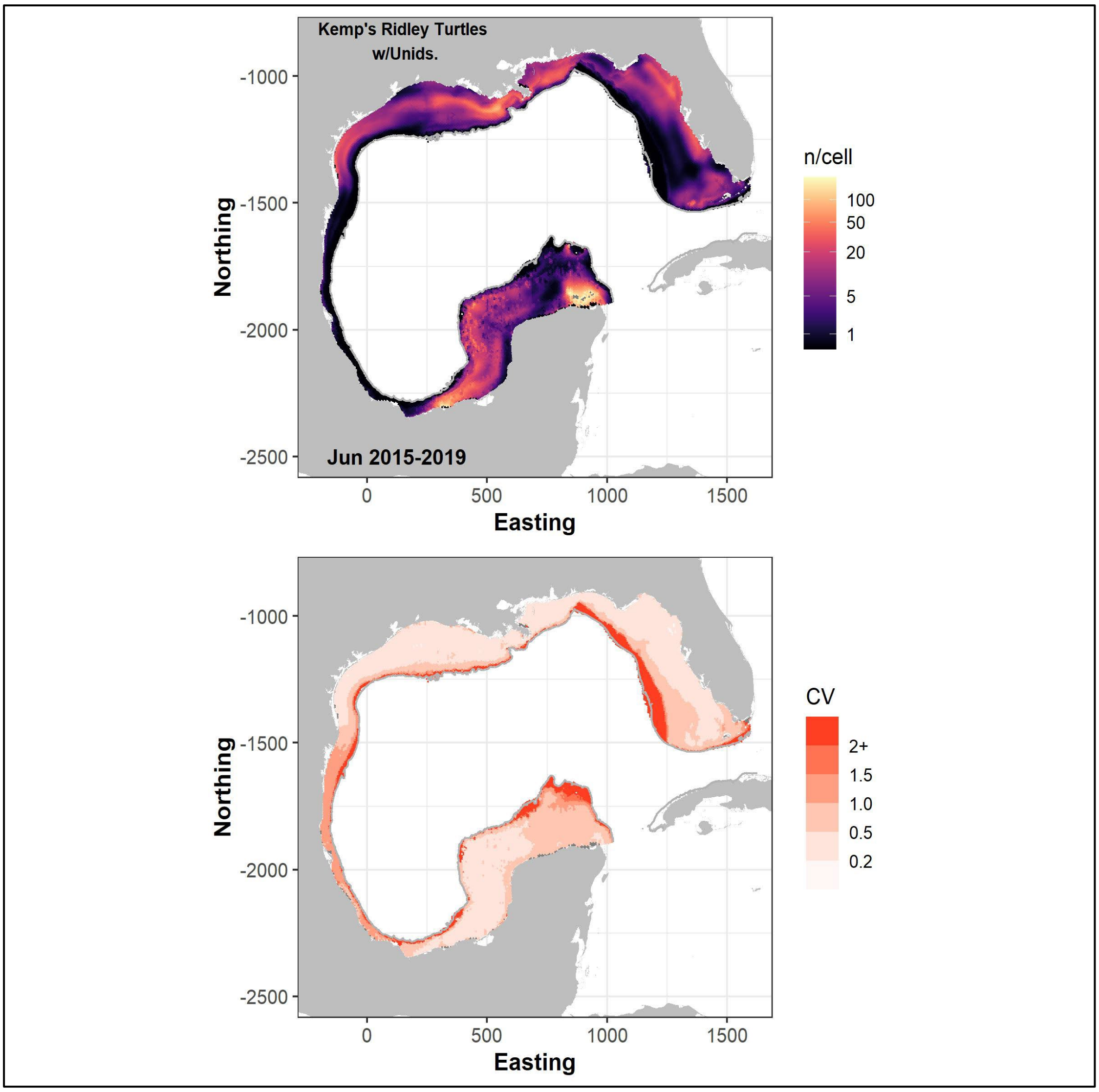

Figure D.3-67. Projected density model for shelf Kemp's ridley turtles in the entire GOM for the months of June 2015–2019.

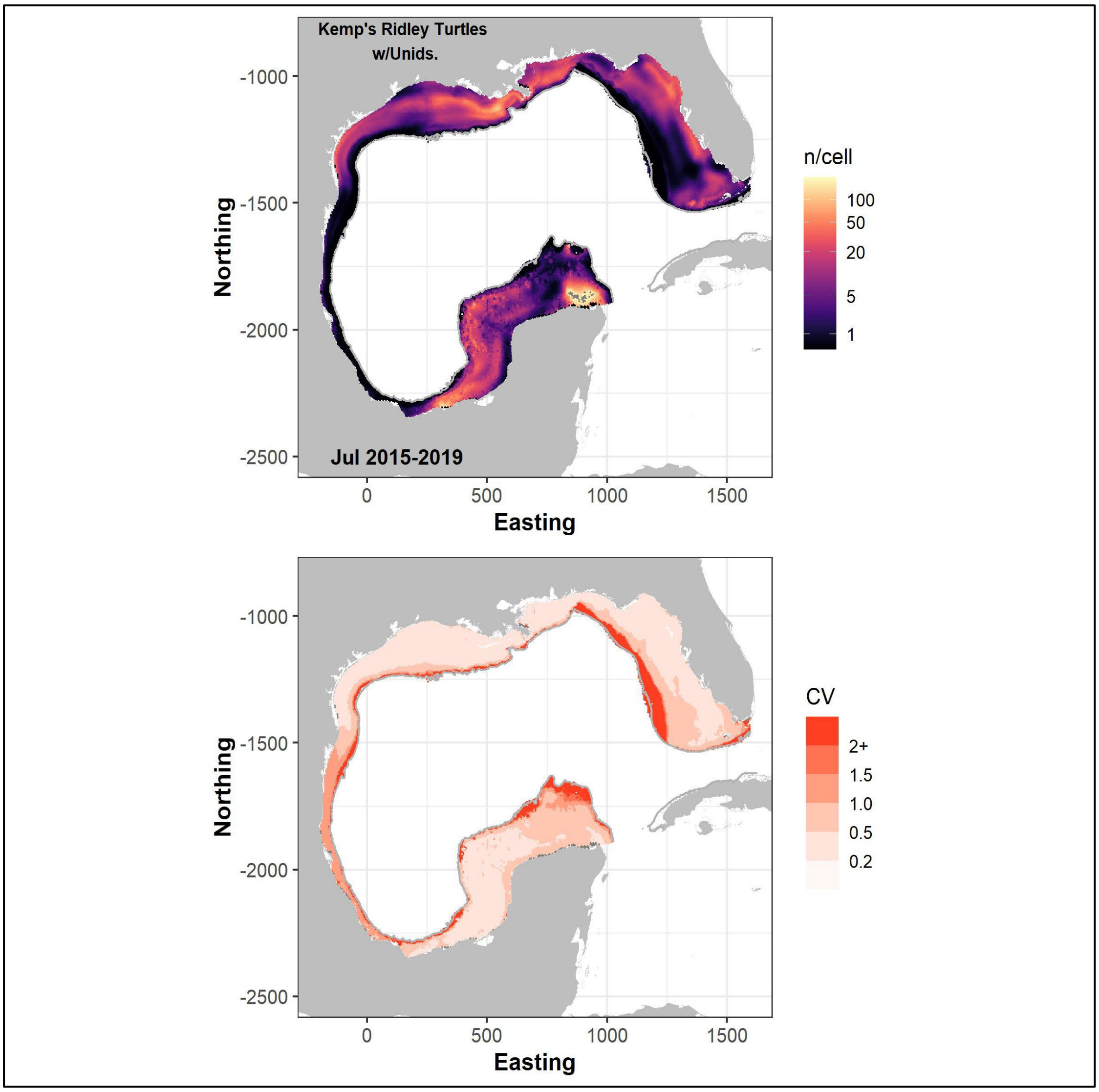

Figure D.3-68. Projected density model for shelf Kemp's ridley turtles in the entire GOM for the months of July 2015–2019.

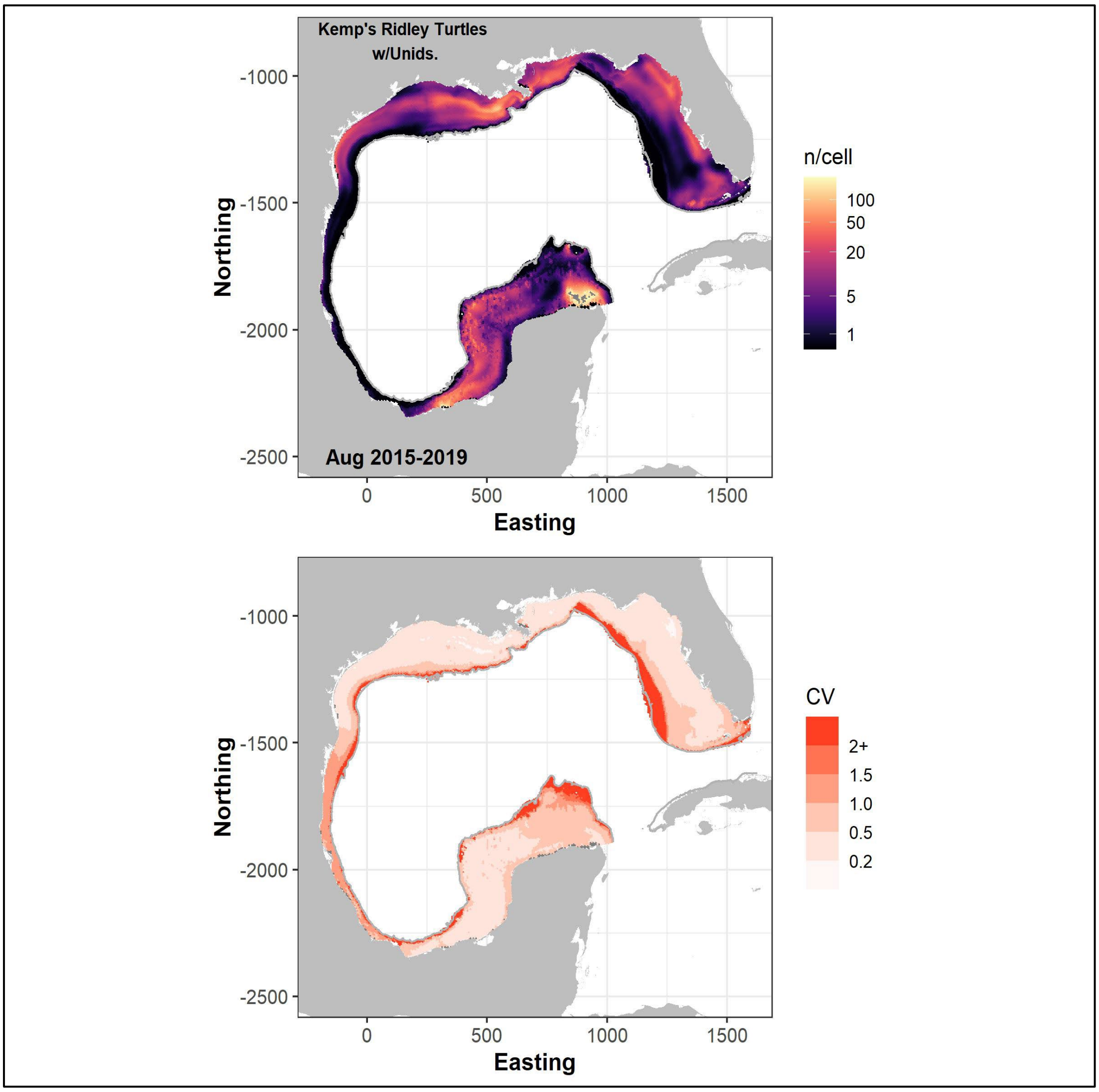

Figure D.3-69. Projected density model for shelf Kemp's ridley turtles in the entire GOM for the months of August 2015–2019.

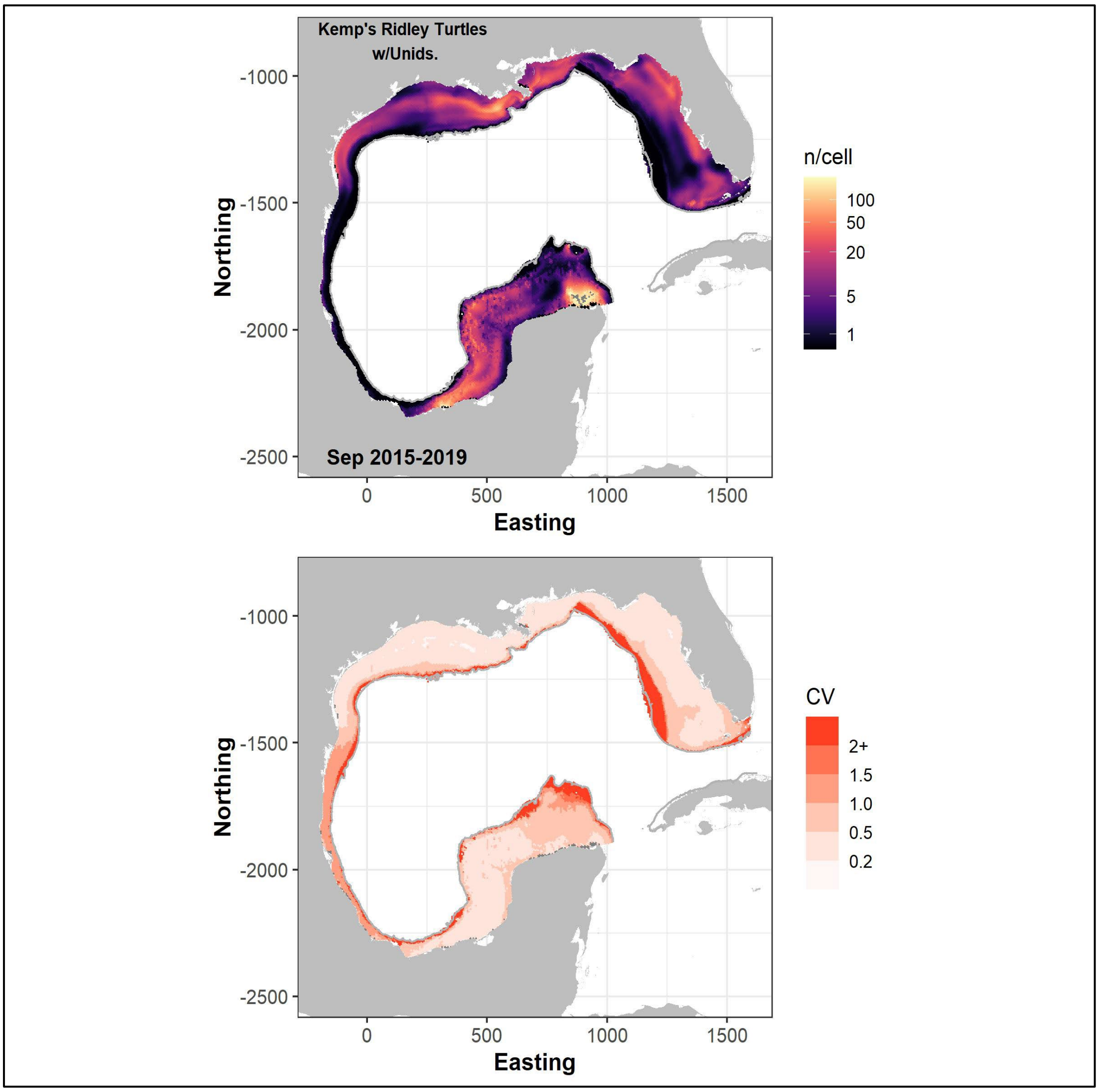

Figure D.3-70. Projected density model for shelf Kemp's ridley turtles in the entire GOM for the months of September 2015–2019.

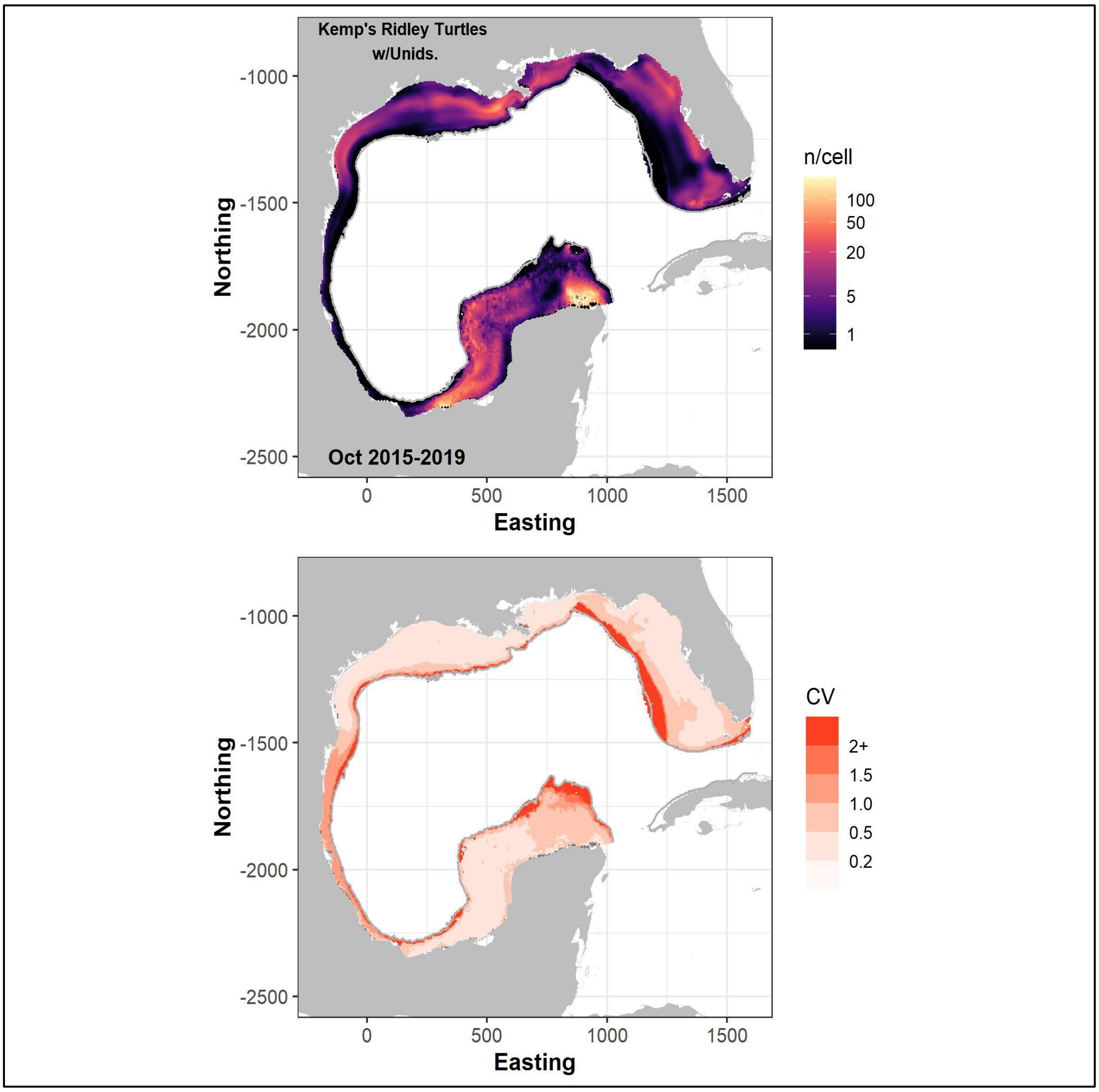

Figure D.3-71. Projected density model for shelf Kemp's ridley turtles in the entire GOM for the months of October 2015–2019.

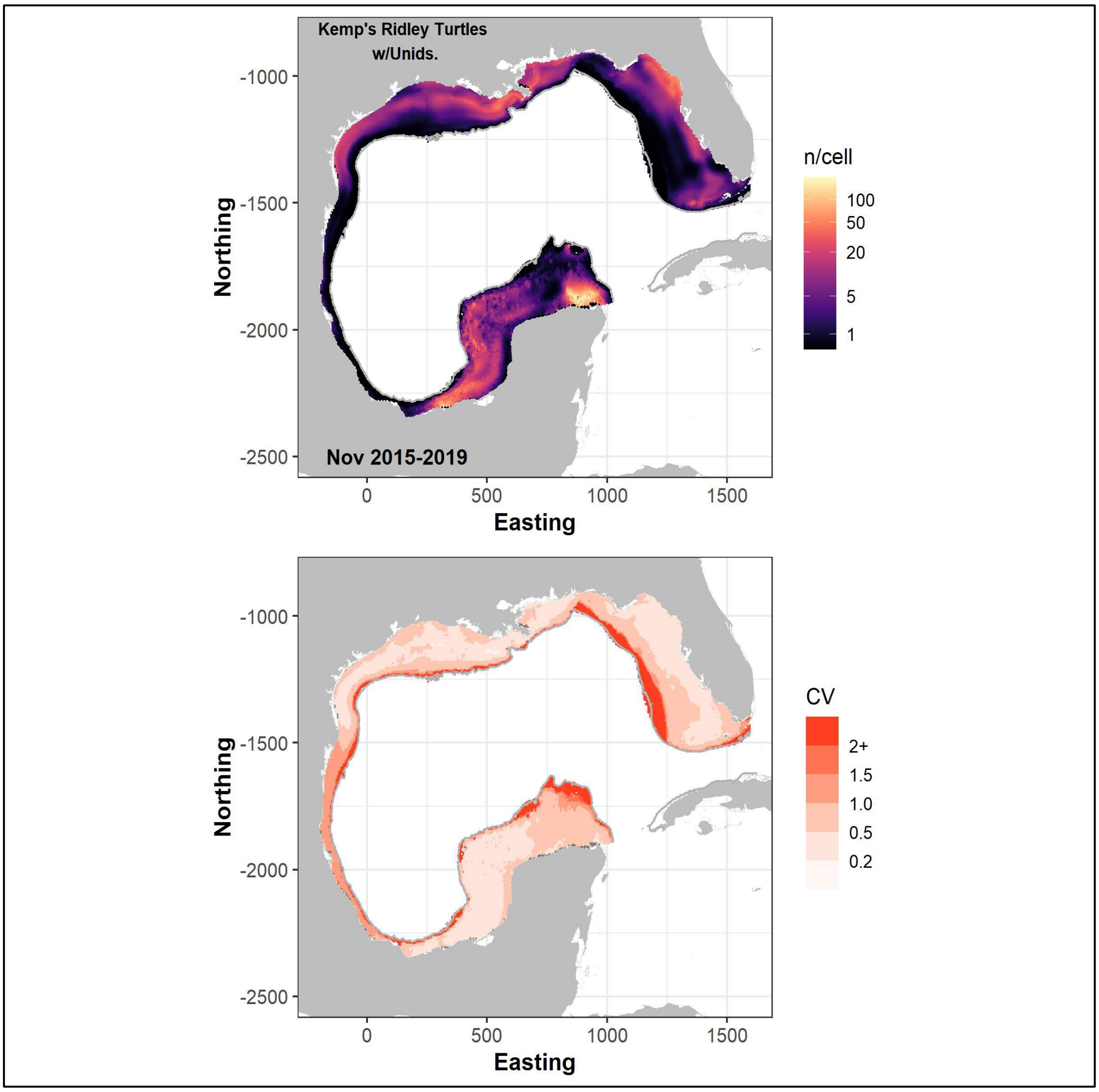

Figure D.3-72. Projected density model for shelf Kemp's ridley turtles in the entire GOM for the months of November 2015–2019.

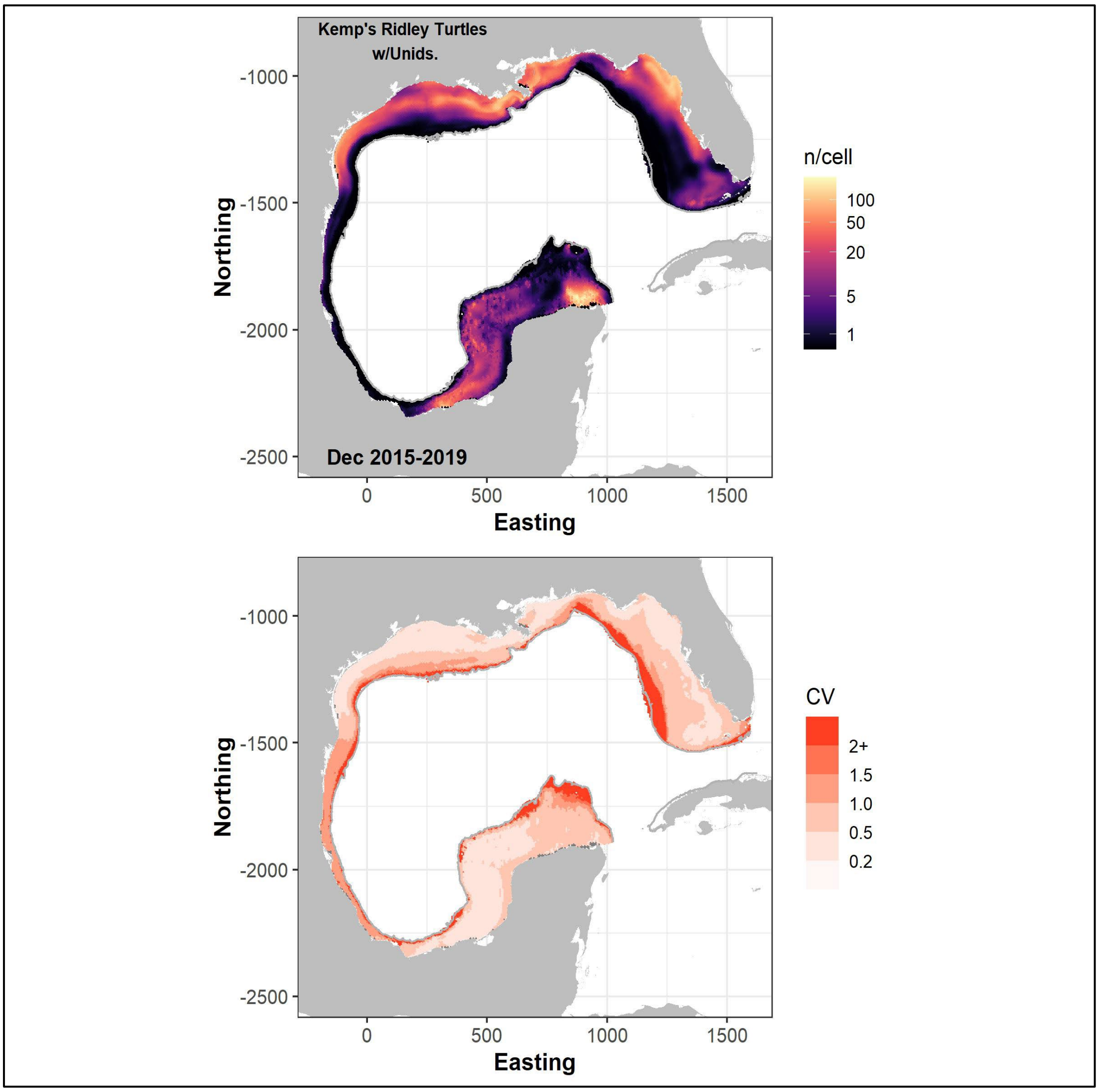

Figure D.3-73. Projected density model for shelf Kemp's ridley turtles in the entire GOM for the months of December 2015–2019.

D.4 Gulf of Mexico Loggerhead Turtle Density Models

Photo credit: NOAA Fisheries

This section describes the development of spatial density models (SDMs) for loggerhead turtles (*Caretta caretta*) occurring over the continental shelf based upon seasonal aerial surveys conducted in 2011–2012 and 2017–2018, including average abundance prediction maps generated using monthly environmental parameters for the period of 2015–2019. This section also includes projected density and prediction maps for shelf waters of the entire Gulf of Mexico (GOM).

D.4.1 Survey Data and Sightings

Aerial line-transect surveys were conducted over the continental shelf of the northern Gulf of Mexico (NGOM) in a survey region extending from the shoreline to the shelf break (approximately the 200 m isobath) between Key West, Florida and the US-Mexico border near Brownsville, Texas. Each survey was conducted in a NOAA Twin Otter flying at a survey altitude of 183 m (600 ft) and an approximate speed of 100 knots. Survey tracklines were spaced approximately 20 km apart and were oriented so as to be perpendicular to the shoreline. The aircraft was equipped with two large bubble windows in the forward portion of the aircraft (left and right sides) and one right bubble window and a belly window in the aft portion of the aircraft to allow effective visualization of the trackline (see Figure 2 in the GoMMAPPS project final report). Surveys were conducted using two independent teams to allow estimation of detection probability within the surveyed strip and on the trackline using Mark Recapture Distance Sampling (MRDS) approaches. Aerial surveys were conducted in spring 2011, summer 2011, fall 2011, and winter 2012 as part of the Natural Resource Damage Assessment (NRDA) associated with the *Deepwater Horizon* oil spill. Additional surveys were conducted in the summer of 2017, winter 2018, and fall 2018 as part of the Gulf of Mexico Marine Assessment Program for Protected Species (GoMMAPPS) project. Additional details about the survey design and execution are contained in Garrison et al. (2022). The total number of loggerhead turtle groups sighted is shown in Table D.4-1.

Table D.4-1. Loggerhead turtles observed for each survey included in this analysis

Survey	Groups	Individuals
TOSE11F	436	474
TOSE11Sp	287	309
TOSE11Su	336	354
TOSE12W	331	354
TOSE17Su	290	299
TOSE18F	112	112
TOSE18W	139	145

Loggerhead turtles were observed through the survey range in all seasons with higher densities of animals typically occurring in the eastern portion of the NGOM. A region of persistent high occurrence is apparent in intermediate depth waters along the southern coast of Louisiana (Figure D.4-1).

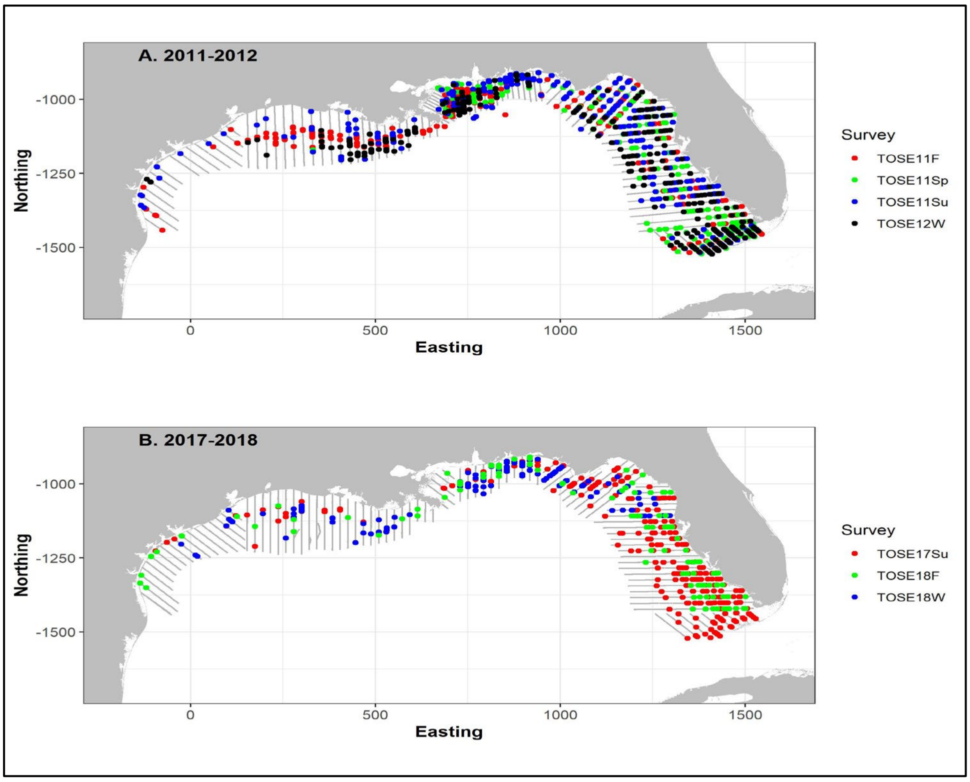

Figure D.4-1. Survey effort and loggerhead turtle sightings during (A) 2011–2012 and (B) 2017–2018.

D.4.2 Distribution of Sightings and Physical Oceanography during Each Survey

Loggerhead turtles were observed throughout the coastal and shelf waters of the NGOM during all seasons, with the highest occurrence in the northeastern GOM and in nearshore waters of the central NGOM. There is some seasonal variation in spatial distribution with animals occurring in the northwestern GOM in greater numbers during summer and fall surveys. The spatial pattern in the winter 2018 survey reflects incomplete survey effort where tracklines in the northeastern GOM were not completed due to poor weather conditions. The distribution of sightings and surface temperature and chlorophyll-a concentrations are shown in Figures D.4-2–D.4-8.

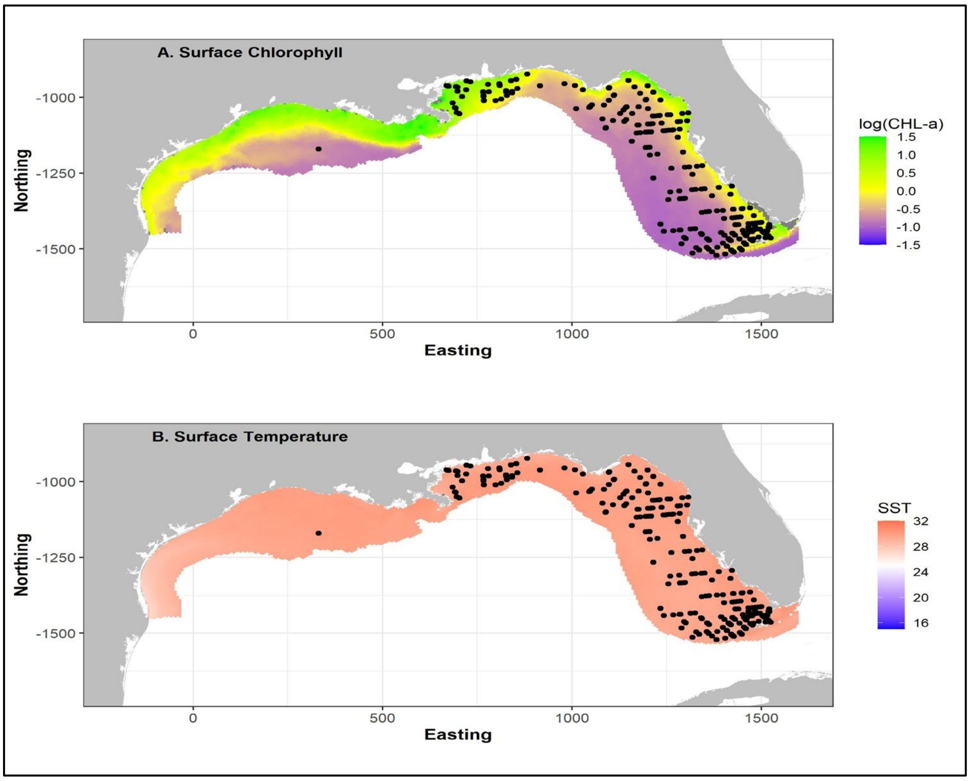

Figure D.4-2. Loggerhead turtle sightings during spring 2011.

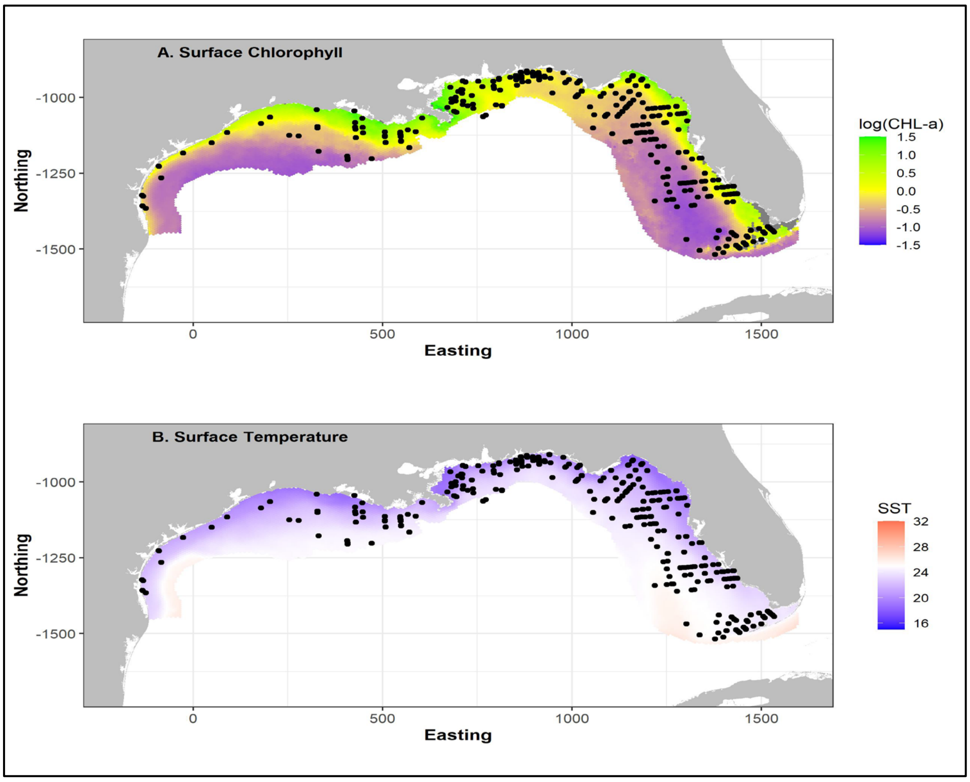

Figure D.4-3. Loggerhead turtle sightings during summer 2011.

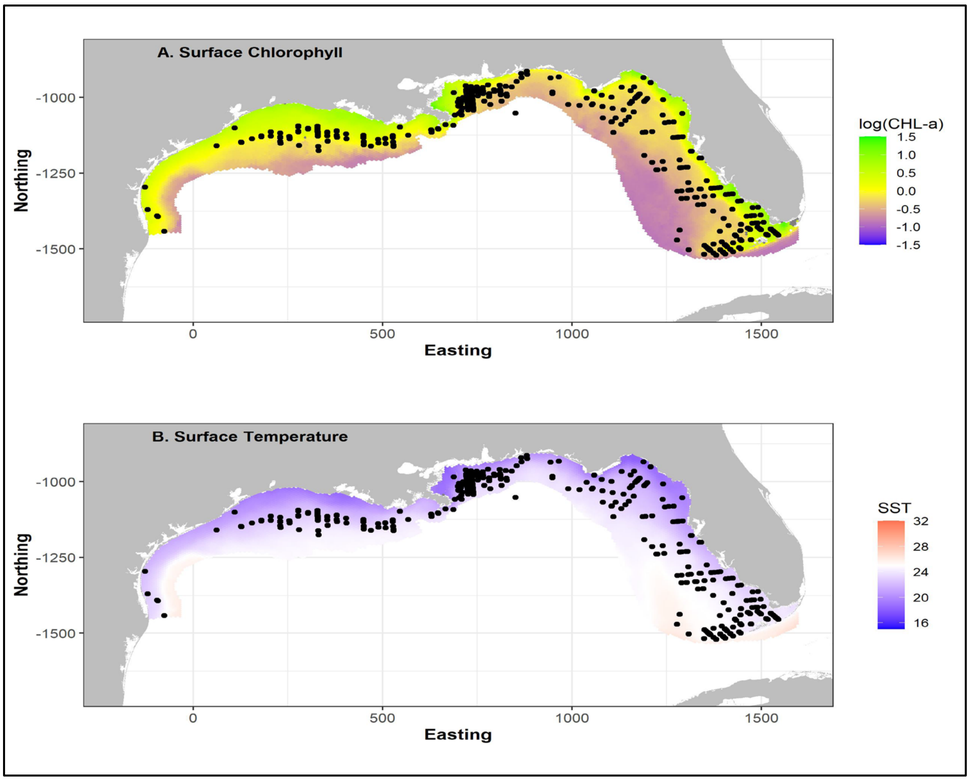

Figure D.4-4. Loggerhead turtle sightings during fall 2011.

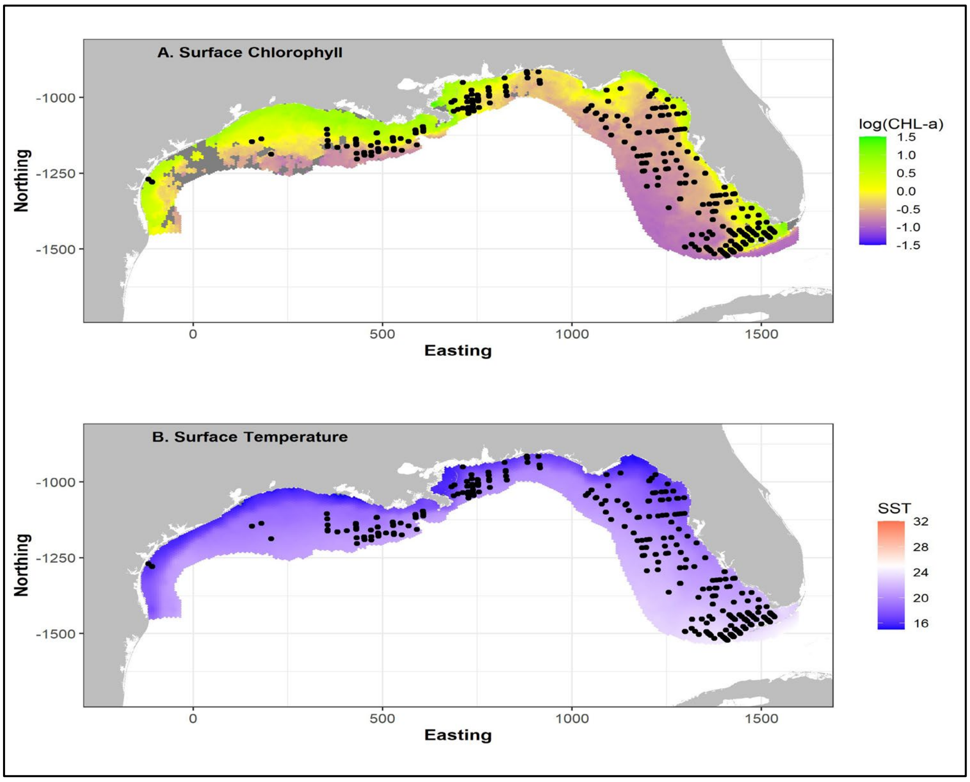

Figure D.4-5. Loggerhead turtle sightings during winter 2012.

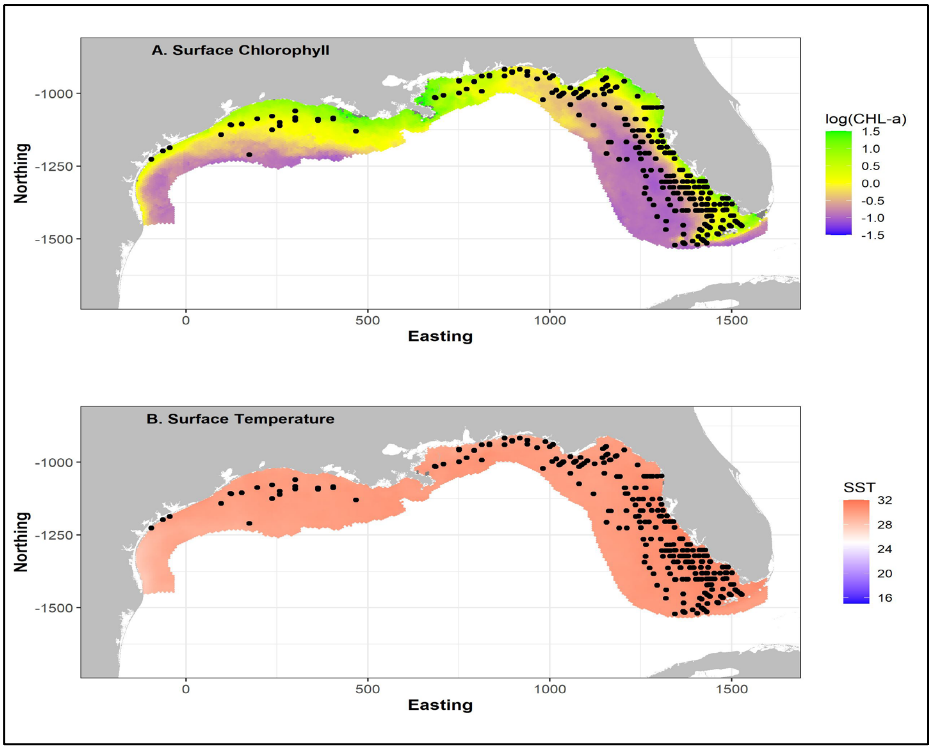

Figure D.4-6. Loggerhead turtle sightings during summer 2017.

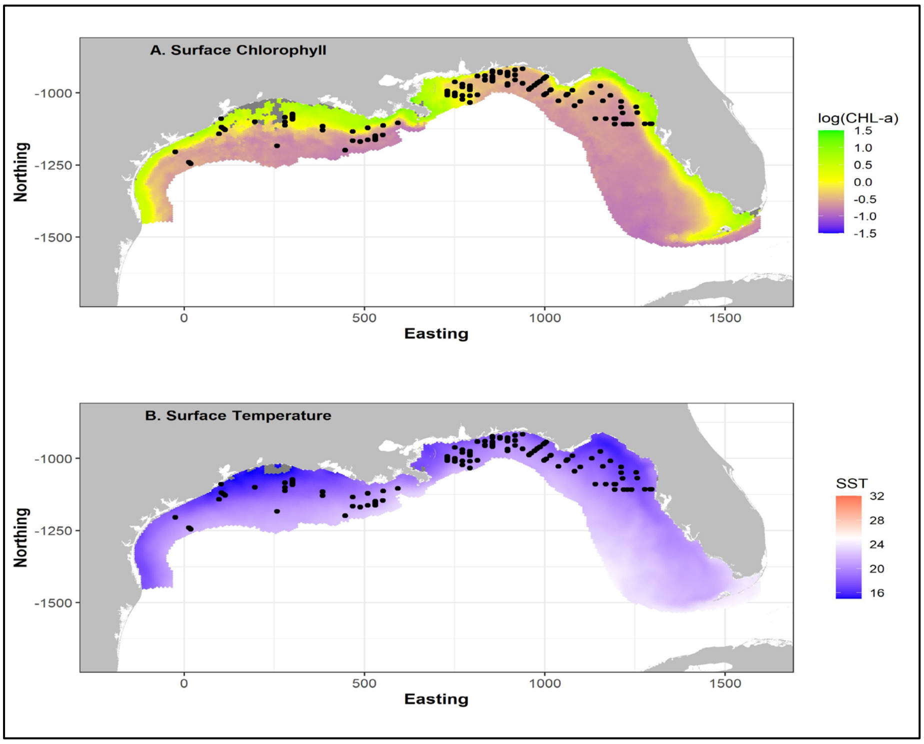

Figure D.4-7. Loggerhead turtle sightings during winter 2018.

Note that survey effort was incomplete in the northeastern GOM during this survey.

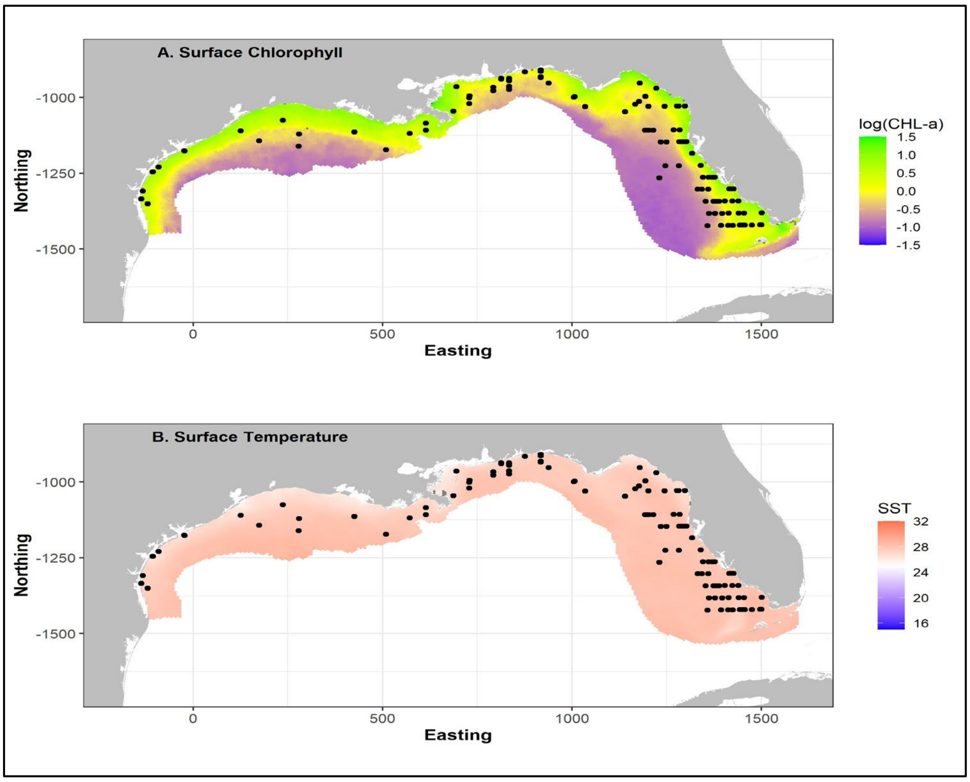

Figure D.4-8. Loggerhead turtle sightings during fall 2018.

D.4.3 Distance Analysis and Detection Probability

Detection probability within the surveyed strip was estimated using MRDS approaches. Covariates considered for inclusion in the detection function included sea state, cloud cover, water turbidity, and sun penetration. In addition, the correlation between ln(group size) and perpendicular sighting distance (PSD) was examined, but there was no relationship between group size and detection distances, so group size was not considered for inclusion in the model.

The best model was selected by first examining the distribution of PSD and selecting an appropriate right truncation distance and key function. Then, all combinations of detection covariates were considered for both the detection function and mark-recapture portion of the model, and the model with the lowest Akaike's Information Criterion (AIC) was selected. The best model included a hazard-rate key function with a right truncation distance of 300 m. Sea State, Cloud Cover and Turbidity were included as covariates in the distance component of the model. Sea state, Turbidity, Weather Condition, and an interaction term with observer position were included in the mark-recapture component of the model (Table D.4-2).

Table D.4-2. Parameters included in the detection probability function

(MCDS = Multiple covariate distance sampling)

Model	Parameter	Estimate	SE
MCDS	MCDS Intercept	4.6102	0.0991
MCDS	Sea State	-0.0342	0.0250
MCDS	Sun Penetration	0.1426	0.0464
MRDS	MRDS Intercept	0.9932	0.3687
MRDS	Distance	0.0037	0.0019
MRDS	Observer	-0.6155	0.1111
MRDS	Sea State	-0.2329	0.0601
MRDS	Cloud Cover	0.1219	0.0495
MRDS	Sun Penetration	0.2089	0.1374
MRDS	Distance x Observer	-0.0024	0.0010

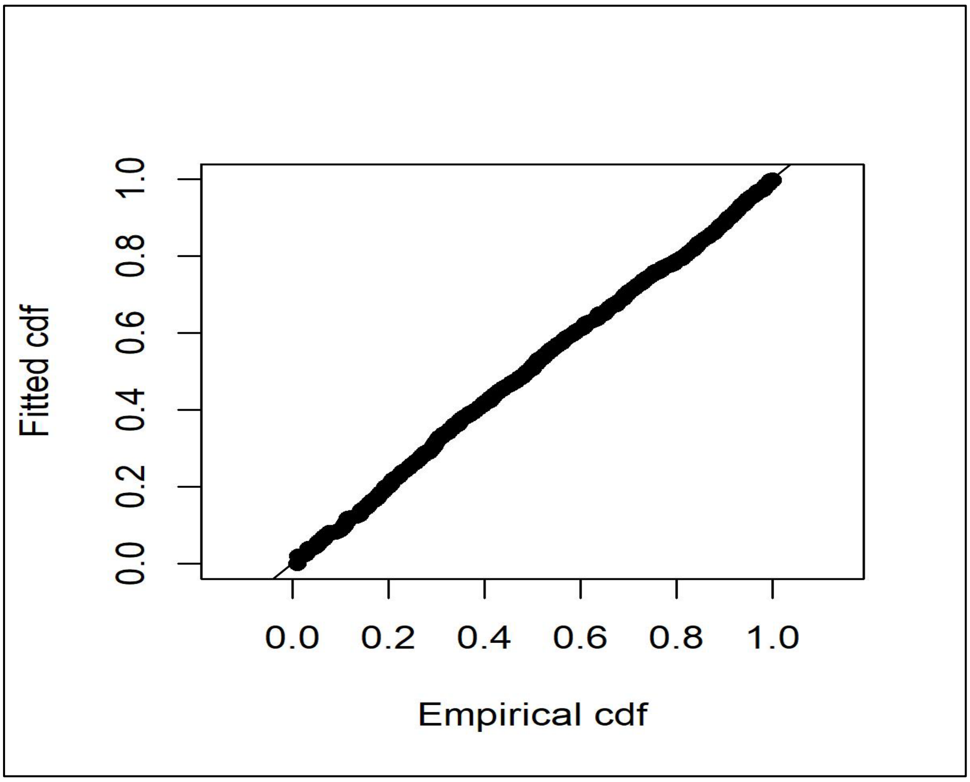

Figure D.4-9. MRDS detection function Q-Q plot

(cdf = cumulative distribution function).

The resulting detection probability function had a good overall fit as indicated by the linear Quantile-Quantile (Q-Q) plot (Figure D.4-9). The Chi-square goodness of fit test p-value was 0 (Chi-square = 89.87, df = 7) indicating some deviation from the expected model especially in the mark-recapture component at high PSD. However, the Cramer-von Mises test p-value was 0.16 (test statistic = 0.275) suggesting an adequate model fit overall.

The estimated detection probability on the trackline is shown in Table D.4-3, and the detection probability function is shown in Figure D.4-10.

Table D.4-3. Estimated detection probability and number of detections in the surveyed area from Multiple Covariate Distance function

Parameter	Estimate	SE	CV
Detection probability	0.493	0.010	0.020
Team 1 p(0)	0.594	0.028	0.047
Team 2 p(0)	0.444	0.024	0.054
Combined p(0)	0.771	0.022	0.029
Overall Avg. Detection Prob.	0.380	0.013	0.034

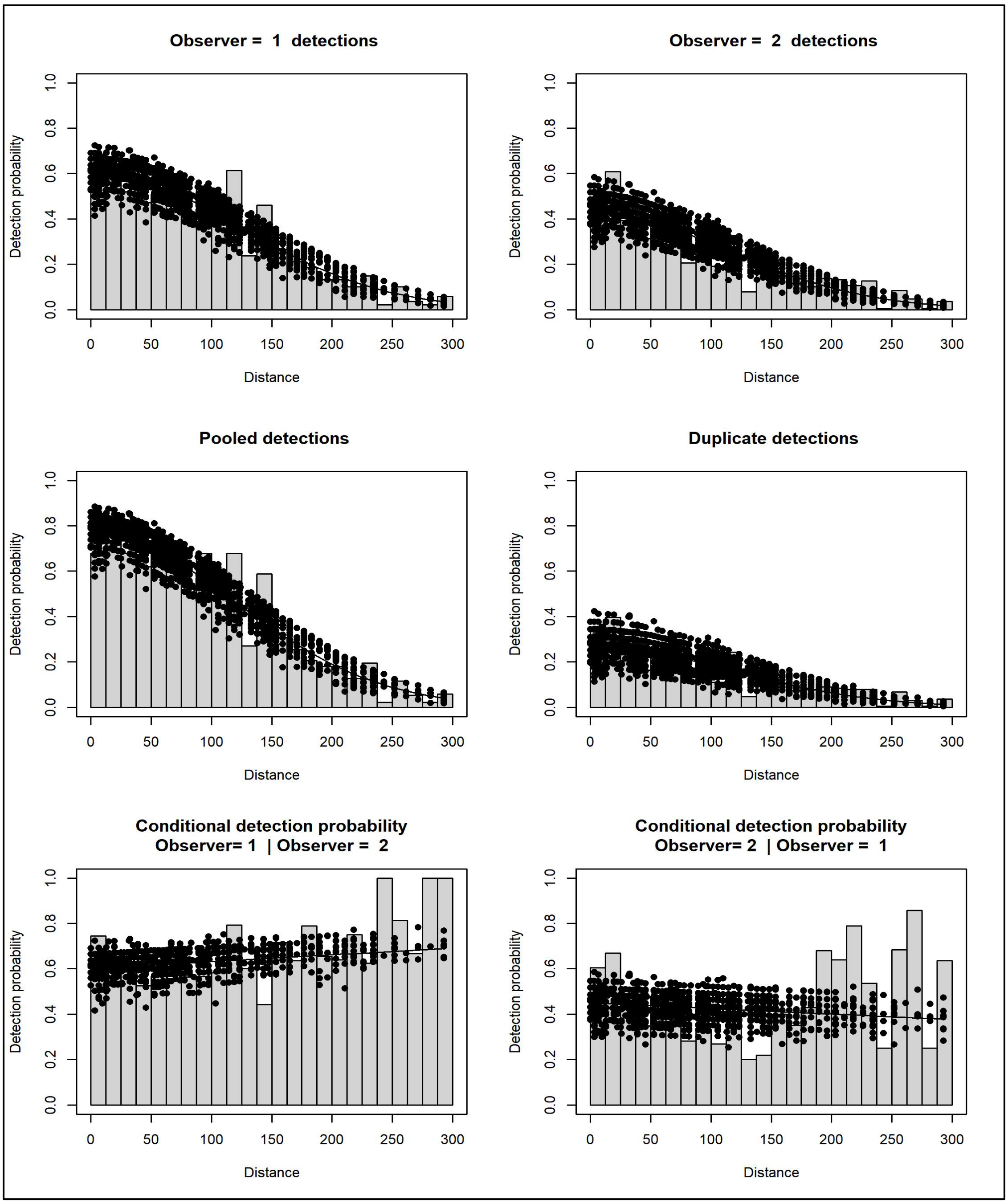

Figure D.4-10. Mark-recapture distance sampling detection probability.

D.4.3.1 Estimating Availability Bias

Loggerhead turtles spend a significant amount of time underwater where they are not available to be counted by aerial observers. The amount of time below the surface varies both spatially and temporally as a function of the behavioral state of the turtles (e.g., feeding vs. traveling) and in response to environmental conditions. To account for availability bias, we applied a generalized additive model (GAM) of loggerhead turtle occurrence in the upper 2 m of the water column based upon an extensive database of telemetry tag data (Roberts et al. 2022). This GAM used environmental variables to predict the probability that loggerhead turtles would be near the surface and available to the aerial survey team. For loggerhead turtles, significant environmental predictors of availability included season, sea surface temperature, distance from the shelf break, water depth, salinity, the occurrence of fronts, and spatial location. The probability that each turtle observed in the aerial survey was near the surface was predicted based upon the environmental conditions at the time of observation (Figure D.4-11). The median probability that a loggerhead turtle was at the surface was 0.291 (Inter-quartile range: 0.198–0.456).The number of turtles observed at the location was divided by the estimated probability to account for availability to the survey team. This corrected number was the response variable in the SDM.

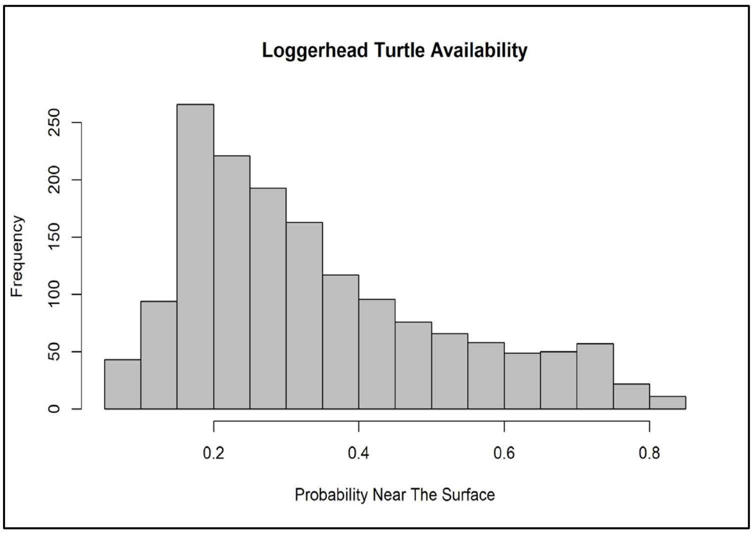

Figure D.4-11. Probability that loggerhead turtles observed during the aerial surveys were near the surface based upon a generalized additive model accounting for spatial and temporal variability in turtle dive behavior

(Roberts et al. 2022).

D.4.4 Spatial Density Model Selection

A GAM was used to develop a spatial density model to describe the effect of habitat variables on the density and abundance of loggerhead turtles in the NGOM. Survey effort (kilometers of survey trackline) was partitioned into segments within a grid of hexagonal cells of 40 km^2 area and matched to physical oceanographic parameter values within each cell. Each resulting segment was considered a sampling unit within the GAM, and the number of animals observed on the segments was the response variable in a log count model assuming a Tweedie error distribution to account for overdispersed count data. An offset term (ln[strip area]) was included in the model to account for the effective area surveyed within each spatial cell based upon the detection probability function described above and covariates during the survey.

An initial GAM model was fit using all available oceanographic and physiographic variables. A reduced model was the selected including only model terms with p-value < 0.2. This reduced model was compared to the full model using AIC to ensure selection of the best fitting, most parsimonious model. Model fit was assessed through the examination of randomized quantile residuals and the associated Q-Q plot for deviance residuals.

For loggerhead turtles, the selected model included Average Depth (AvgDepth), Sea Surface Temperature (Avg_SST), distance from shore, distance from canyons (Dist2Canyo), log(chlorophyll-a concentration) (lAvg_Chl), Mixed Layer Depth (Avg_CMEMS_MLD), and the East-West coordinate (Easting) (Table D.4-4). In addition, a factor variable was included in the model to reflect the overall higher density of loggerhead turtles in the northeastern GOM compared to the northwestern GOM. The model fit to the data was good with a generally linear Q-Q plot and few outlier residual values (Figure D.4-12).

Table D.4-4. Parameter estimates for the selected Generalized Additive Model

(EDF = effective degrees of freedom)

Term	EDF	Max..EDF	F.Statistic	P.value
s(AvgDepth)	3.095	9	13.409	< 0.001
s(Dist2Canyo)	3.732	9	1.977	< 0.001
s(lAvg_Chl)	1.219	9	3.844	< 0.001
s(Avg_SST)	8.272	9	23.465	< 0.001
s(Easting)	7.944	9	19.498	< 0.001
s(Avg_CMEMS_MLD)	6.854	9	9.049	< 0.001

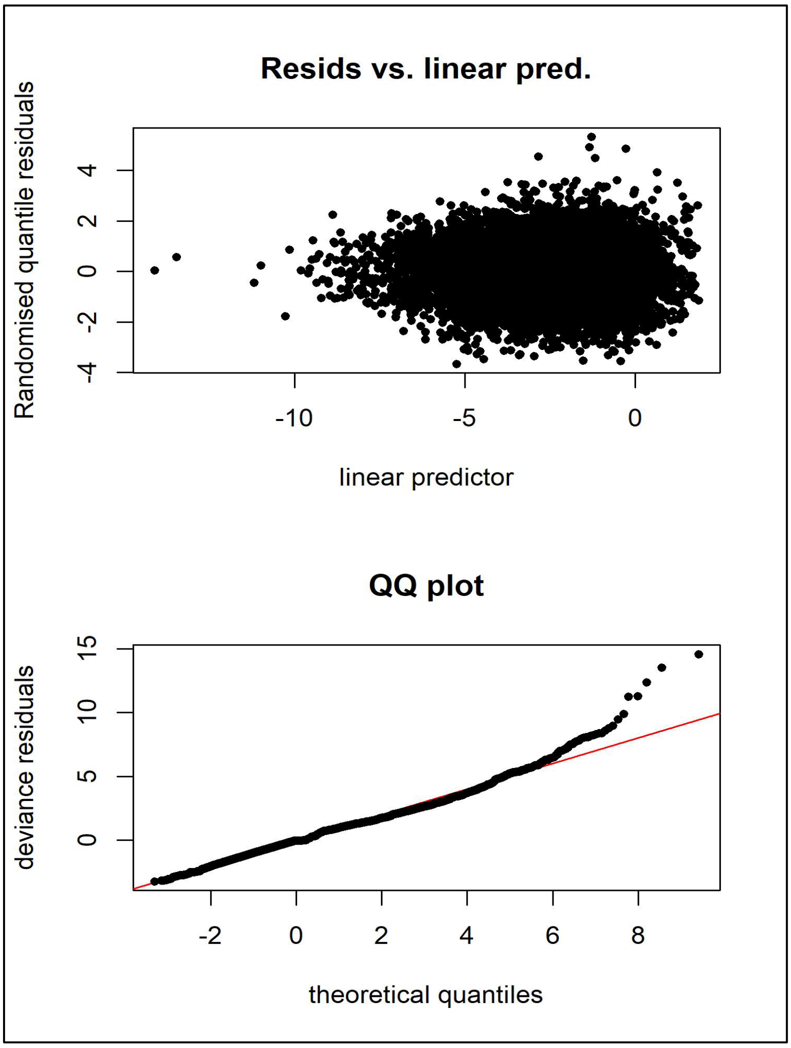

Figure D.4-12. GAM residual plots.

The selected model indicated that loggerhead turtle density was highest in waters close to shore. However, there were also peaks in density at intermediate water depths. Density declined rapidly in waters greater than 100 m depth. The sea surface temperature effect reflects higher densities observed in winter and summer months with lower density in seasons with intermediate temperatures (Figure D.4-13). The highest turtle densities occurred in waters of the central NGOM along the coast of Louisiana.

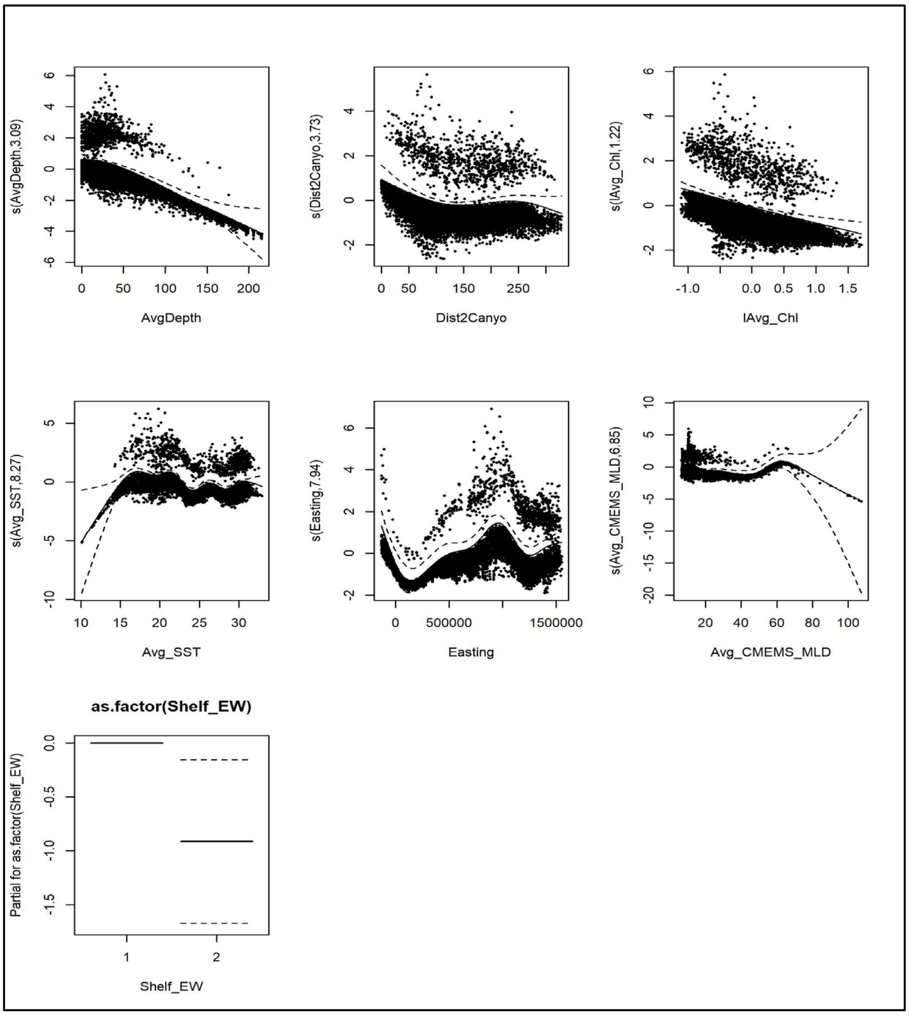

Figure D.4-13. GAM partial plots.

D.4.5 Spatial Density Model Prediction Maps and Model Output

Based upon the selected model, prediction maps were developed based upon monthly average oceanographic variable values for 2018. The estimated uncertainty (coefficient of variation [CV]) reflects only uncertainty in the GAM model fit and does not account for uncertainty in the detection probability function.

D.4.5.1 Northern Gulf of Mexico

Monthly prediction maps demonstrate variability in animal density resulting from variability in the underlying physical oceanography (Figures D.4-14–D.4-25).

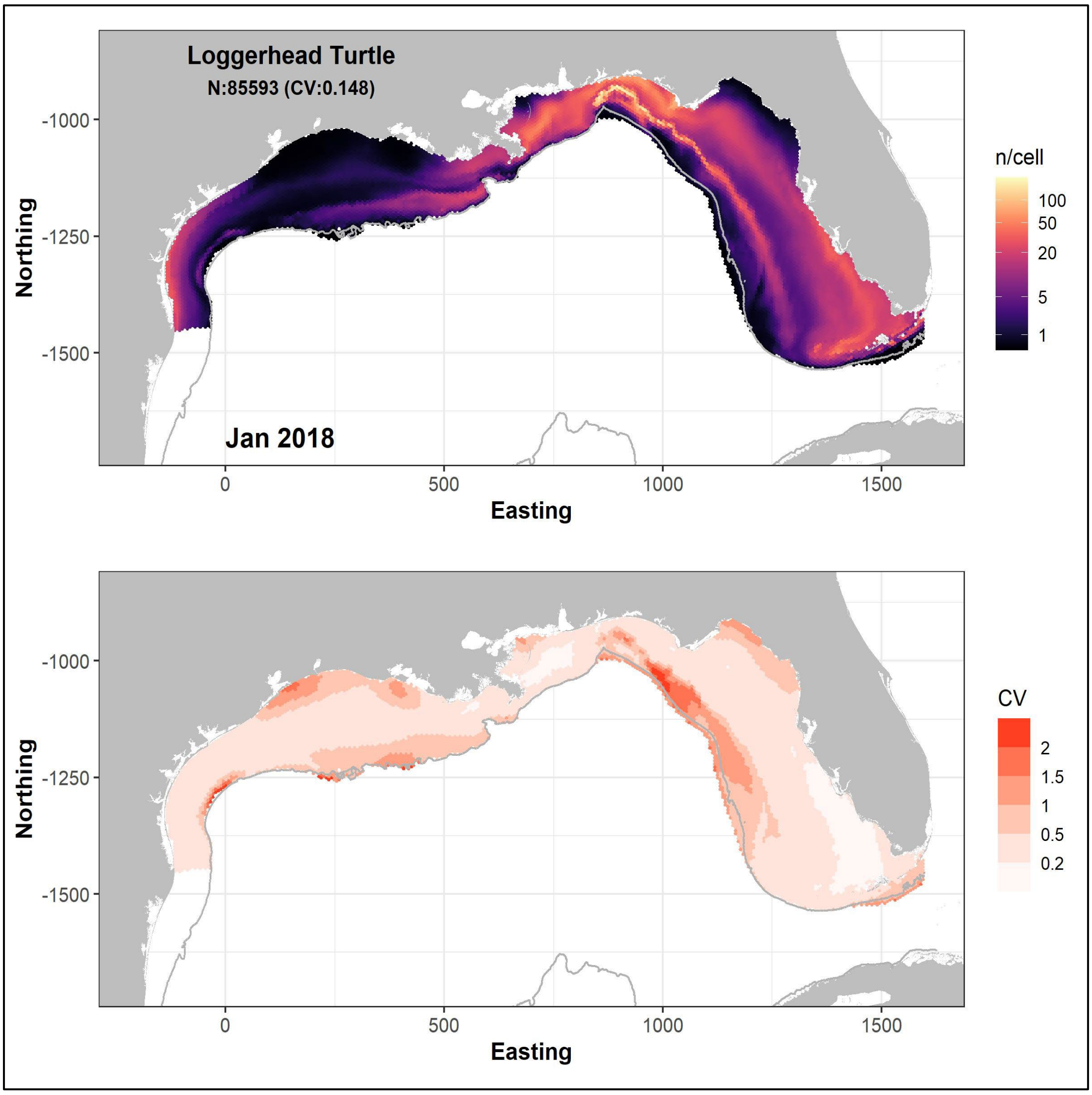

Figure D.4-14. Density model prediction for shelf loggerhead turtles in the NGOM in January 2018.

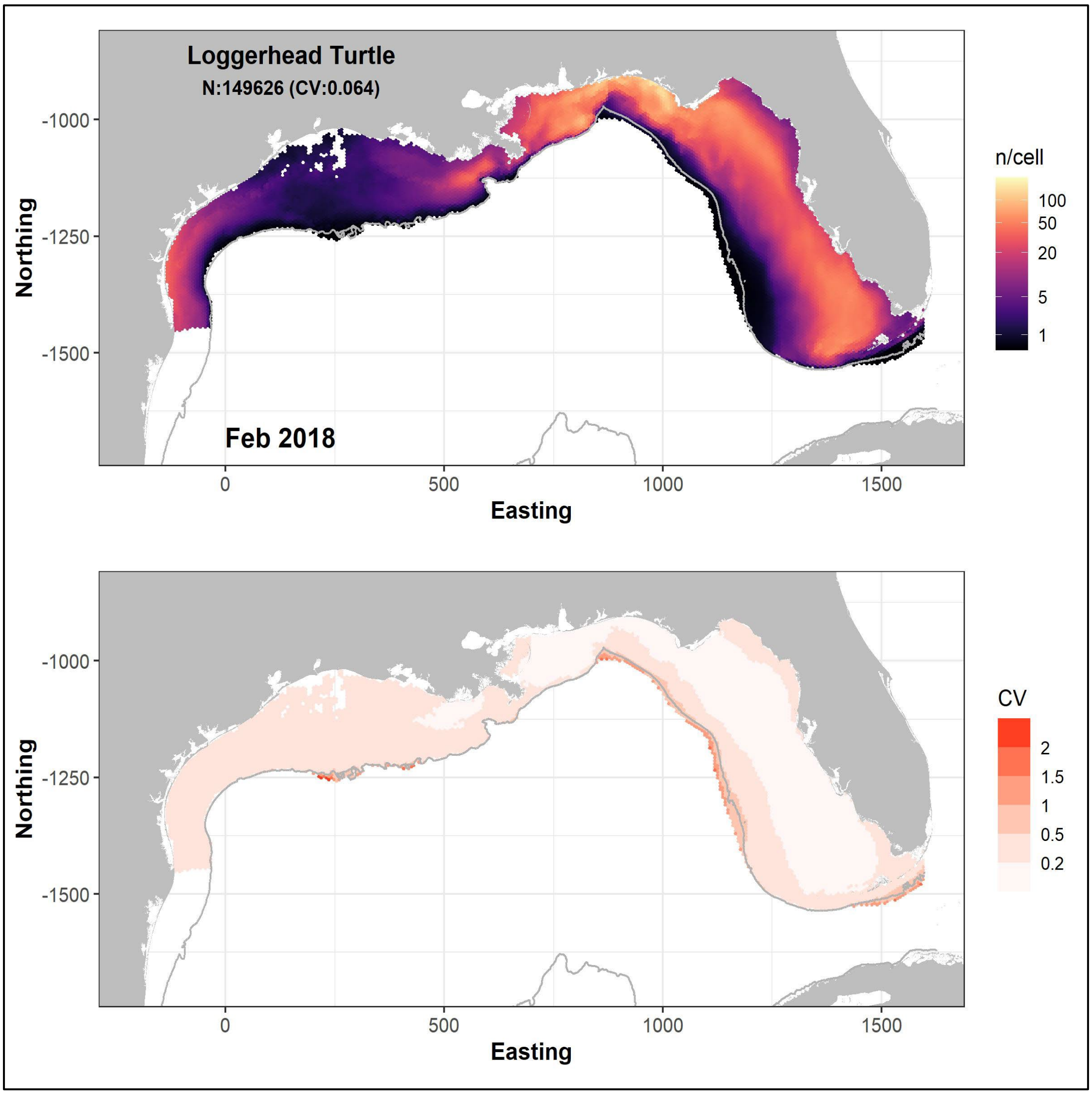

Figure D.4-15. Density model prediction for shelf loggerhead turtles in the NGOM in February 2018.

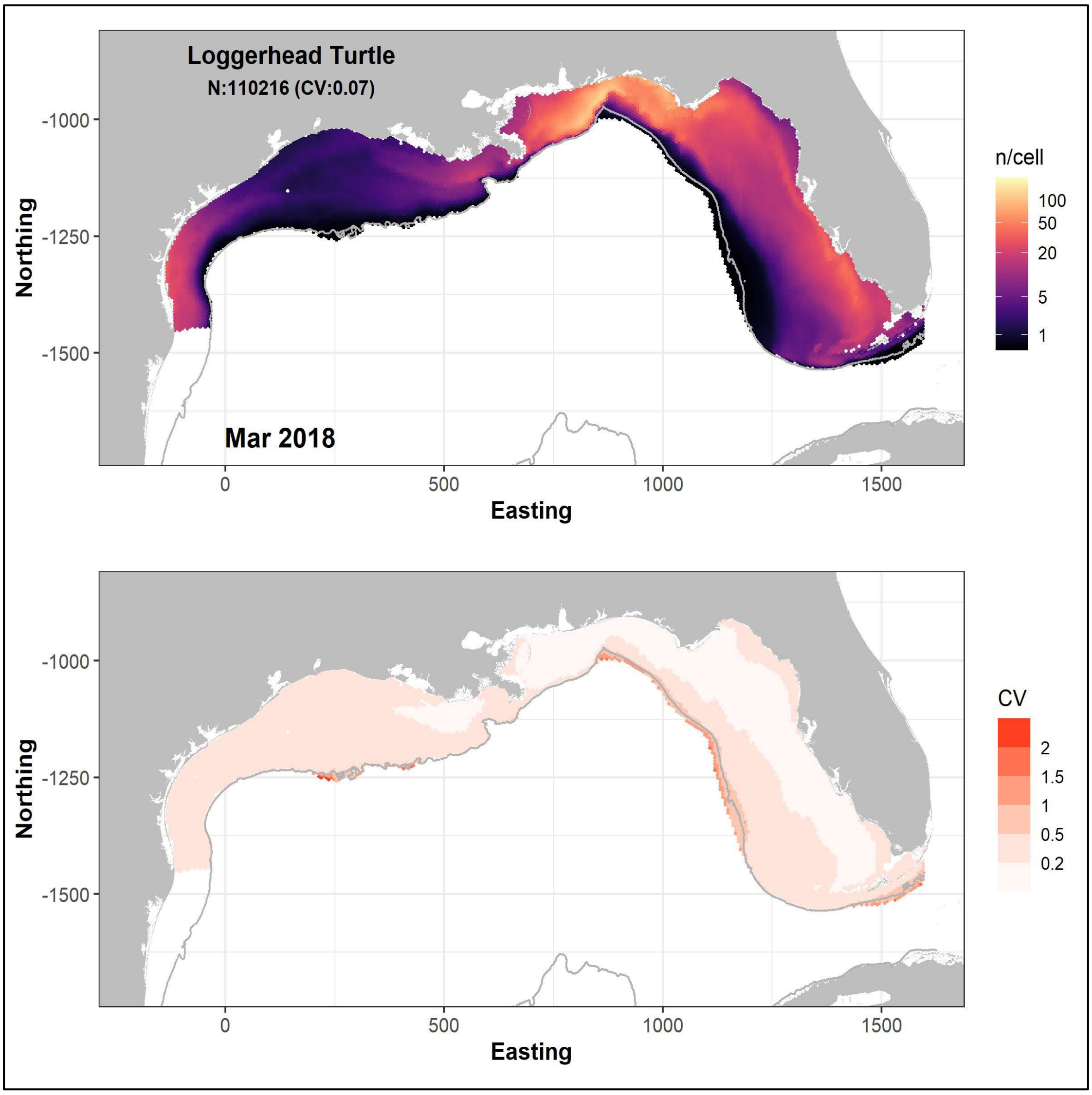

Figure D.4-16. Density model prediction for shelf loggerhead turtles in the NGOM in March 2018.

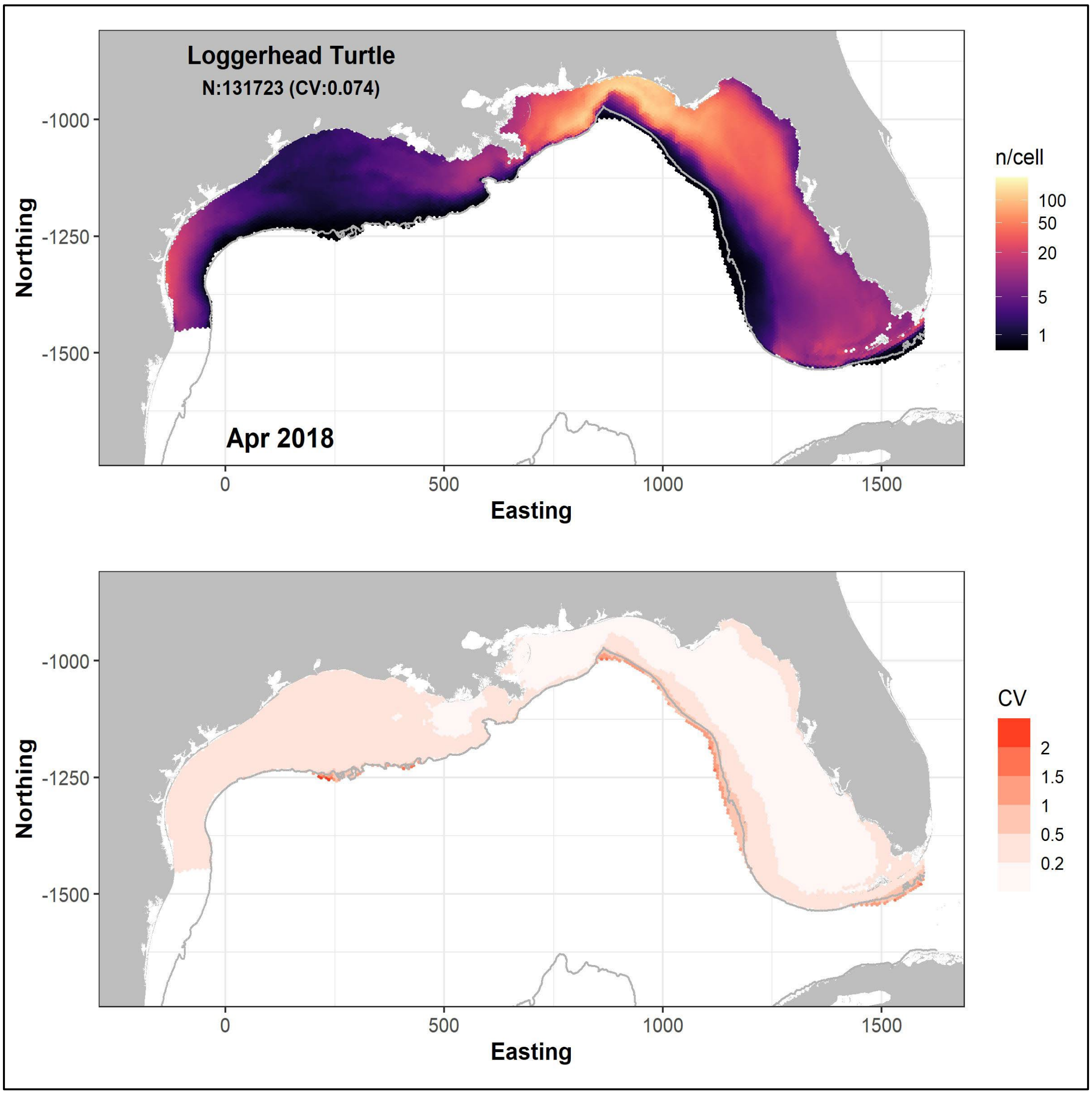

Figure D.4-17. Density model prediction for shelf loggerhead turtles in the NGOM in April 2018.

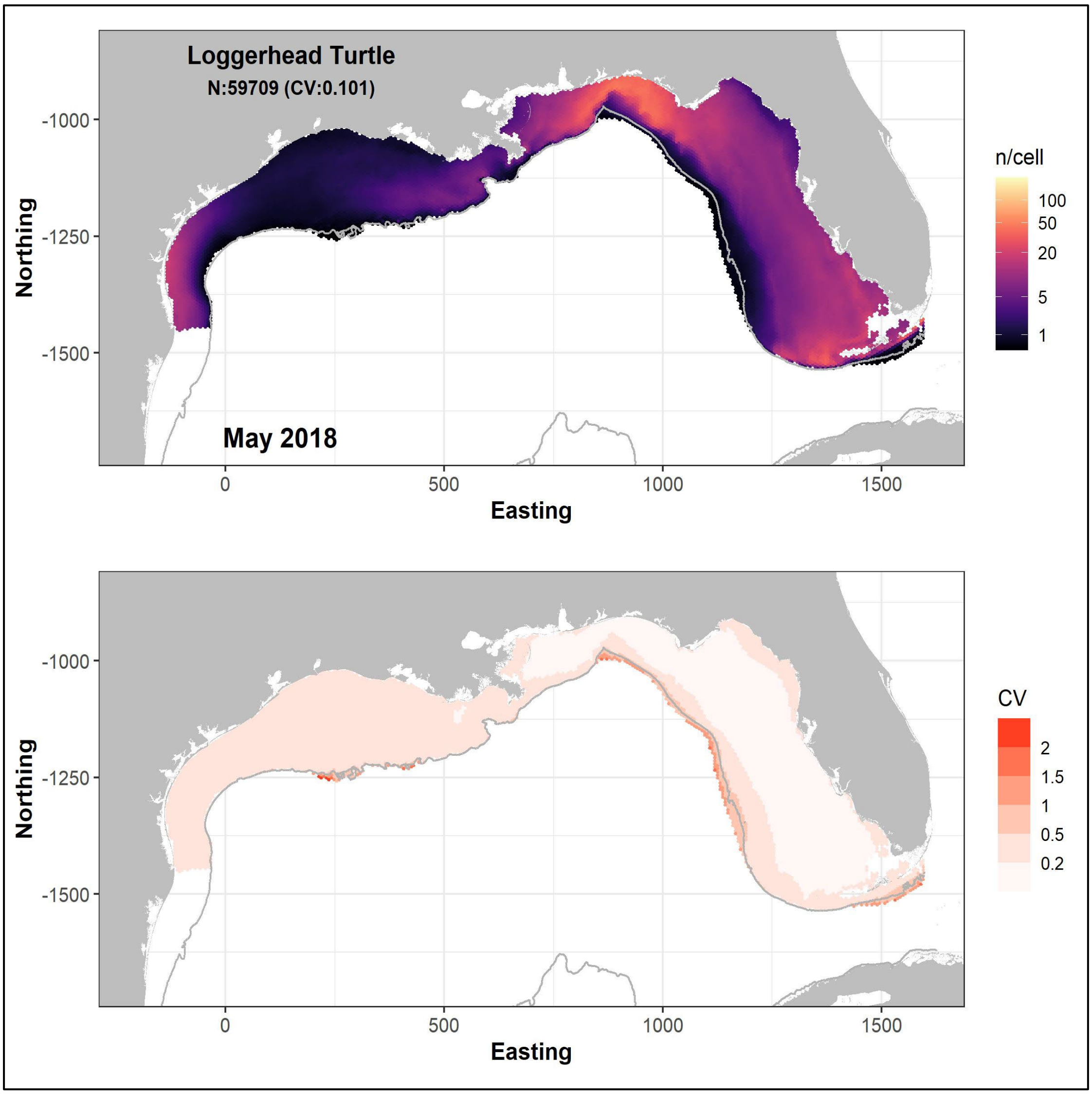

Figure D.4-18. Density model prediction for shelf loggerhead turtles in the NGOM in May 2018.

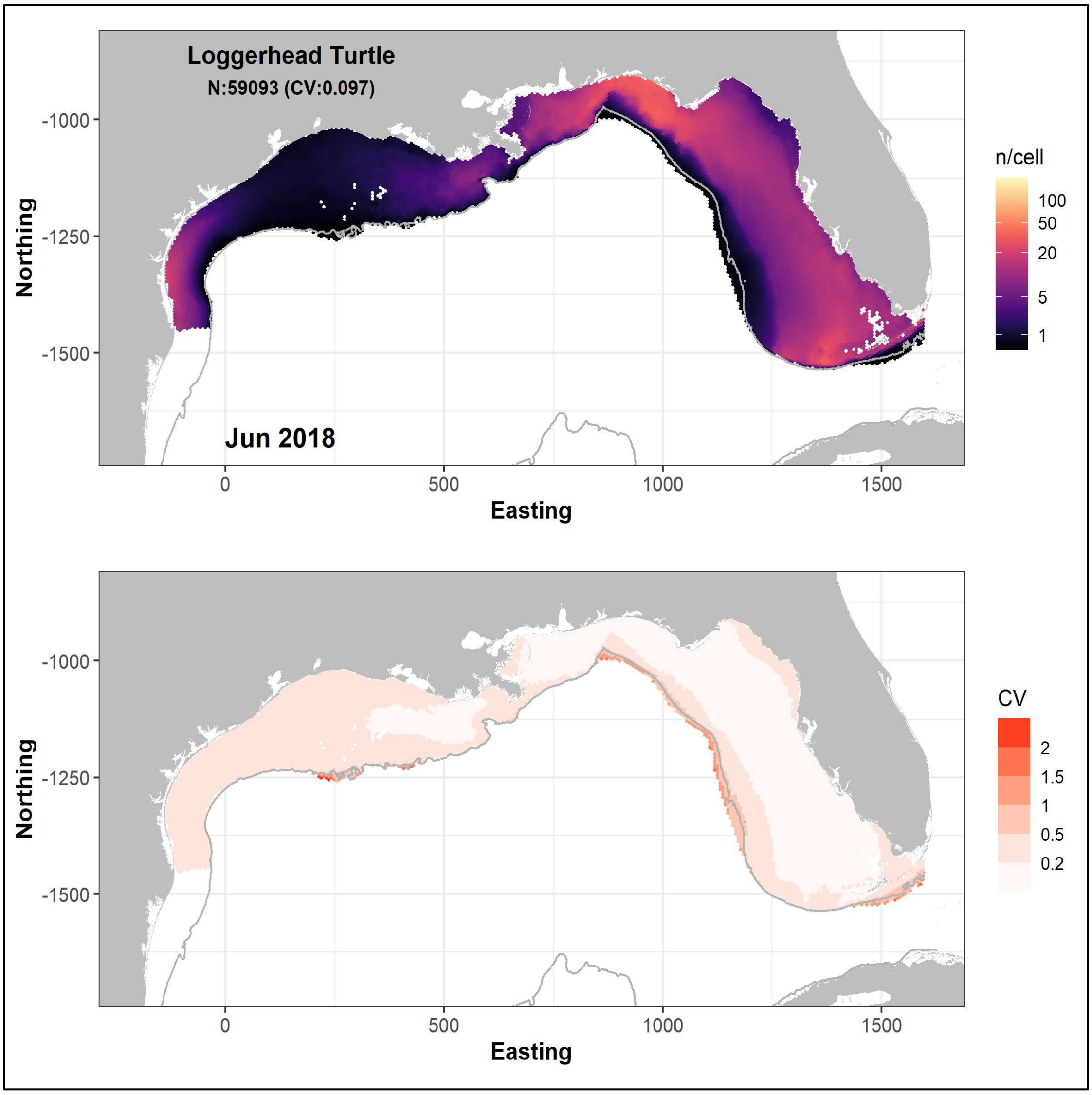

Figure D.4-19. Density model prediction for shelf loggerhead turtles in the NGOM in June 2018.

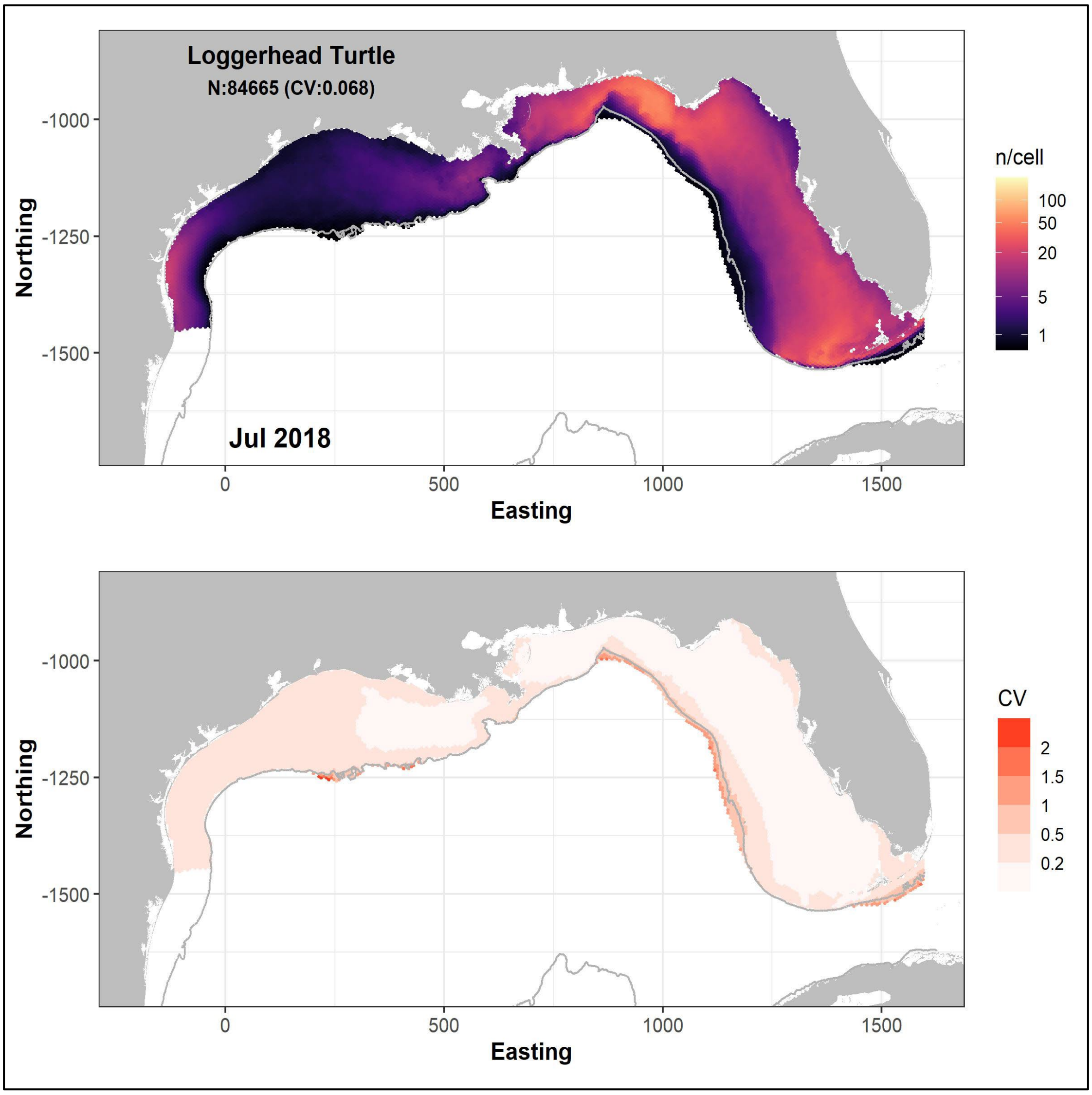

Figure D.4-20. Density model prediction for shelf loggerhead turtles in the NGOM in July 2018.

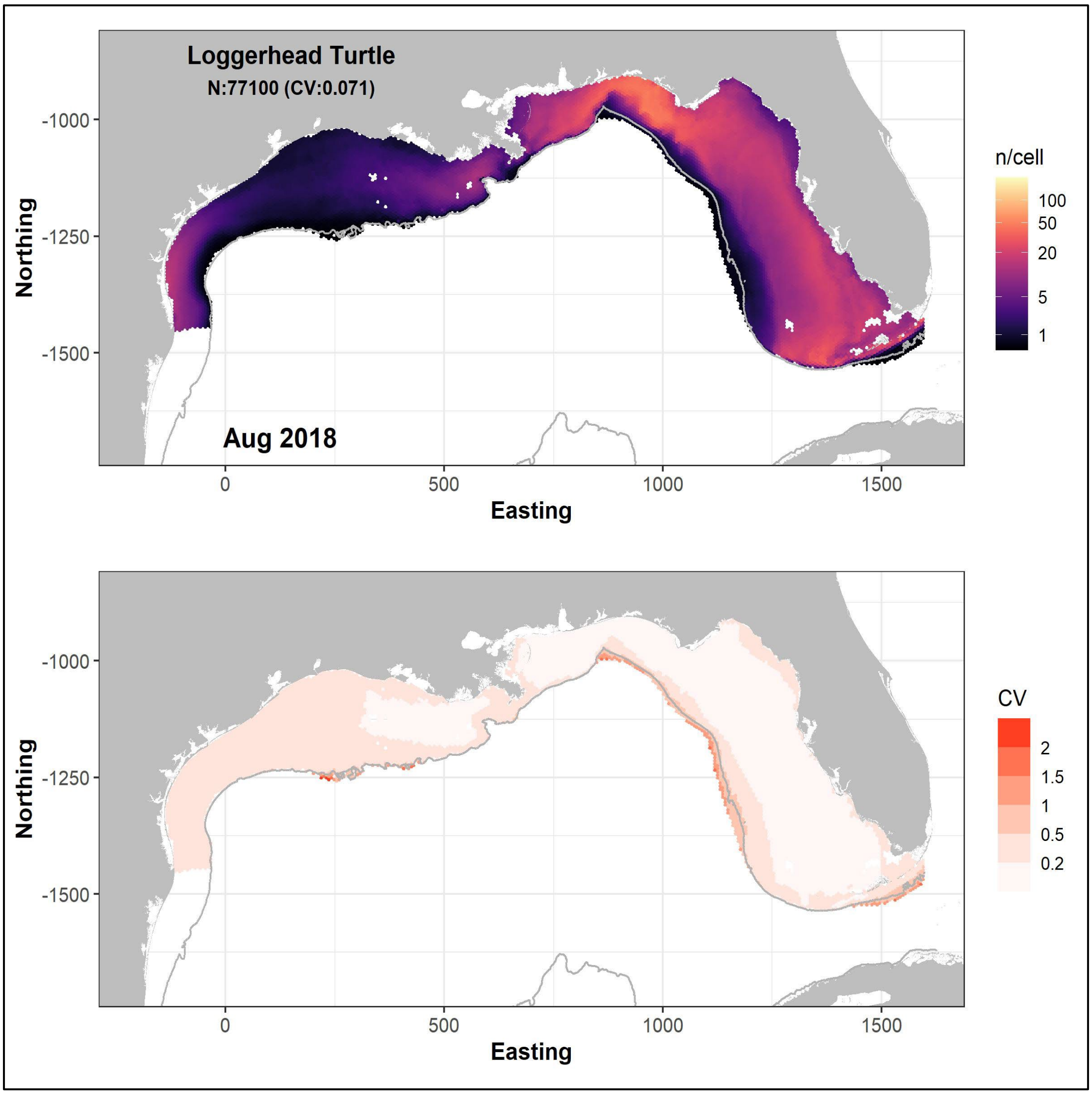

Figure D.4-21. Density model prediction for shelf loggerhead turtles in the NGOM in August 2018.

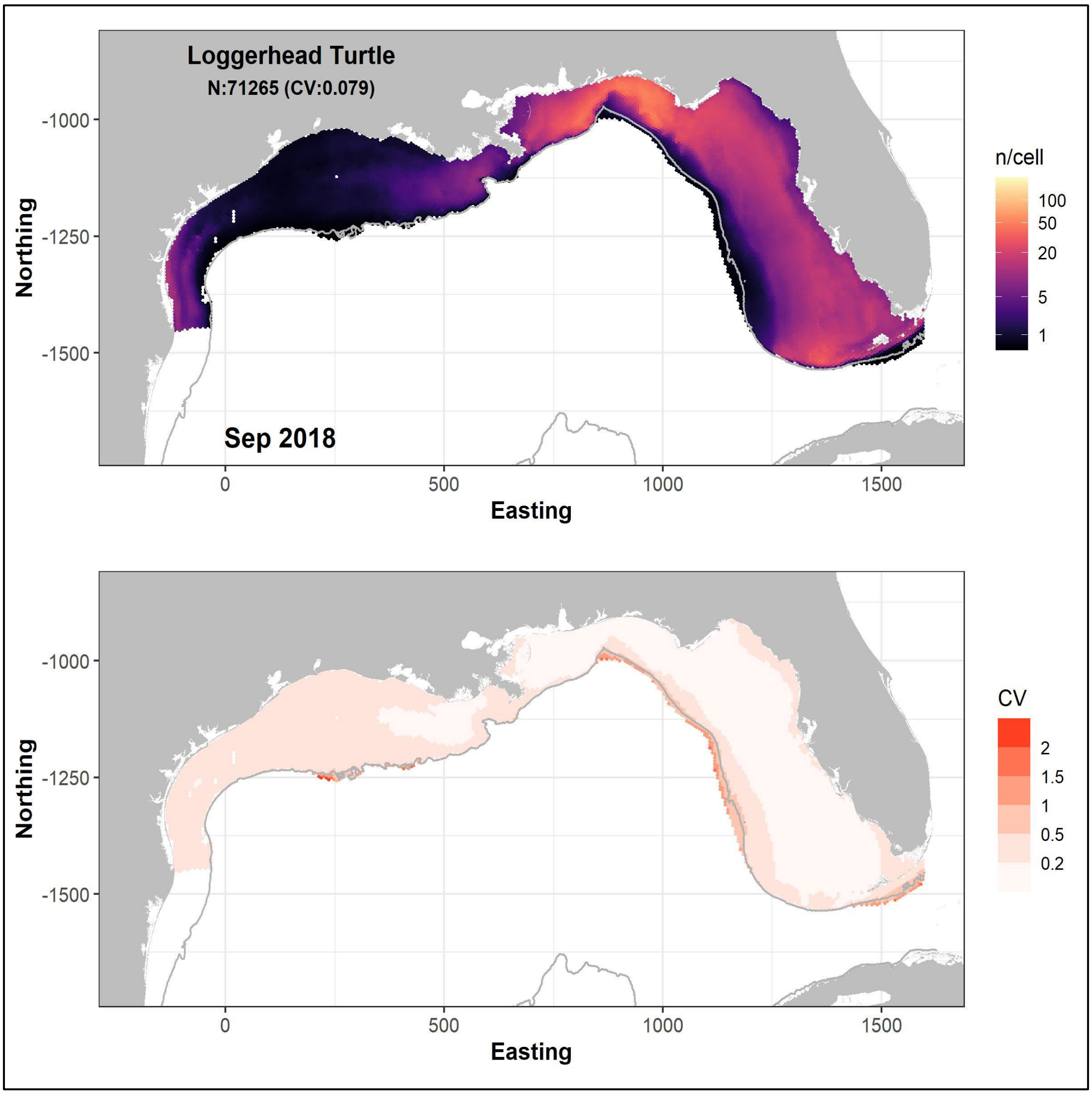

Figure D.4-22. Density model prediction for shelf loggerhead turtles in the NGOM in September 2018.

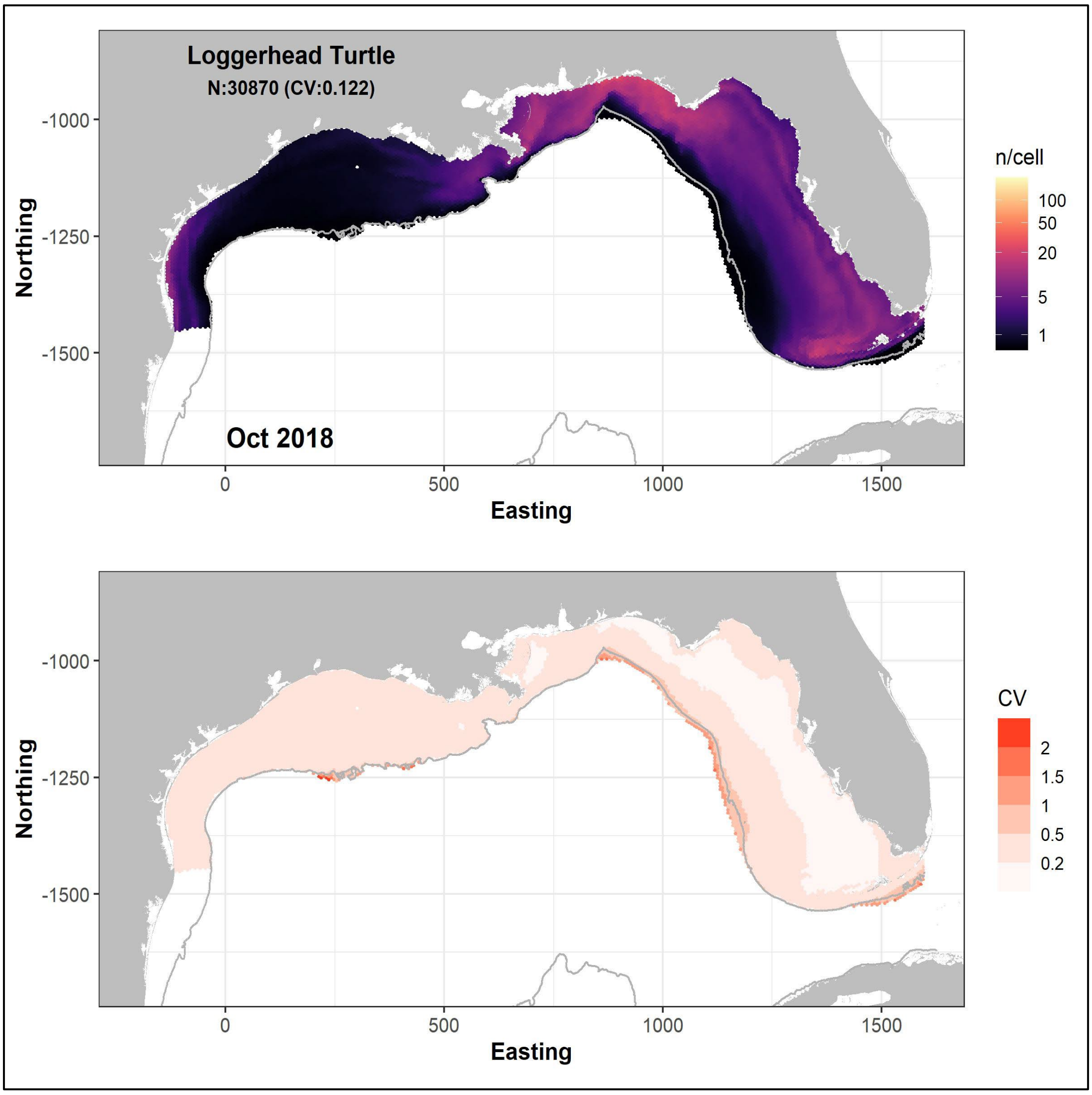

Figure D.4-23. Density model prediction for shelf loggerhead turtles in the NGOM in October 2018.

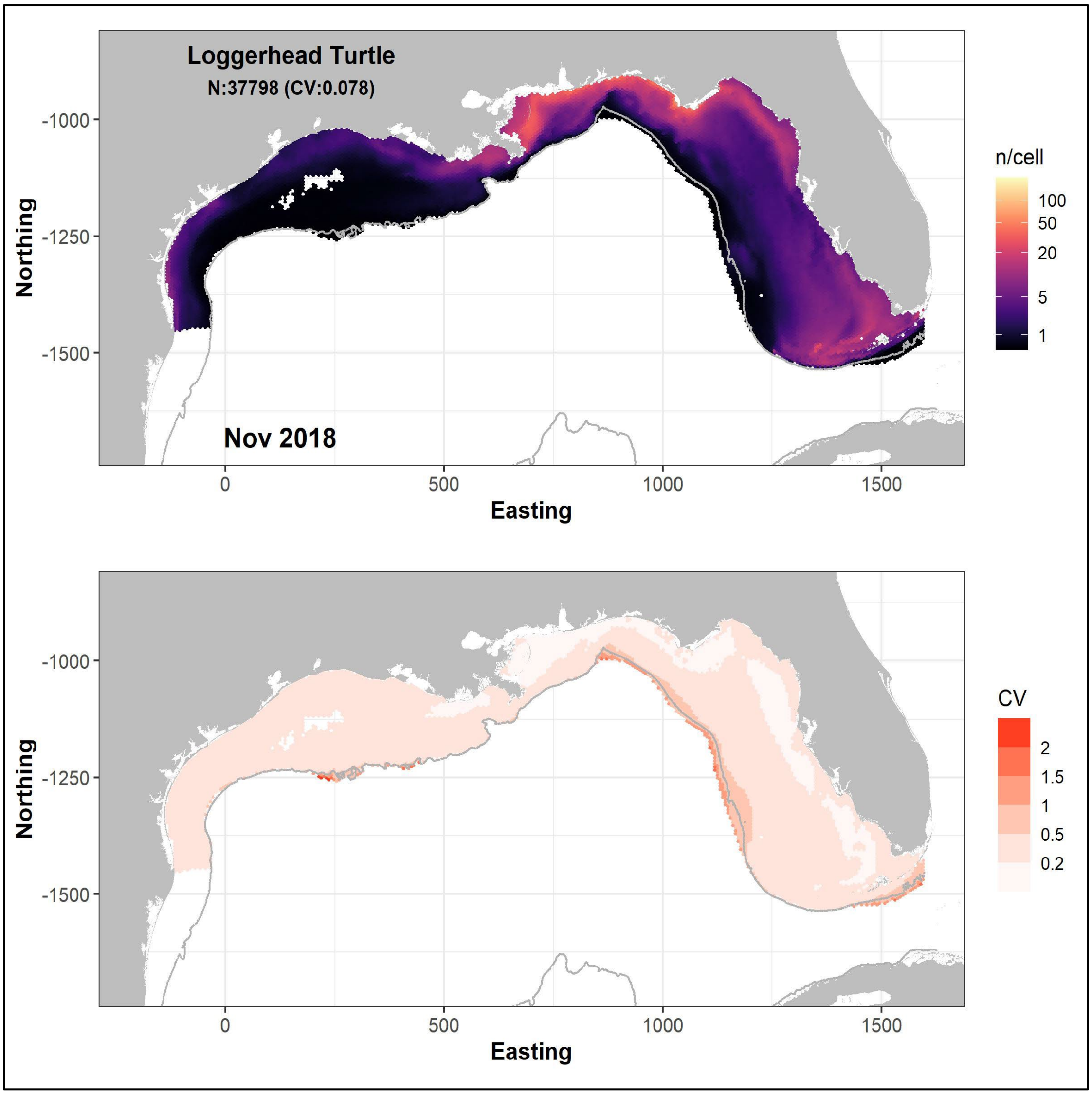

Figure D.4-24. Density model prediction for shelf loggerhead turtles in the NGOM in November 2018.

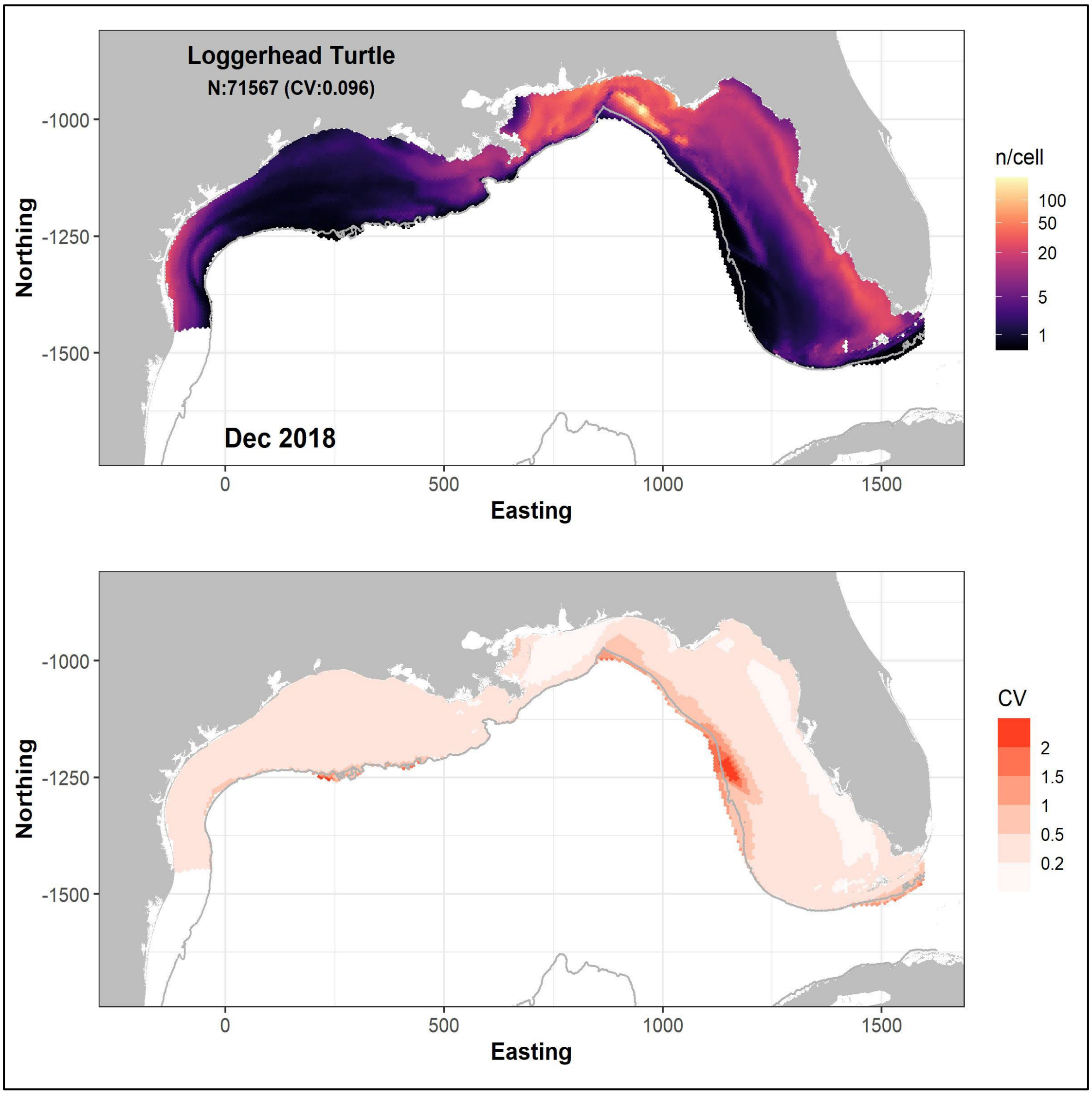

Figure D.4-25. Density model prediction for shelf loggerhead turtles in the NGOM in December 2018.

D.4.5.2 Inclusion of Unidentified Turtles

Aside from leatherbacks, sea turtles are difficult to identify reliably from the air, and observers are trained to make positive identification to species only when they feel confident in their identification. In particular, distinguishing between green turtles and loggerhead turtles requires careful observation. In addition, turtles are often observed just below the water surface or diving, making reliable identification more challenging. As a result, many of the observed turtles during the aerial surveys were identified only as "hardshell turtles". Incorporating these unidentified observations into density estimates is essential to developing unbiased estimates. To properly apportion unidentified turtles among species, a SDM model was developed for "hardshell" turtles. The resulting density of hardshell turtles were partitioned among the identified species based upon the relative predicted density of each species in each spatial cell. Monthly density maps for loggerhead turtles including both identified turtles and the proportion of unidentified turtles were generated (Figures D.4-26–D.4-37).

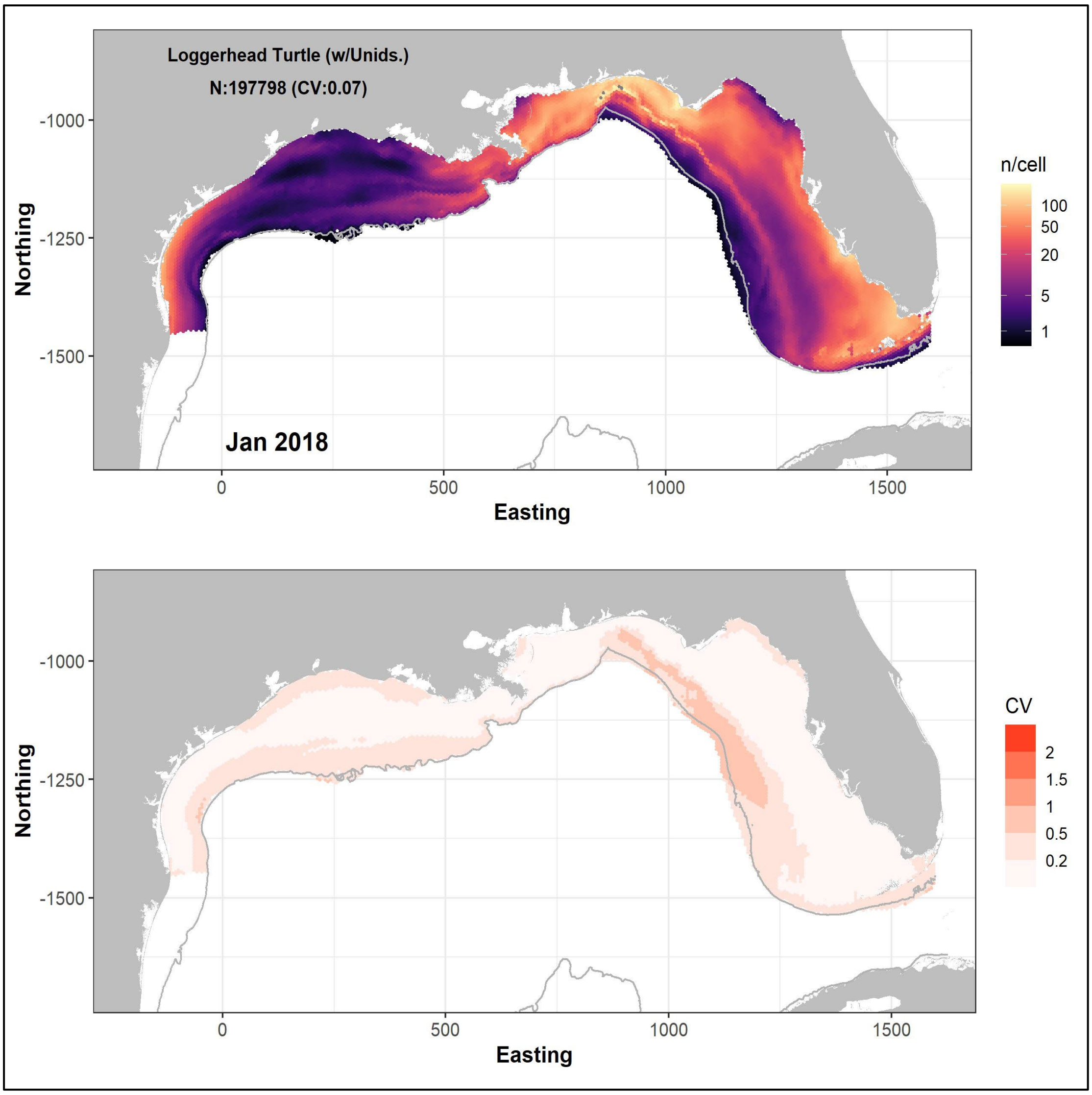

Figure D.4-26. Density model prediction for loggerhead turtles including apportioned unidentified turtles in the NGOM in January 2018.

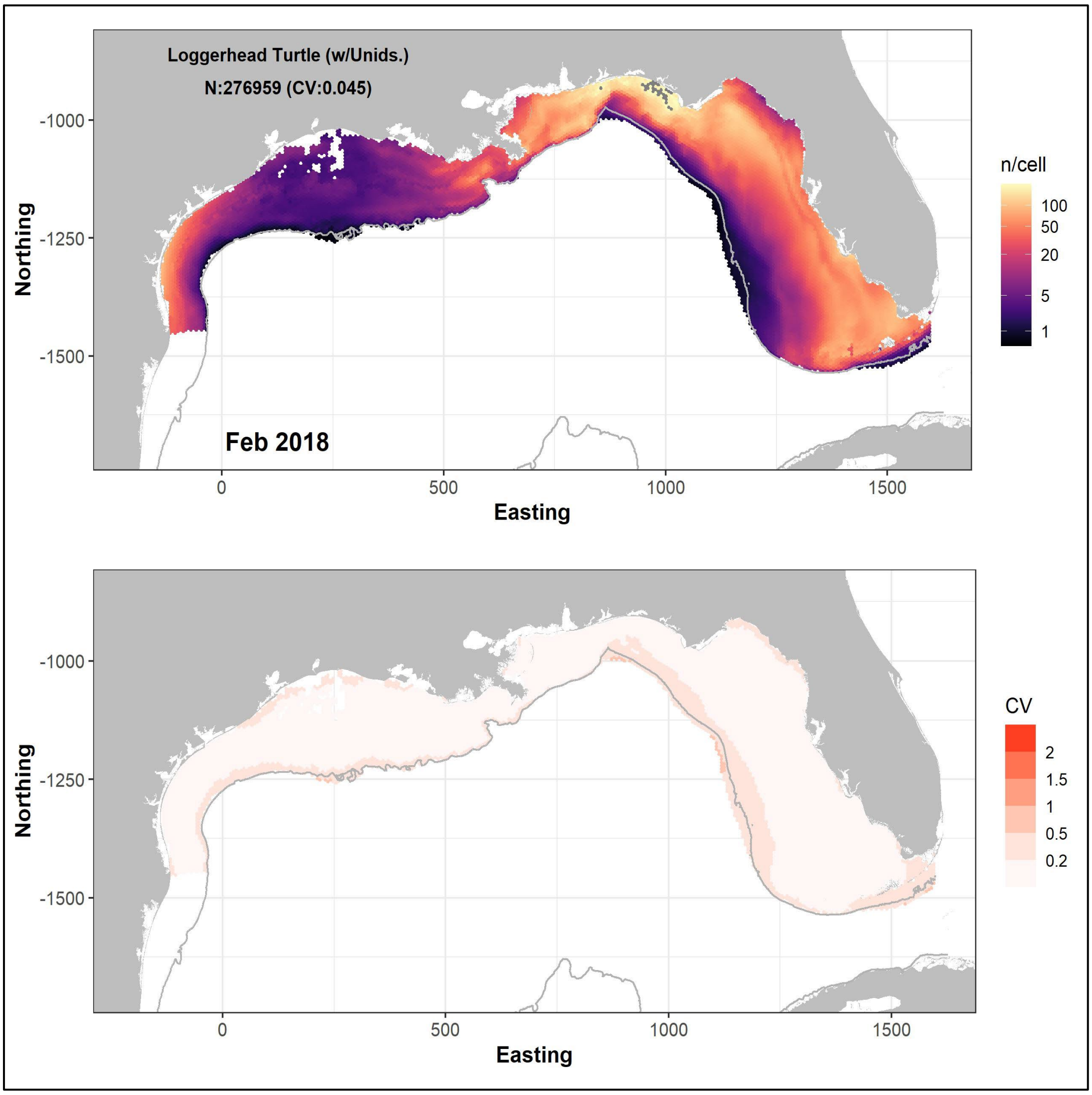

Figure D.4-27. Density model prediction for loggerhead turtles including apportioned unidentified turtles in the NGOM in February 2018.

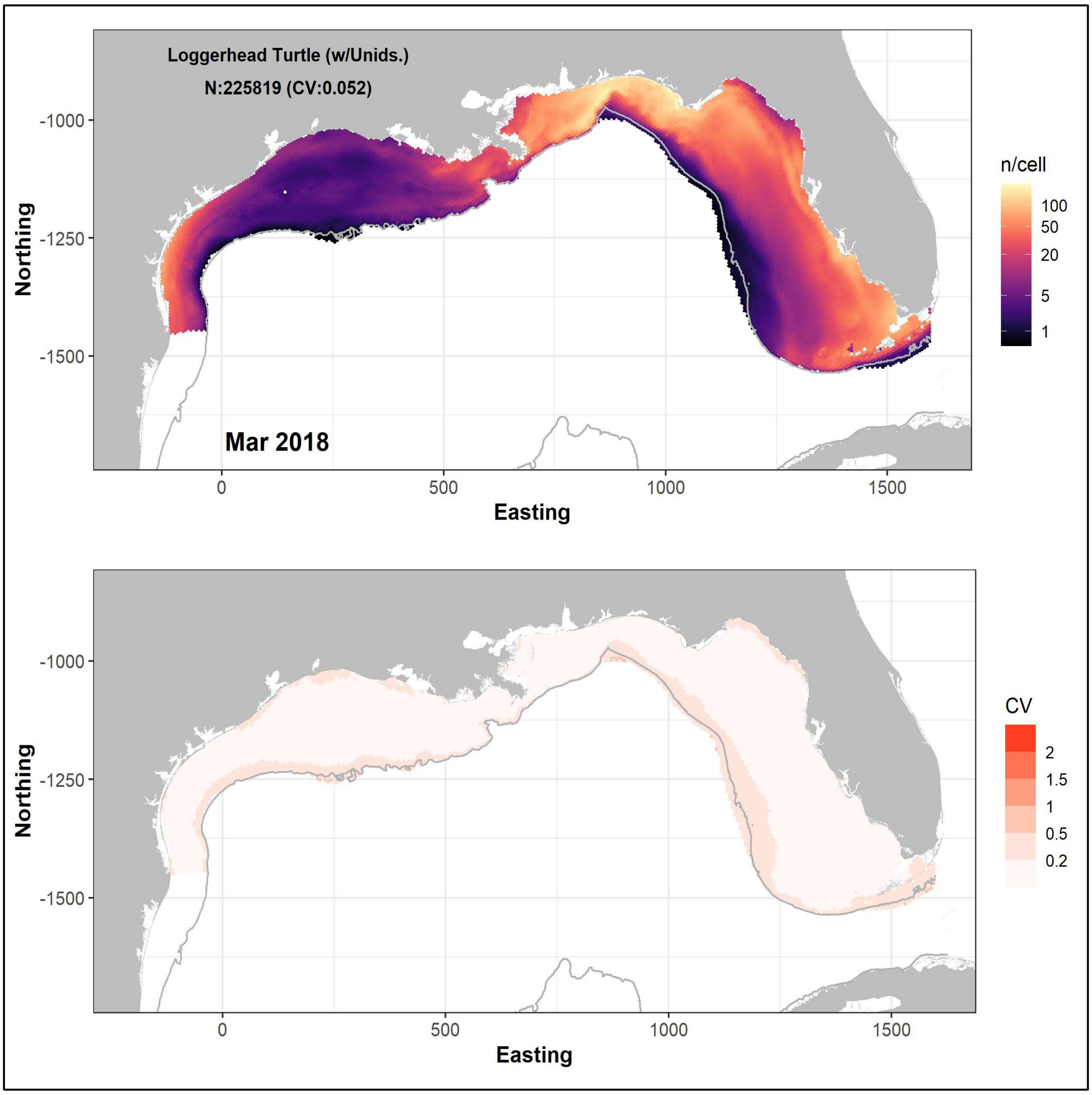

Figure D.4-28. Density model prediction for loggerhead turtles including apportioned unidentified turtles in the NGOM in March 2018.

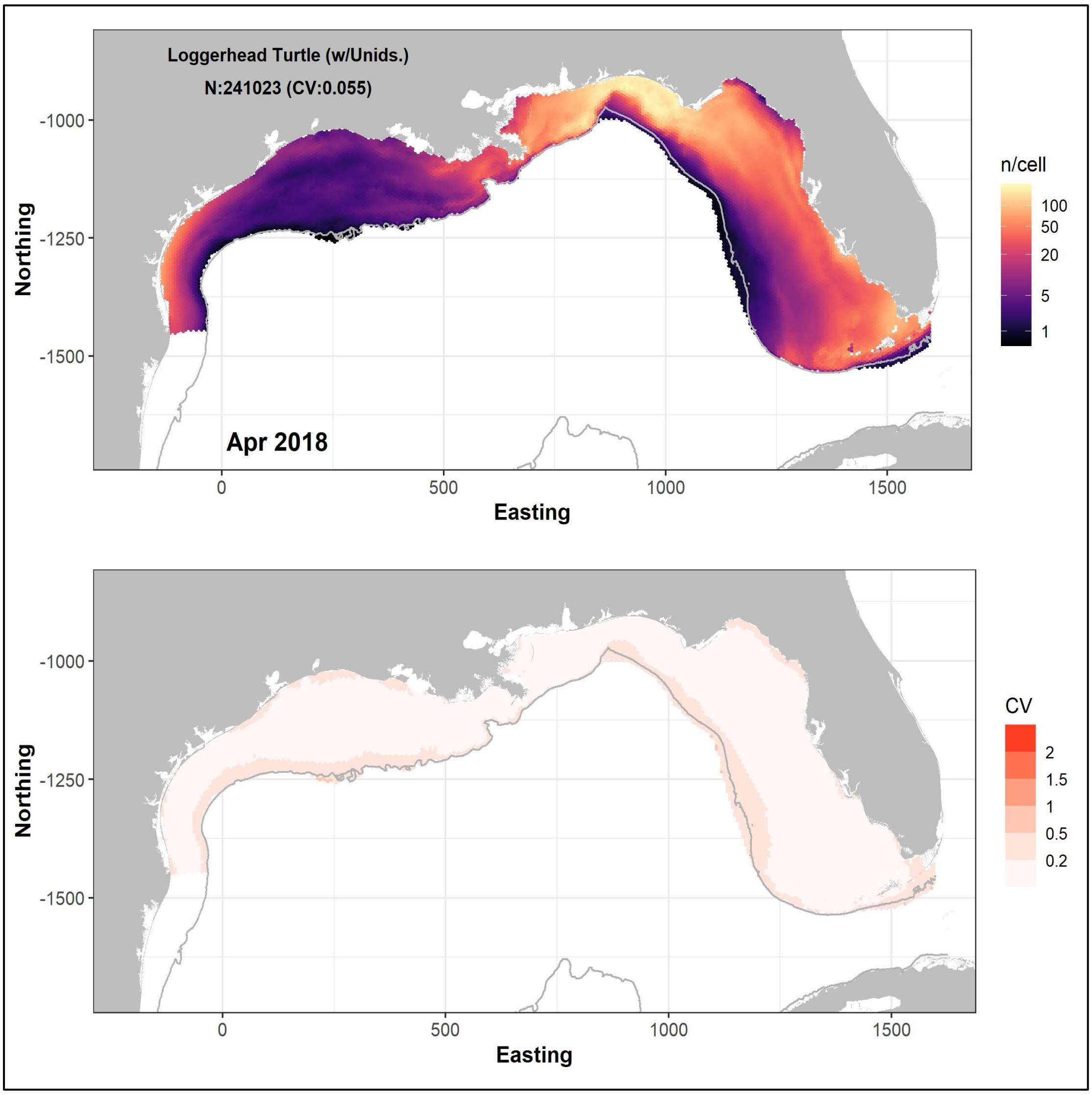

Figure D.4-29. Density model prediction for loggerhead turtles including apportioned unidentified turtles in the NGOM in April 2018.

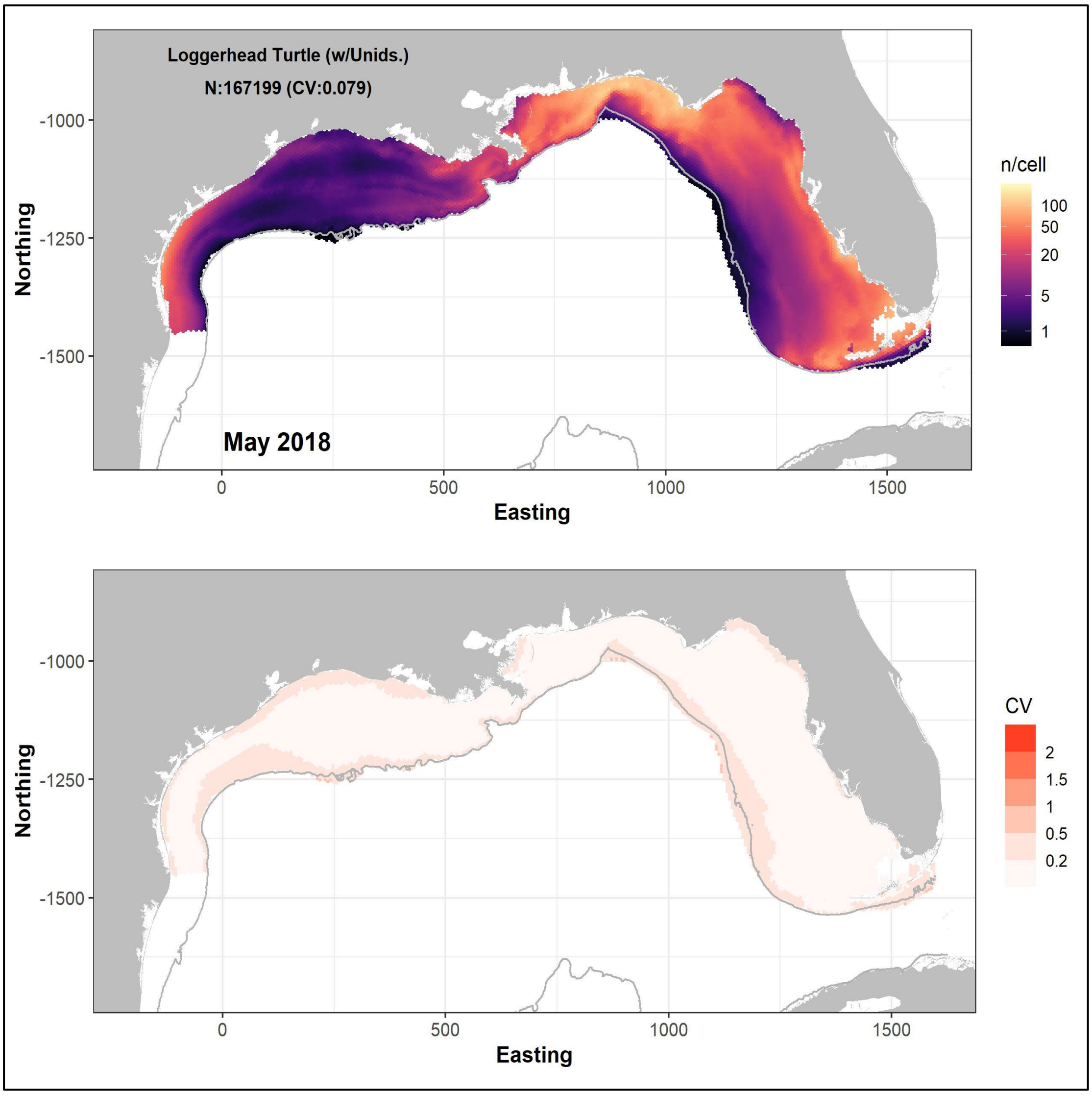

Figure D.4-30. Density model prediction for loggerhead turtles including apportioned unidentified turtles in the NGOM in May 2018.

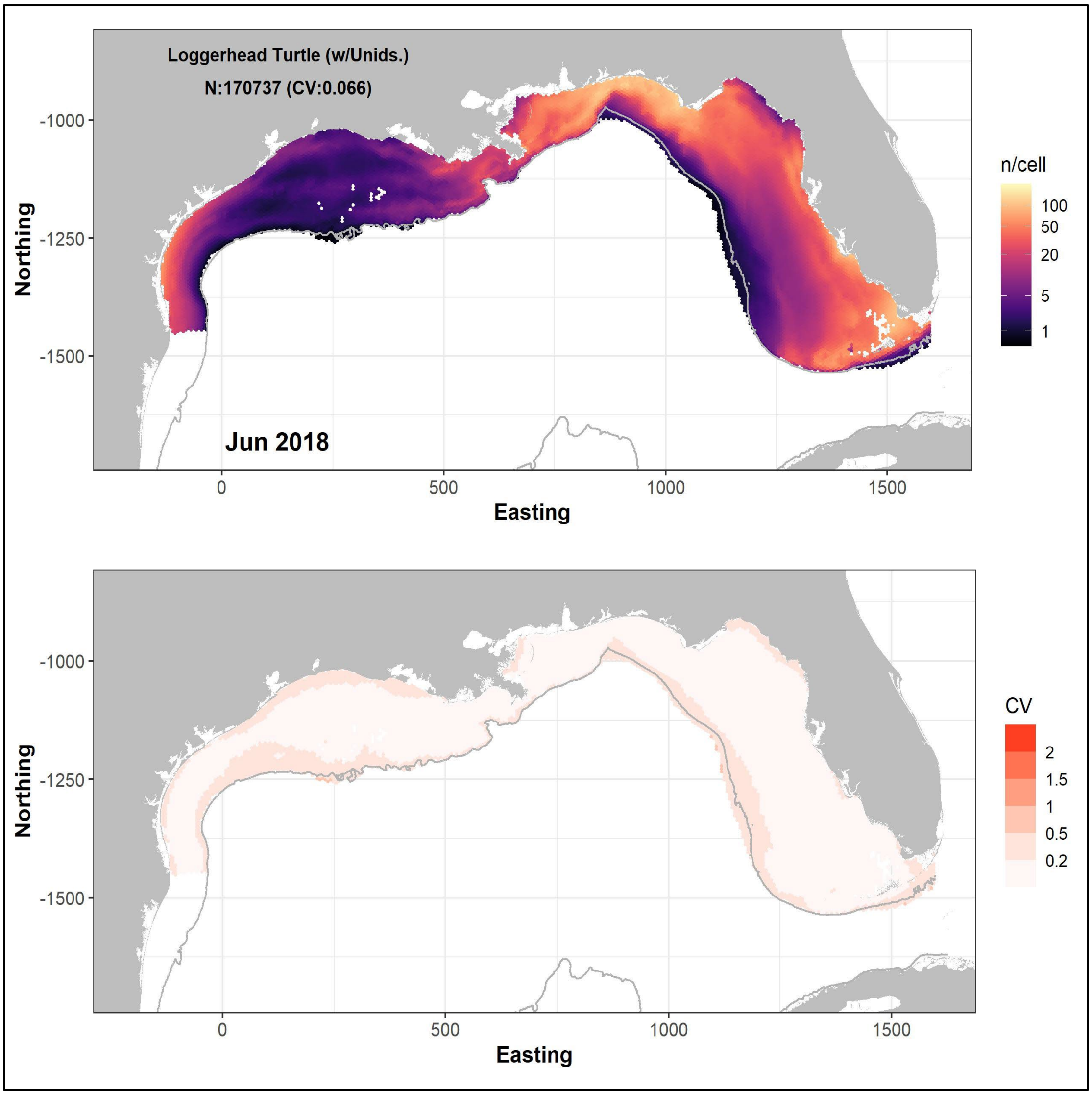

Figure D.4-31. Density model prediction for loggerhead turtles including apportioned unidentified turtles in the NGOM in June 2018.

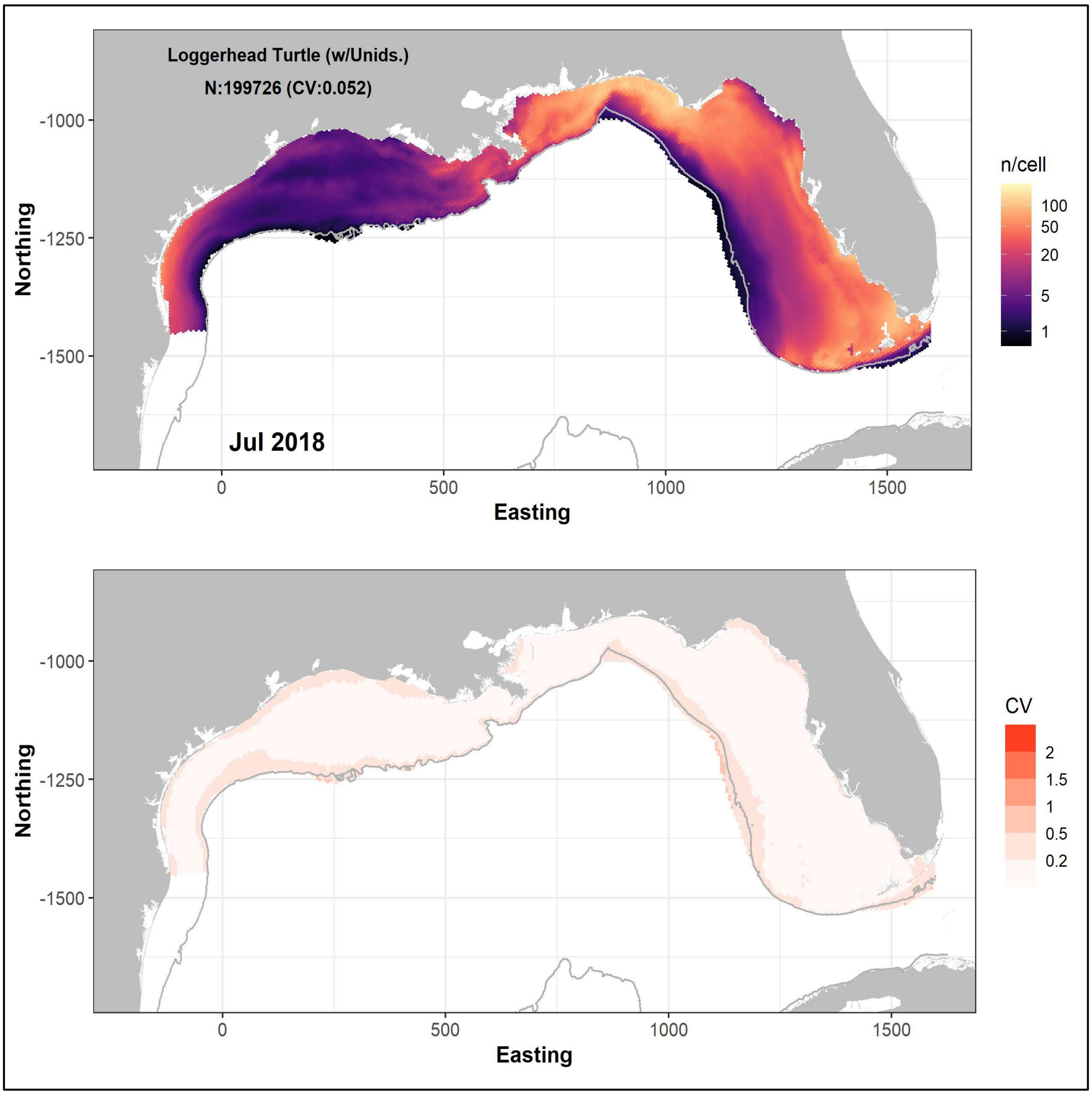

Figure D.4-32. Density model prediction for loggerhead turtles including apportioned unidentified turtles in the NGOM in July 2018.

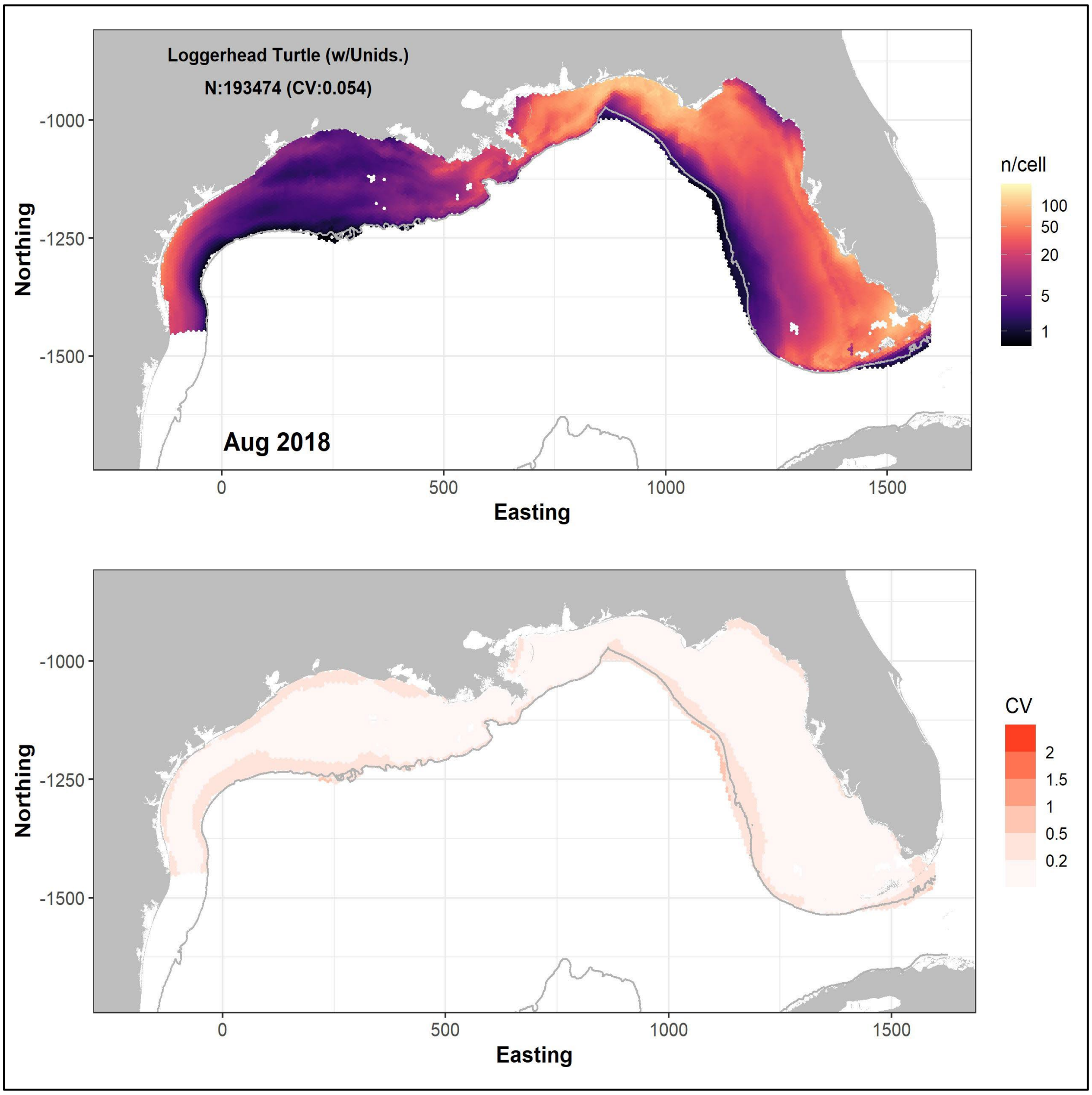

Figure D.4-33. Density model prediction for loggerhead turtles including apportioned unidentified turtles in the NGOM in August 2018.

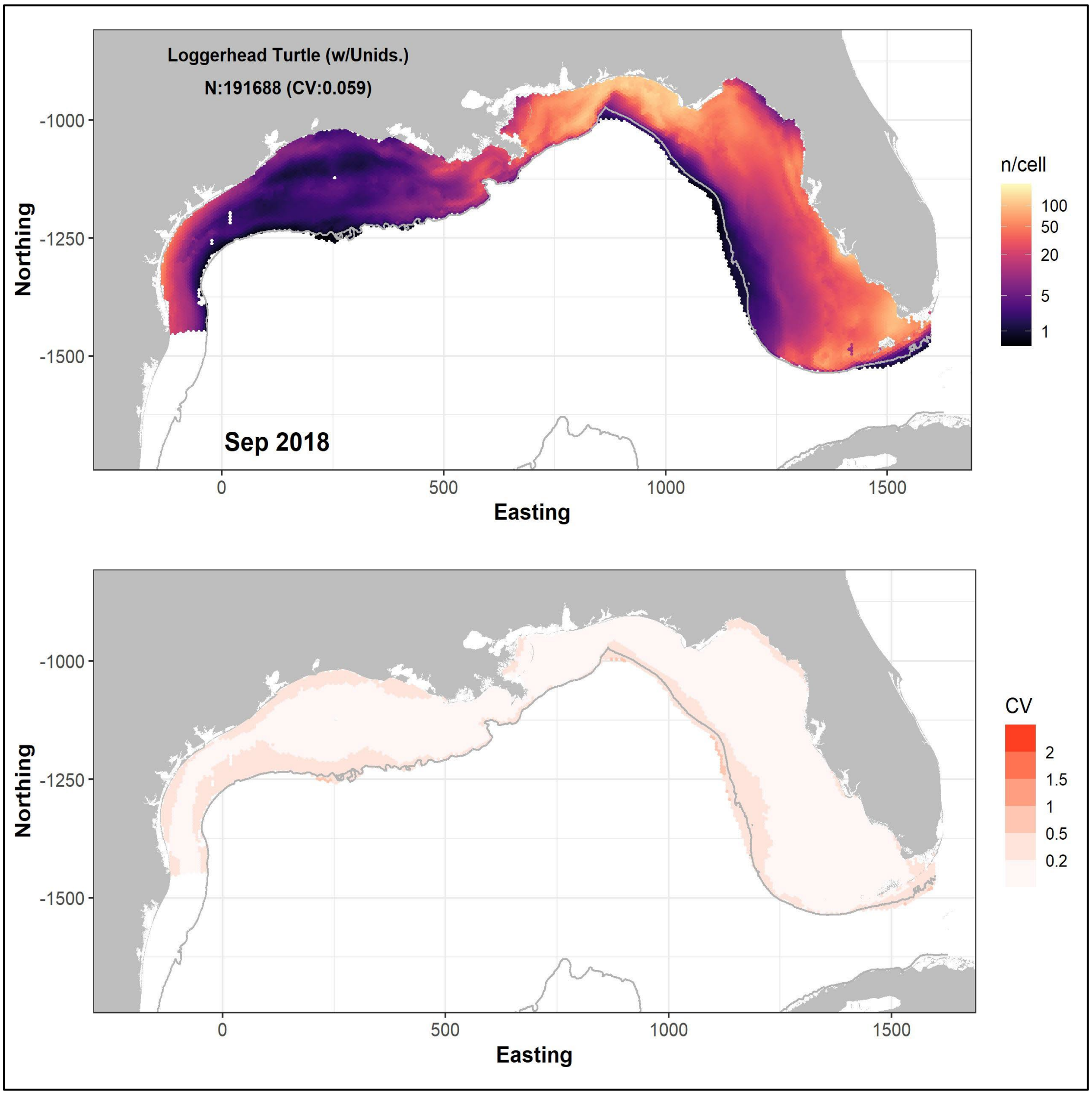

Figure D.4-34. Density model prediction for loggerhead turtles including apportioned unidentified turtles in the NGOM in September 2018.

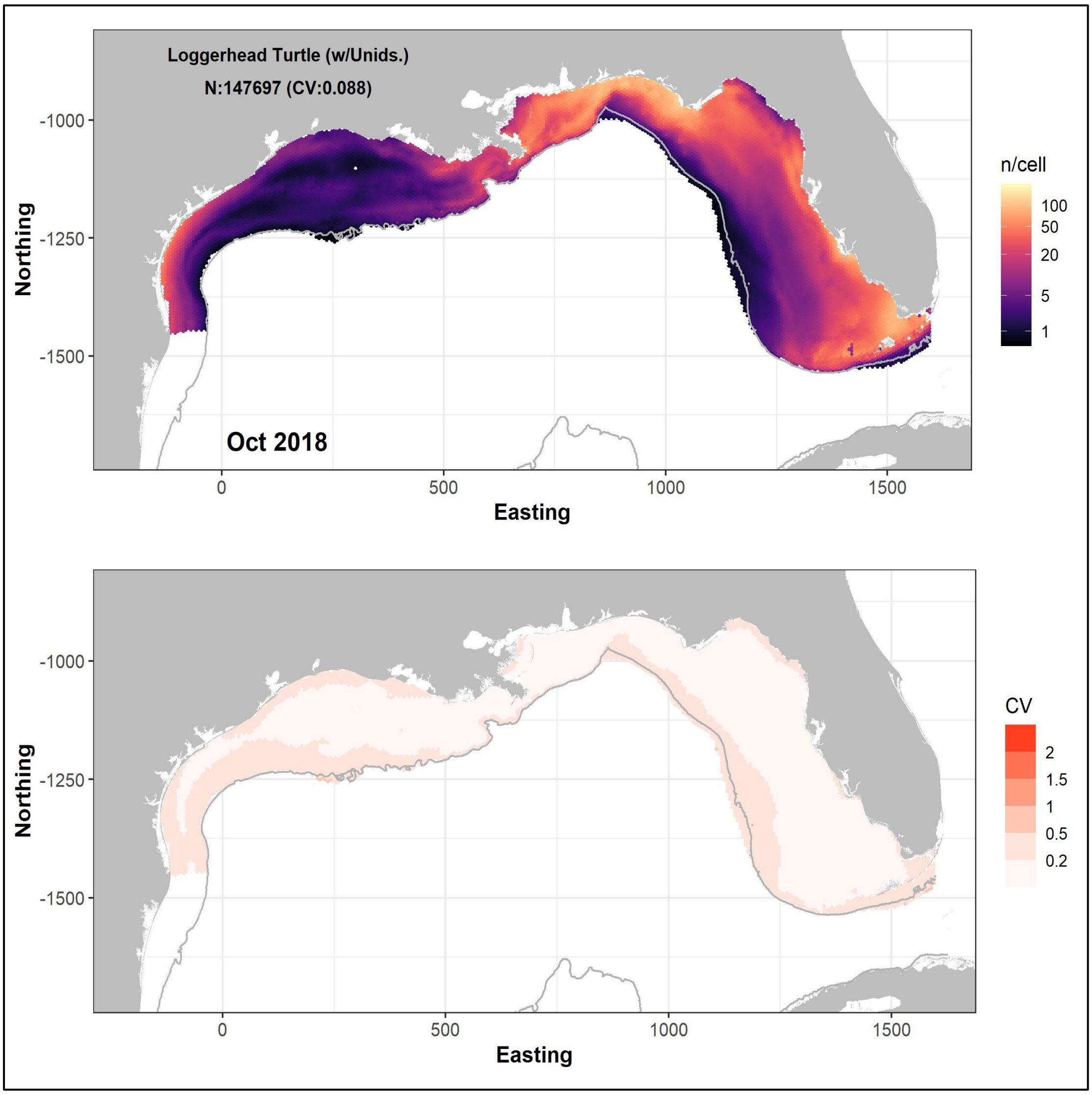

Figure D.4-35. Density model prediction for loggerhead turtles including apportioned unidentified turtles in the NGOM in October 2018.

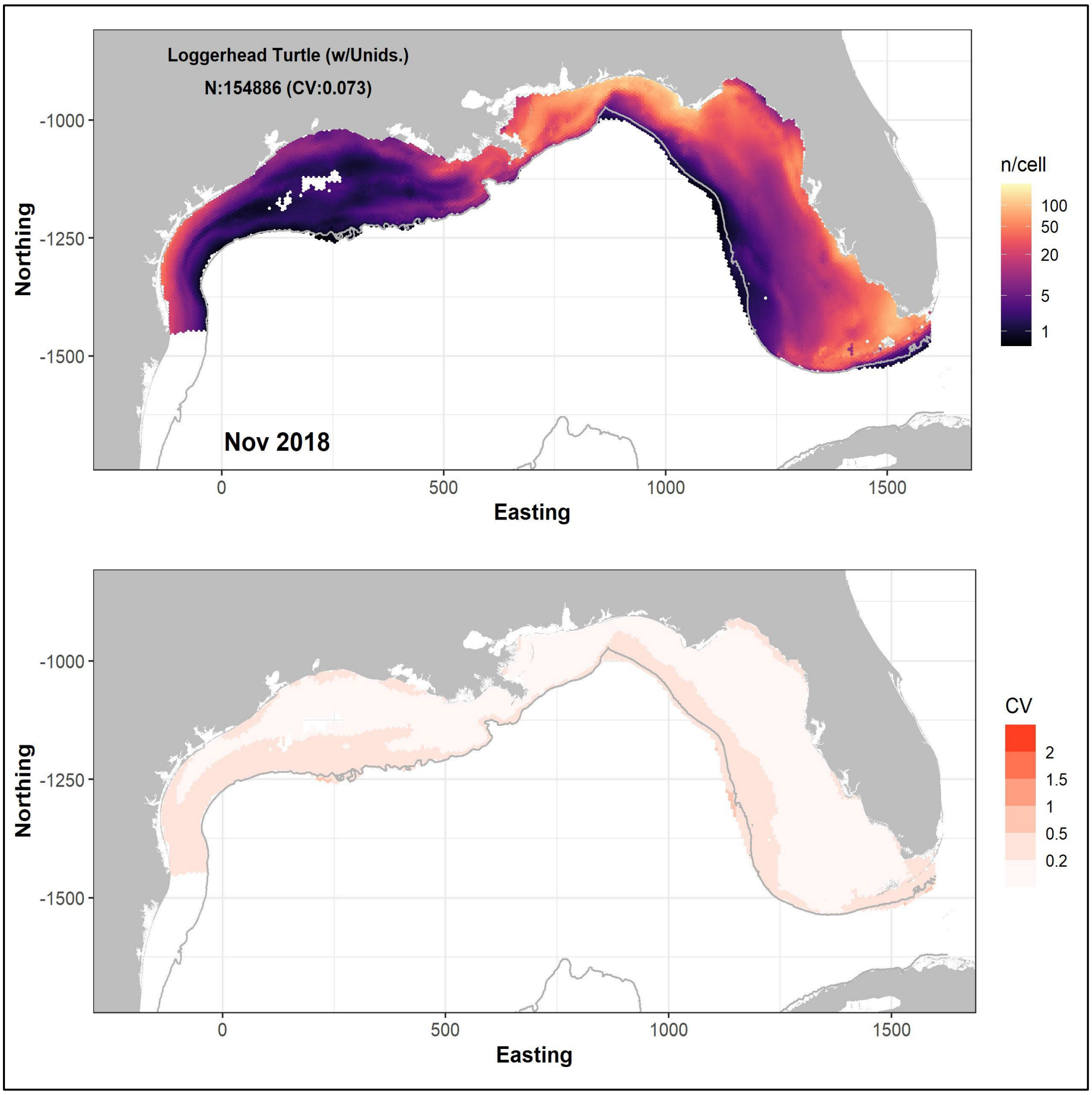

Figure D.4-36. Density model prediction for loggerhead turtles including apportioned unidentified turtles in the NGOM in November 2018.

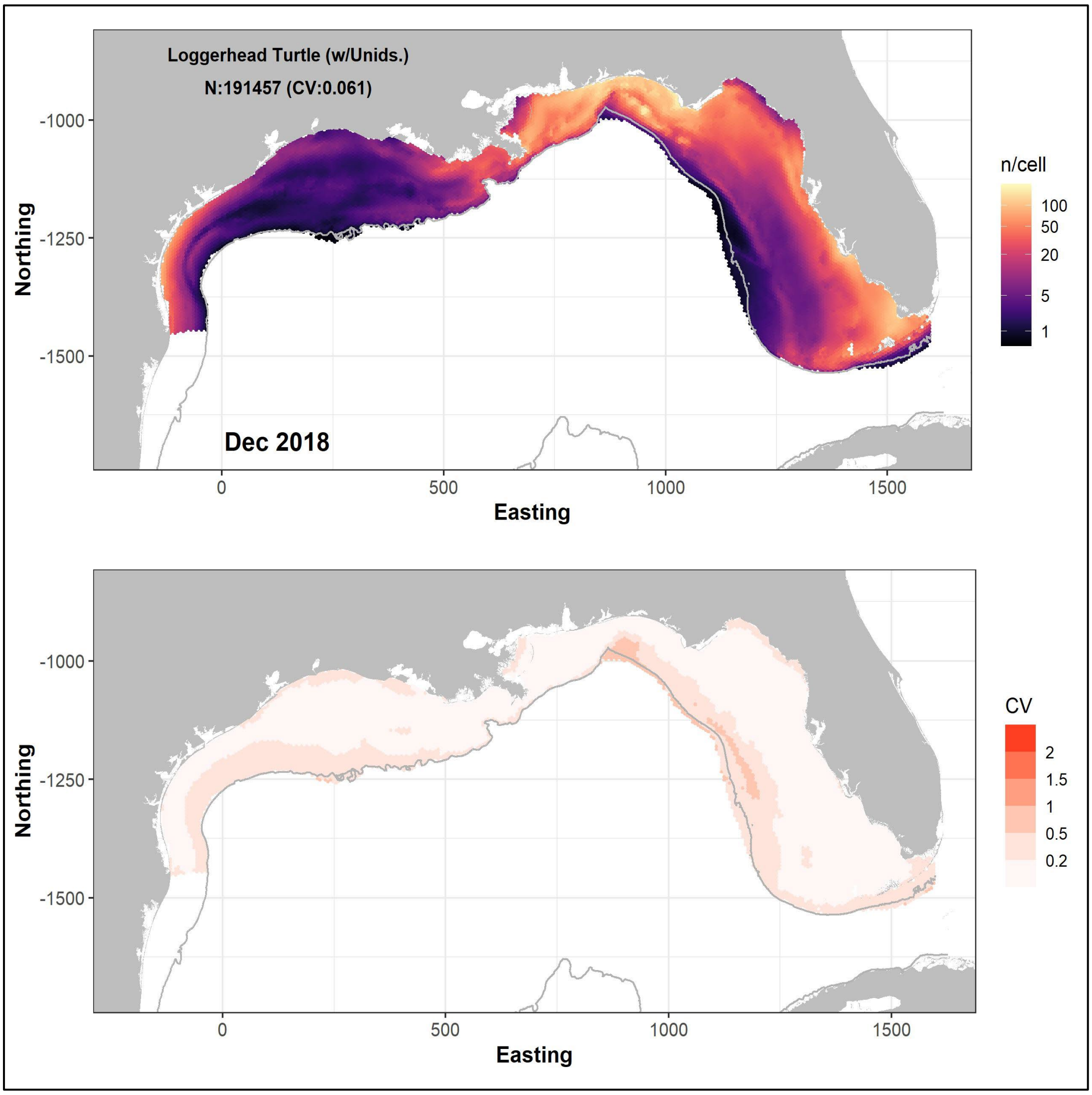

Figure D.4-37. Density model prediction for loggerhead turtles including apportioned unidentified turtles in the NGOM in December 2018.

D.4.5.3 Projected Density throughout the Gulf of Mexico

While aerial survey effort was restricted to the NGOM, loggerhead turtles occur throughout the northern and southern GOM. The projection of the resulting SDM beyond the NGOM assumes that species-habitat relationships are consistent, and it is unknown if this assumption is reliable. To evaluate the potential density of loggerhead turtles outside of the US Economic Exclusive Zone (EEZ), the SDM was projected throughout the GOM. These results should be interpreted with caution given the extrapolation outside of the surveyed area (Figures D.4-38–D.4-49).

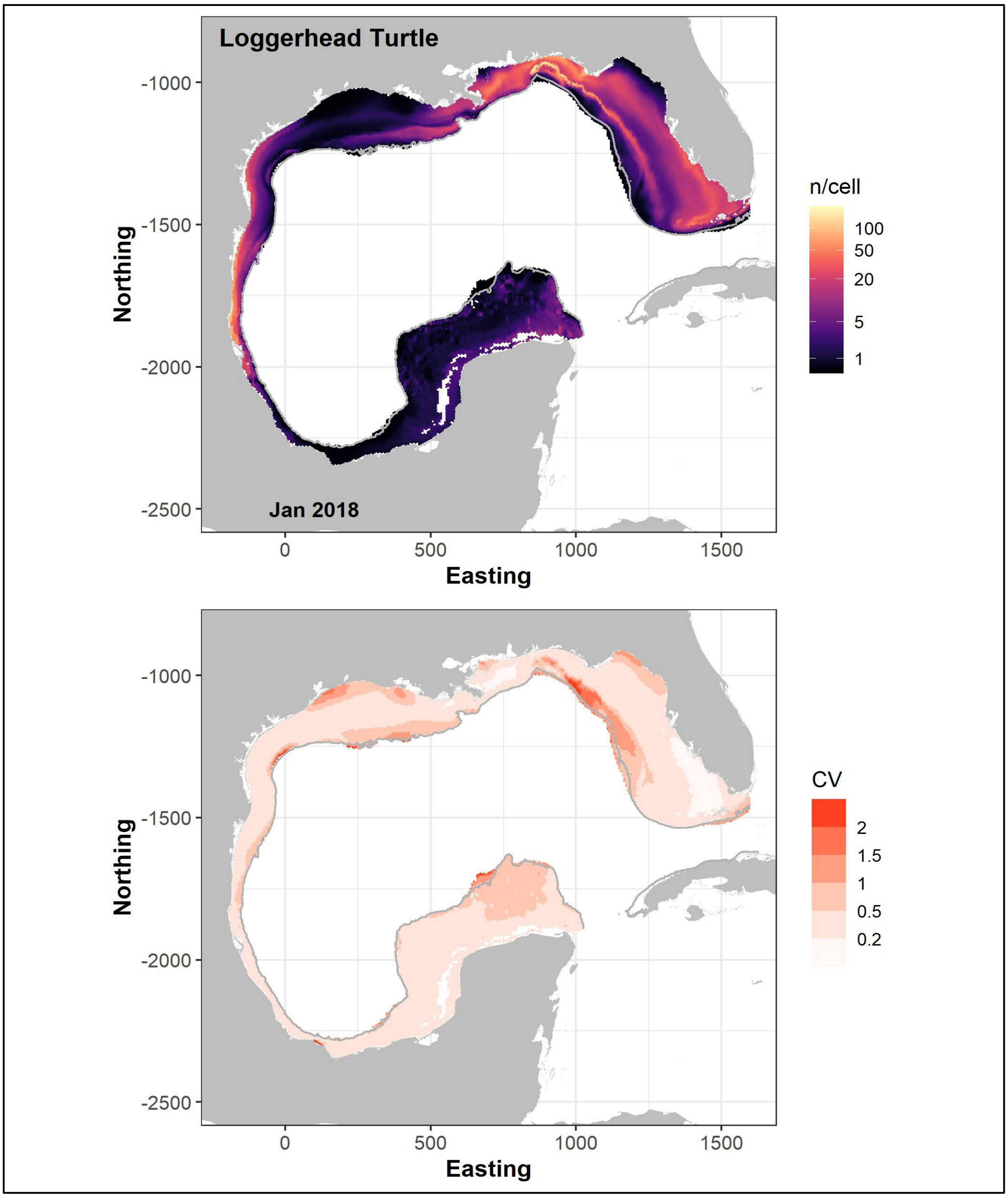

Figure D.4-38. Projected density model for shelf loggerhead turtles in the entire GOM for January 2018.

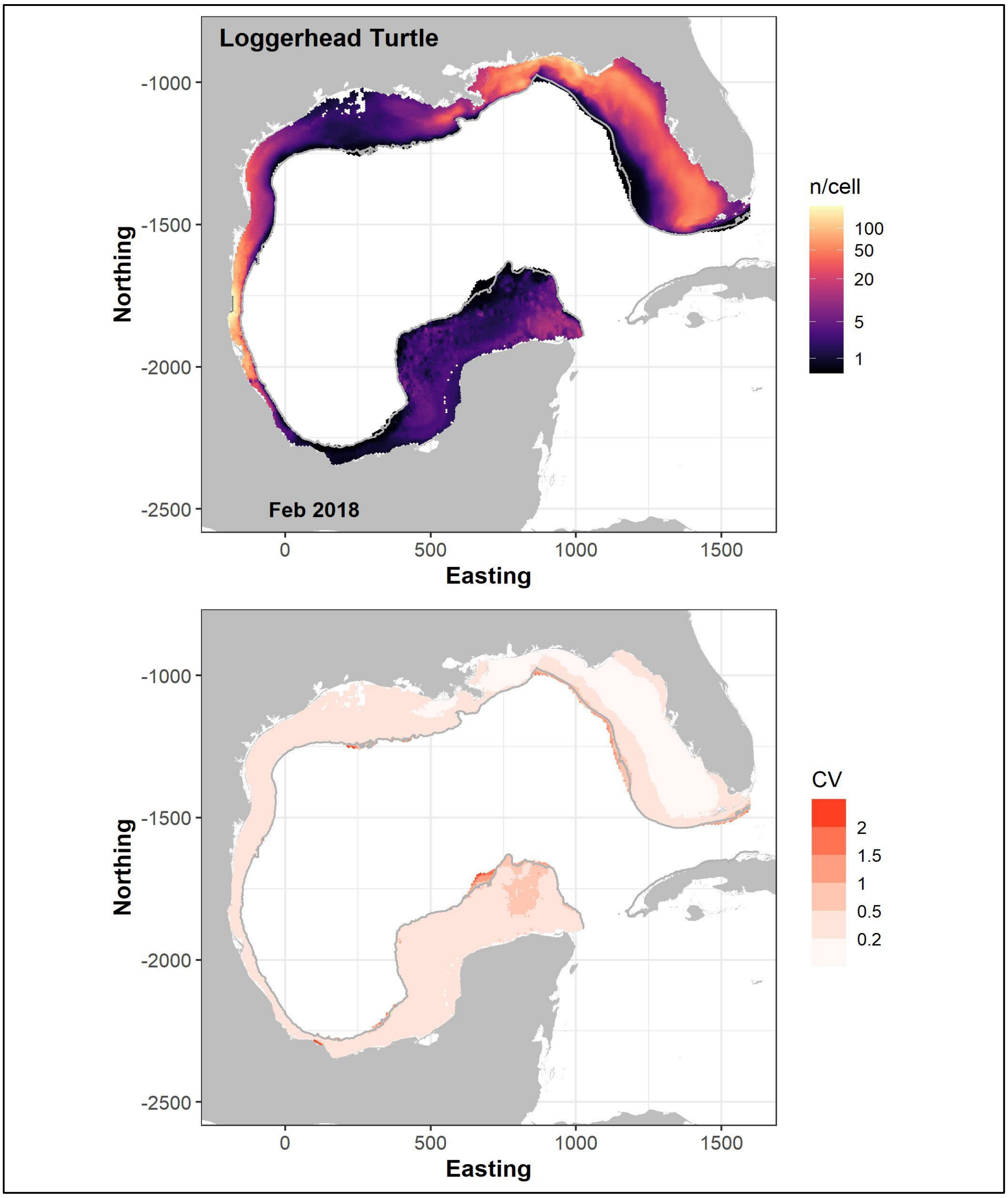

Figure D.4-39. Projected density model for shelf loggerhead turtles in the entire GOM for February 2018.

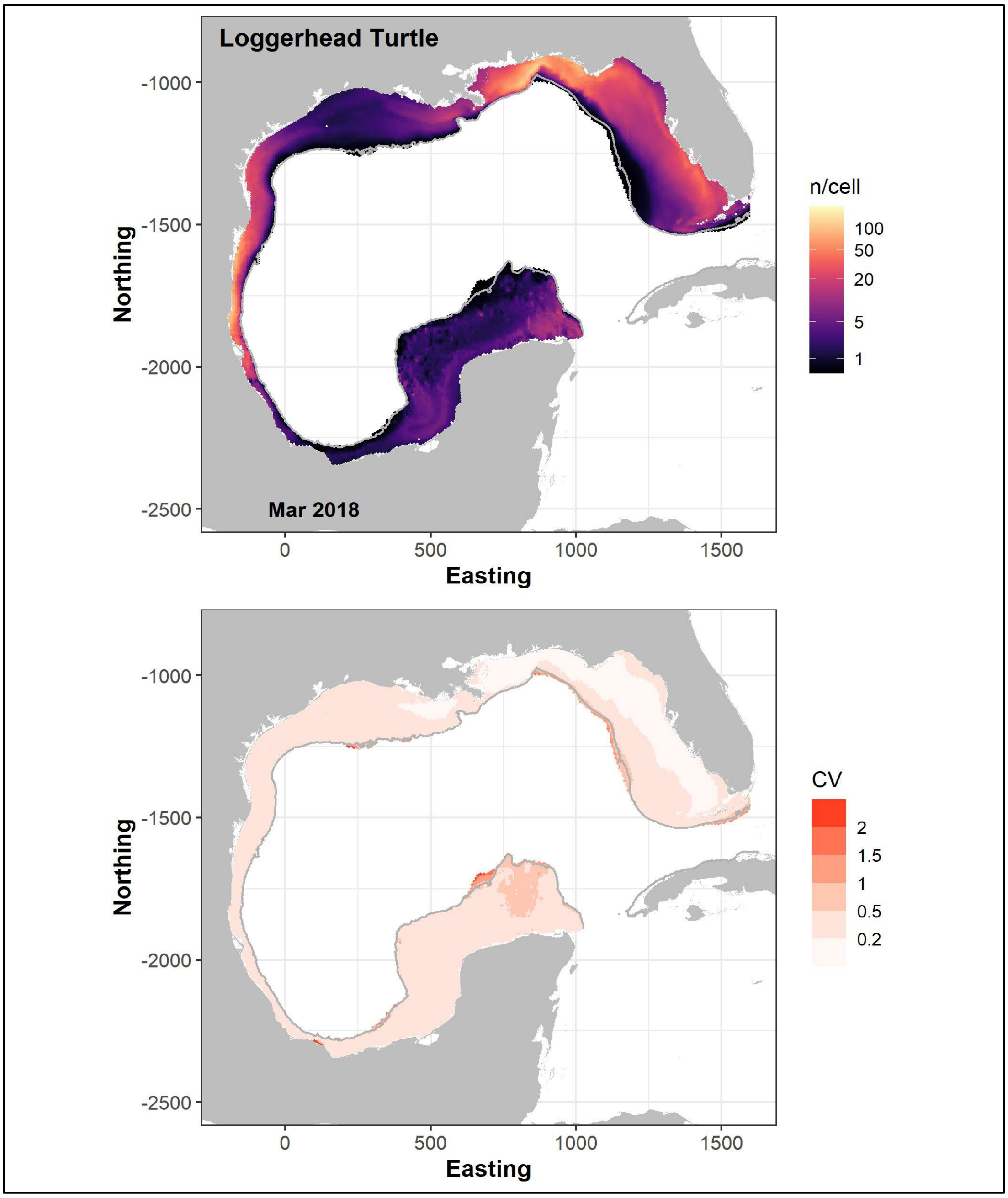

Figure D.4-40. Projected density model for shelf loggerhead turtles in the entire GOM for March 2018.

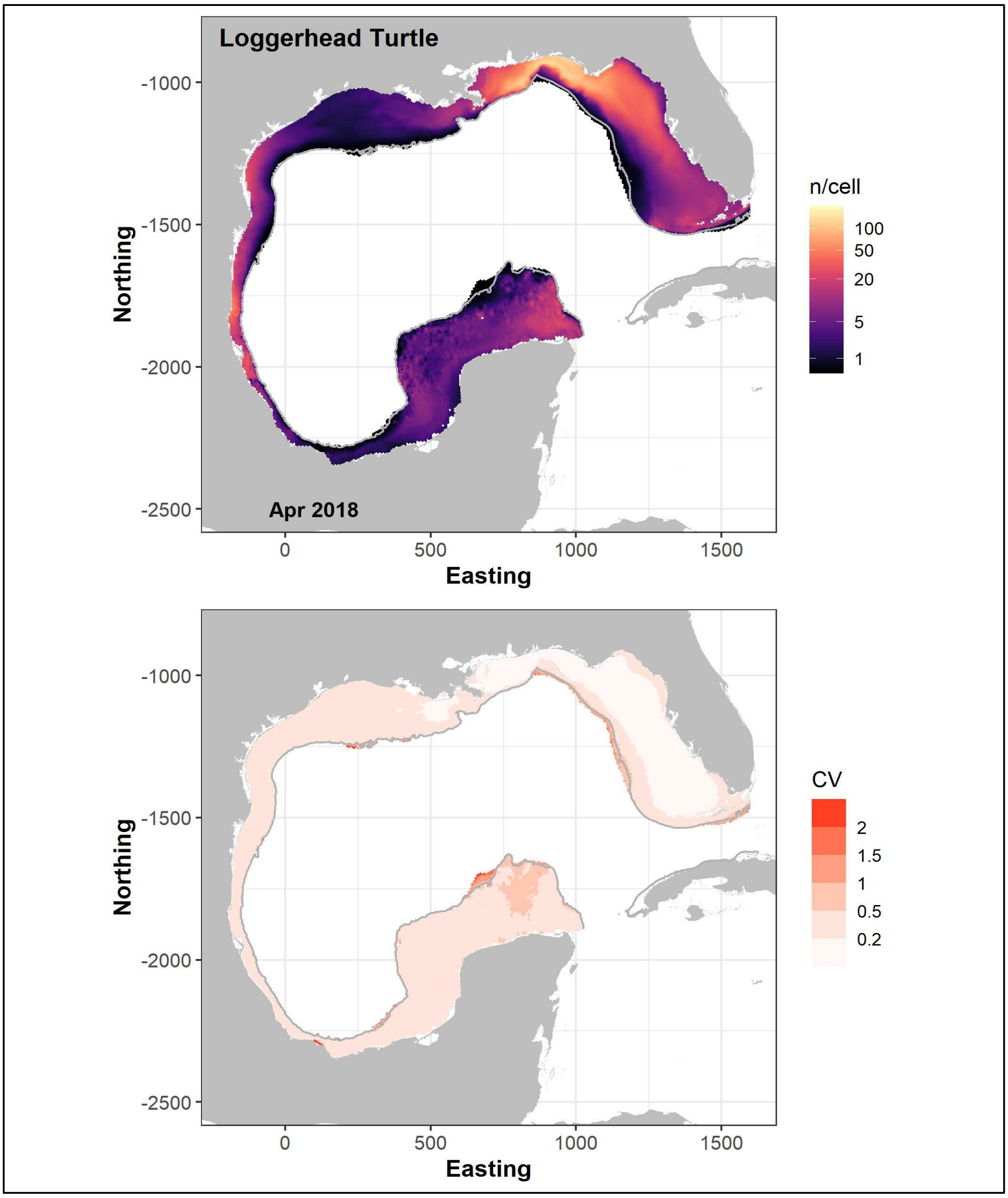

Figure D.4-41. Projected density model for shelf loggerhead turtles in the entire GOM for April 2018.

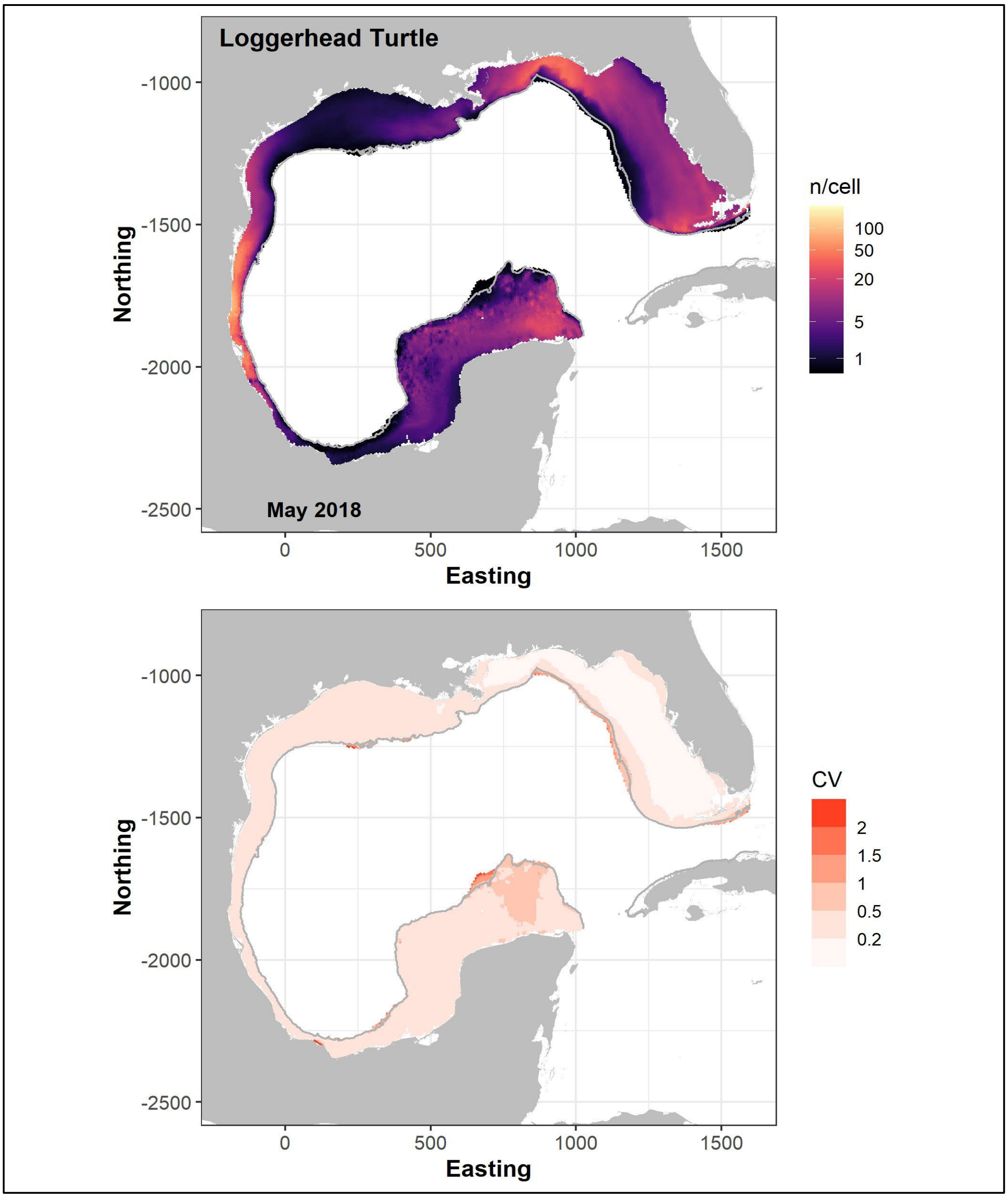

Figure D.4-42. Projected density model for shelf loggerhead turtles in the entire GOM for May 2018.

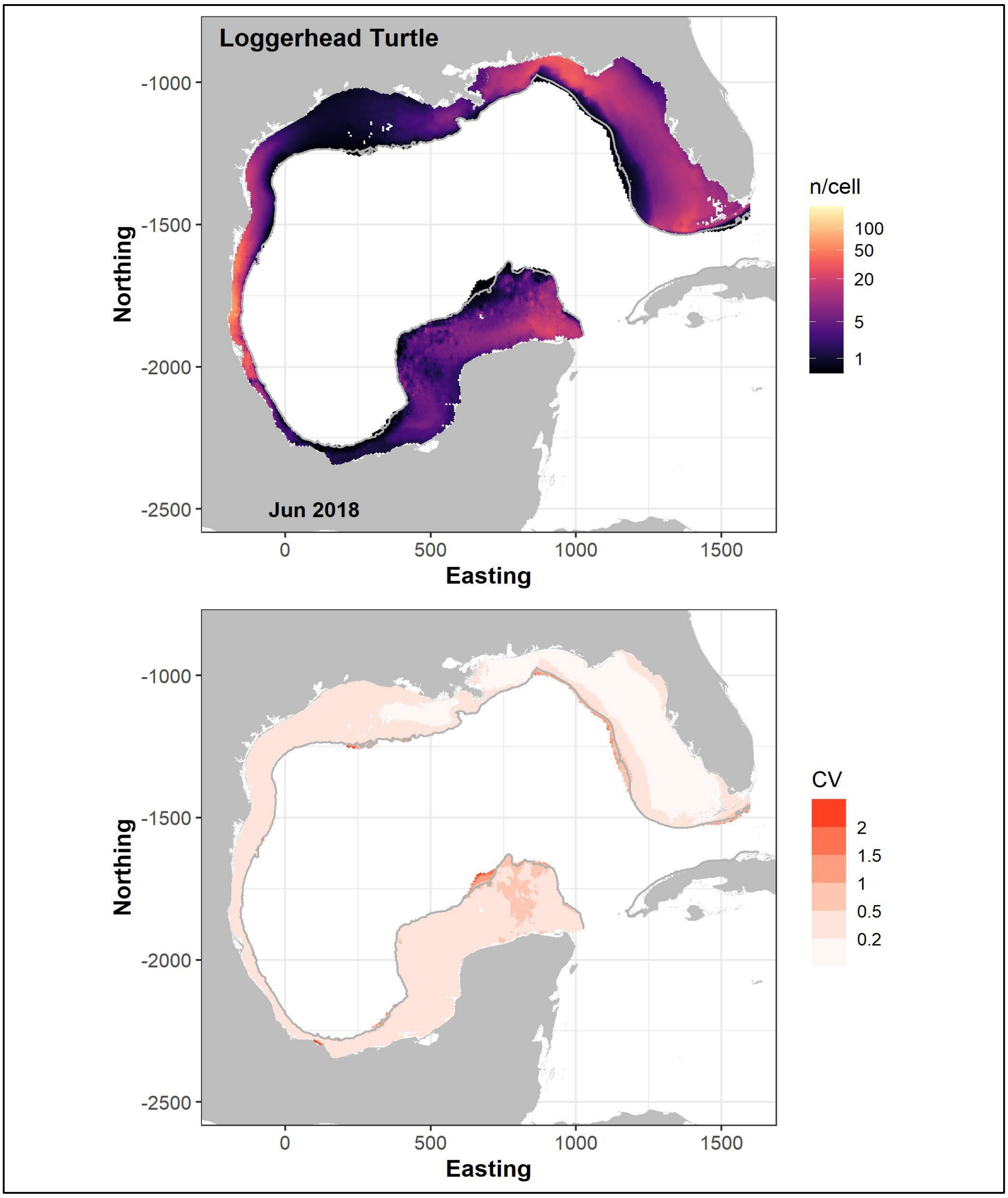

Figure D.4-43. Projected density model for shelf loggerhead turtles in the entire GOM for June 2018.

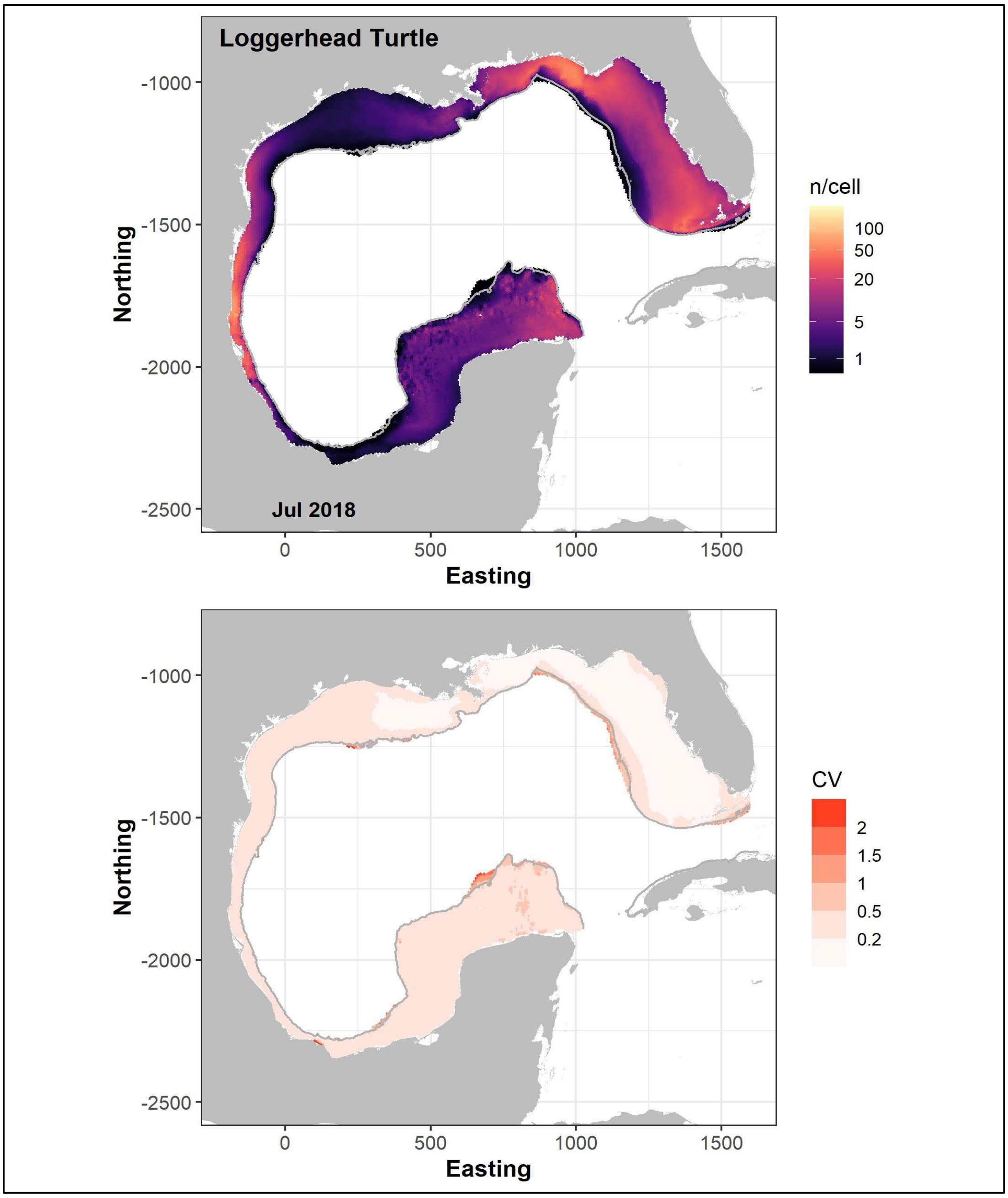

Figure D.4-44. Projected density model for shelf loggerhead turtles in the entire GOM for July 2018.

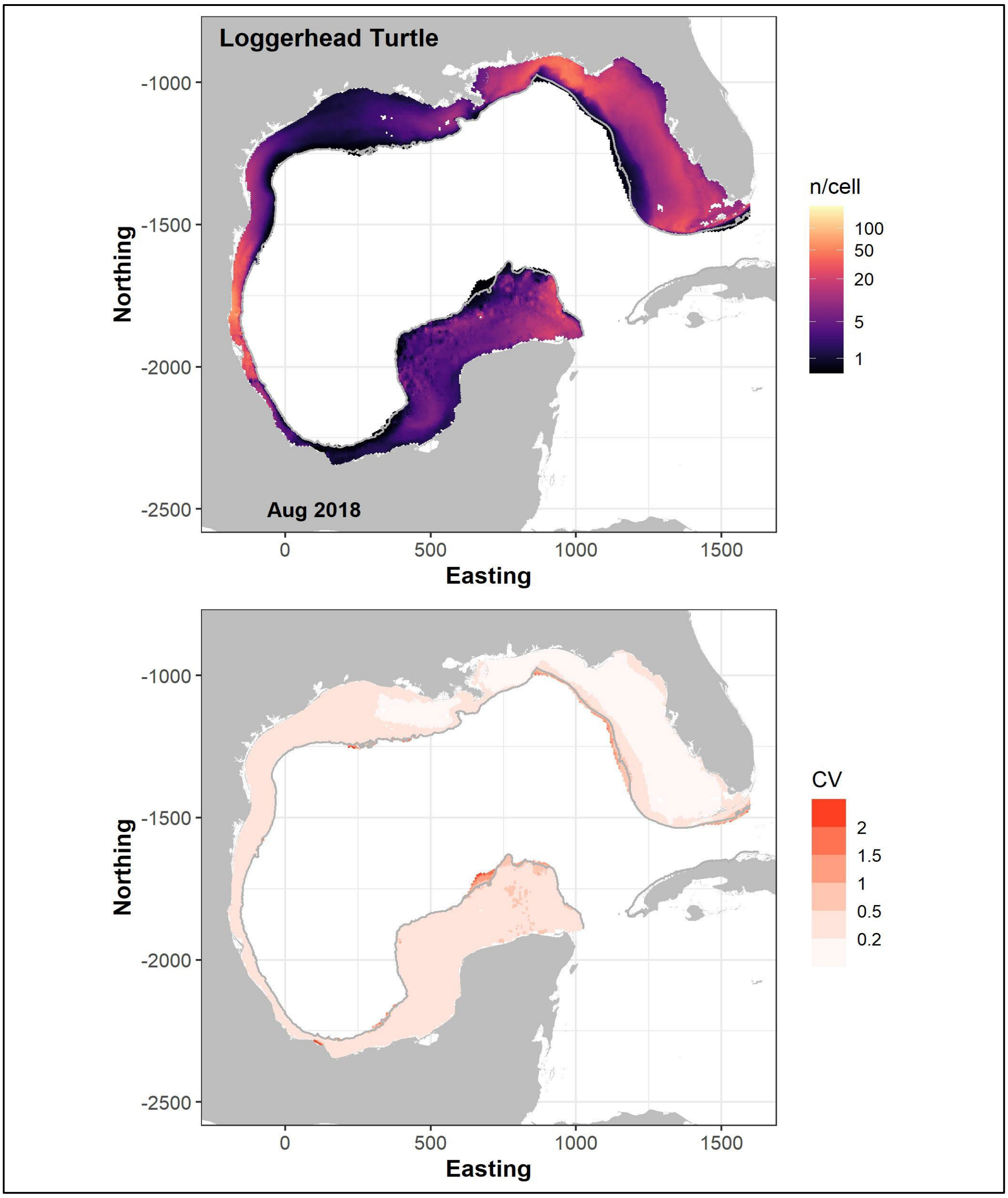

Figure D.4-45. Projected density model for shelf loggerhead turtles in the entire GOM for August 2018.

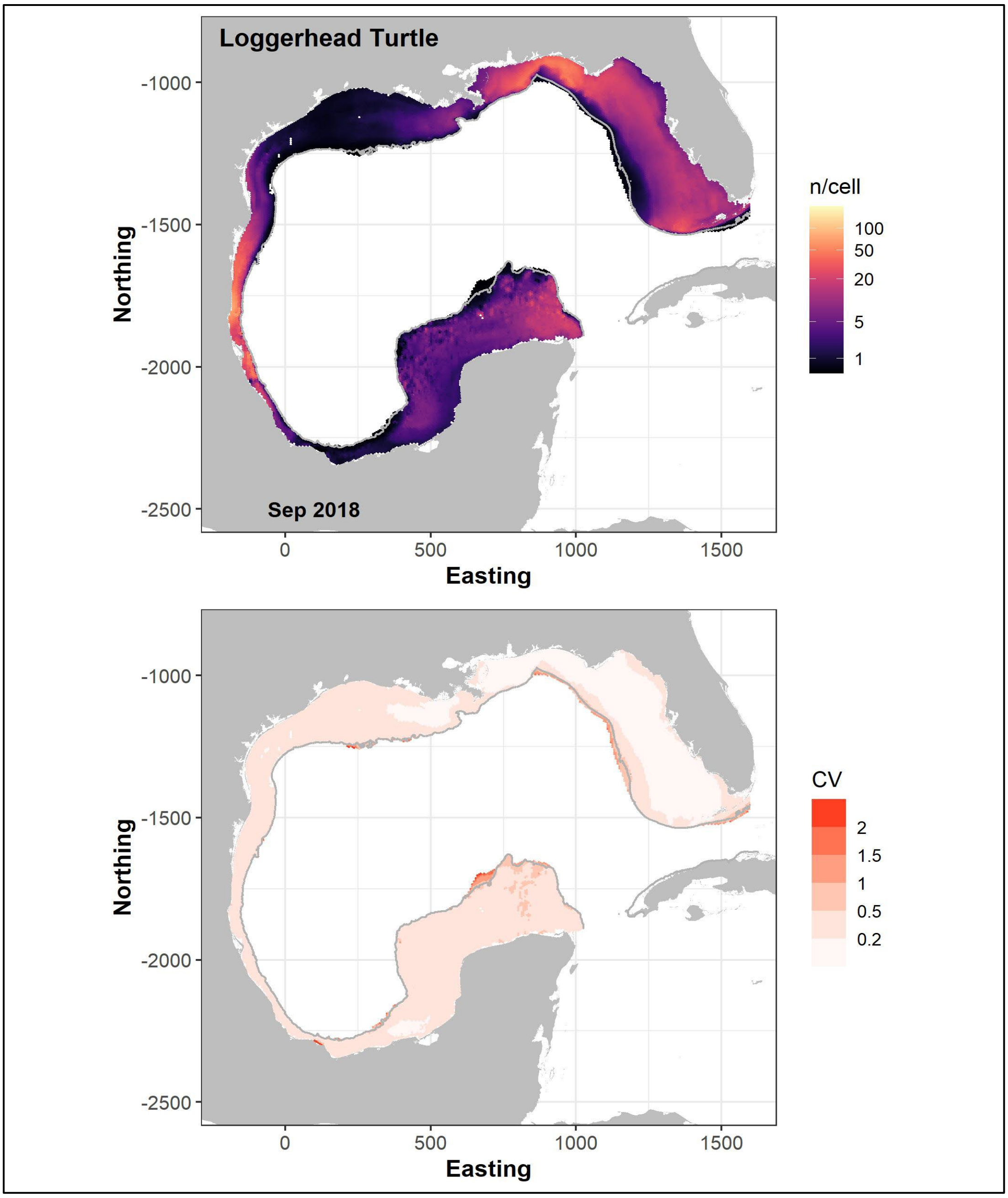

Figure D.4-46. Projected density model for shelf loggerhead turtles in the entire GOM for September 2018.

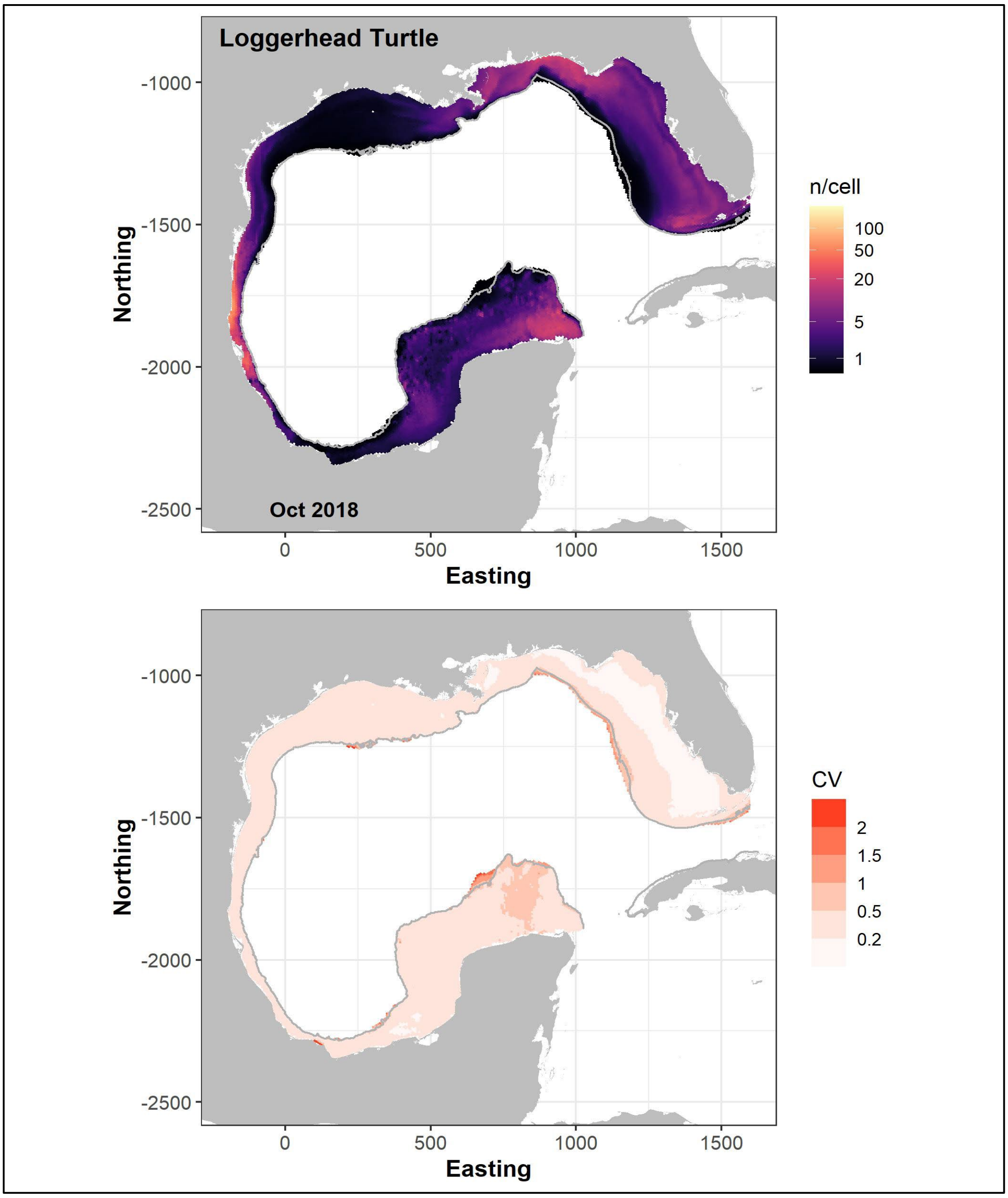

Figure D.4-47. Projected density model for shelf loggerhead turtles in the entire GOM for October 2018.

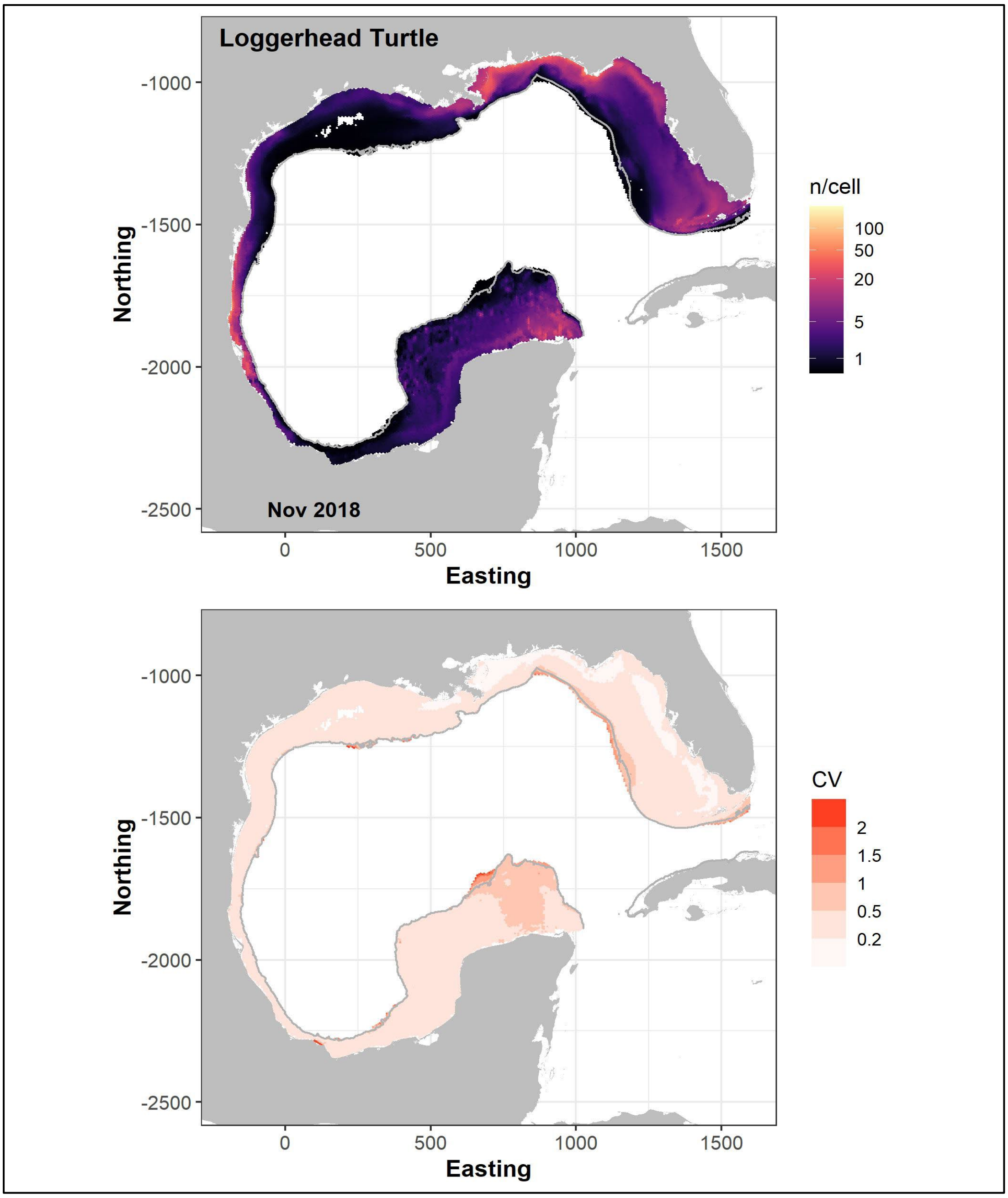

Figure D.4-48. Projected density model for shelf loggerhead turtles in the entire GOM for November 2018.

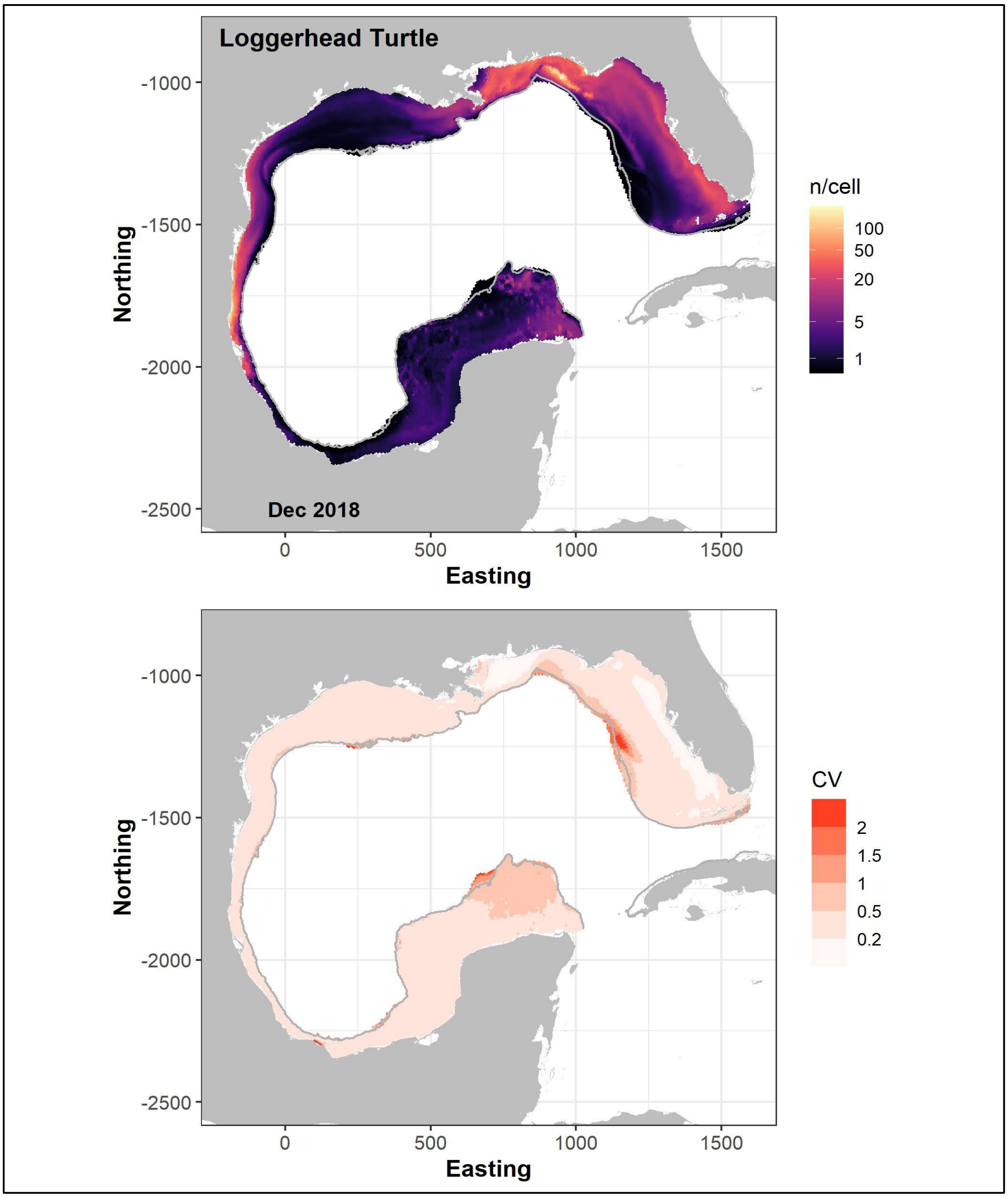

Figure D.4-49. Projected density model for shelf loggerhead turtles in the entire GOM for December 2018.

D.4.5.4 Average Monthly Density: 2015–2019

Prediction maps were generated using monthly environmental parameters for the period of 2015–2019. The posterior distribution of the GAM parameters was sampled 1,000 times to generate a distribution of model coefficients that reflect the statistical uncertainty in the parameter estimation. Predictions of animal density were generated for each month in the 2015–2019 period based on each of these 1,000 parameter sets. In this way, both inter-annual variability in environmental conditions and model uncertainty were included in the resulting samples. The monthly predictions were examined to identify sampled parameters that generated extreme predicted densities, and these extreme values

were excluded from the bootstrap sample before variance estimation. These extreme values, associated with density predictions many orders of magnitude higher than the observed median, reflect projection of the model predictions into poorly sampled parameter space. It was not necessary to trim the bootstrap iterations for loggerhead turtles. The resulting distribution of realizations was used to summarize predicted average densities by month and to calculate metrics of uncertainty. The average monthly abundance for loggerhead turtles in US waters is shown in Table D.4-5 (Figures D.4-50–D.4-61).

Table D.4-5. Monthly average abundance of loggerhead turtles in US shelf waters 2015–2019

Month	Abundance	CV
January	212,969	0.118
February	290,745	0.171
March	287,518	0.124
April	241,691	0.120
May	161,423	0.091
June	151,651	0.102
July	194,732	0.086
August	197,310	0.098
September	152,951	0.172
October	86,867	0.107
November	105,809	0.105
December	172,305	0.110

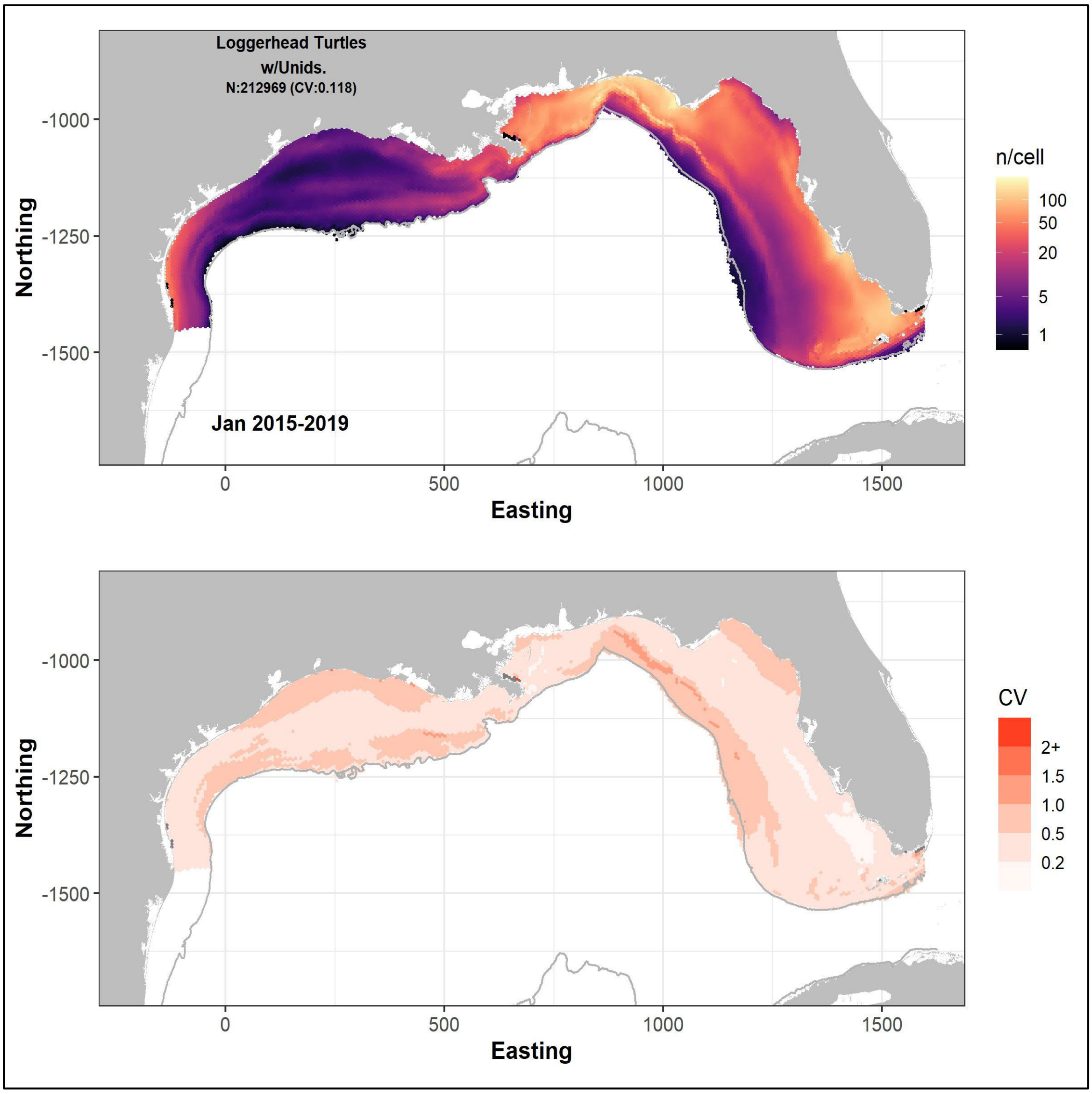

Figure D.4-50. Density model prediction for shelf loggerhead turtles in the NGOM for the months of January 2015–2019.

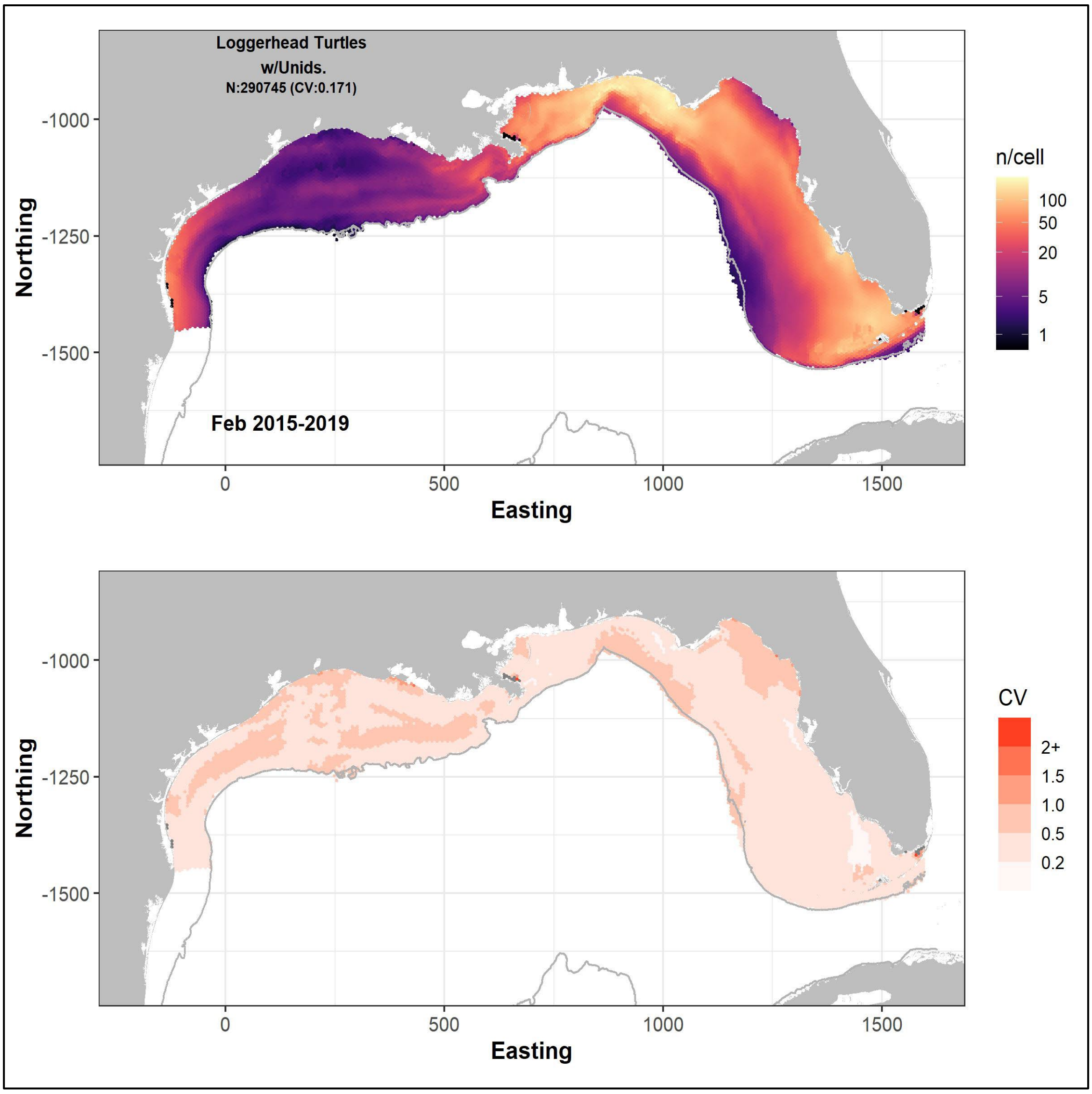

Figure D.4-51. Density model prediction for shelf loggerhead turtles in the NGOM for the months of February 2015–2019.

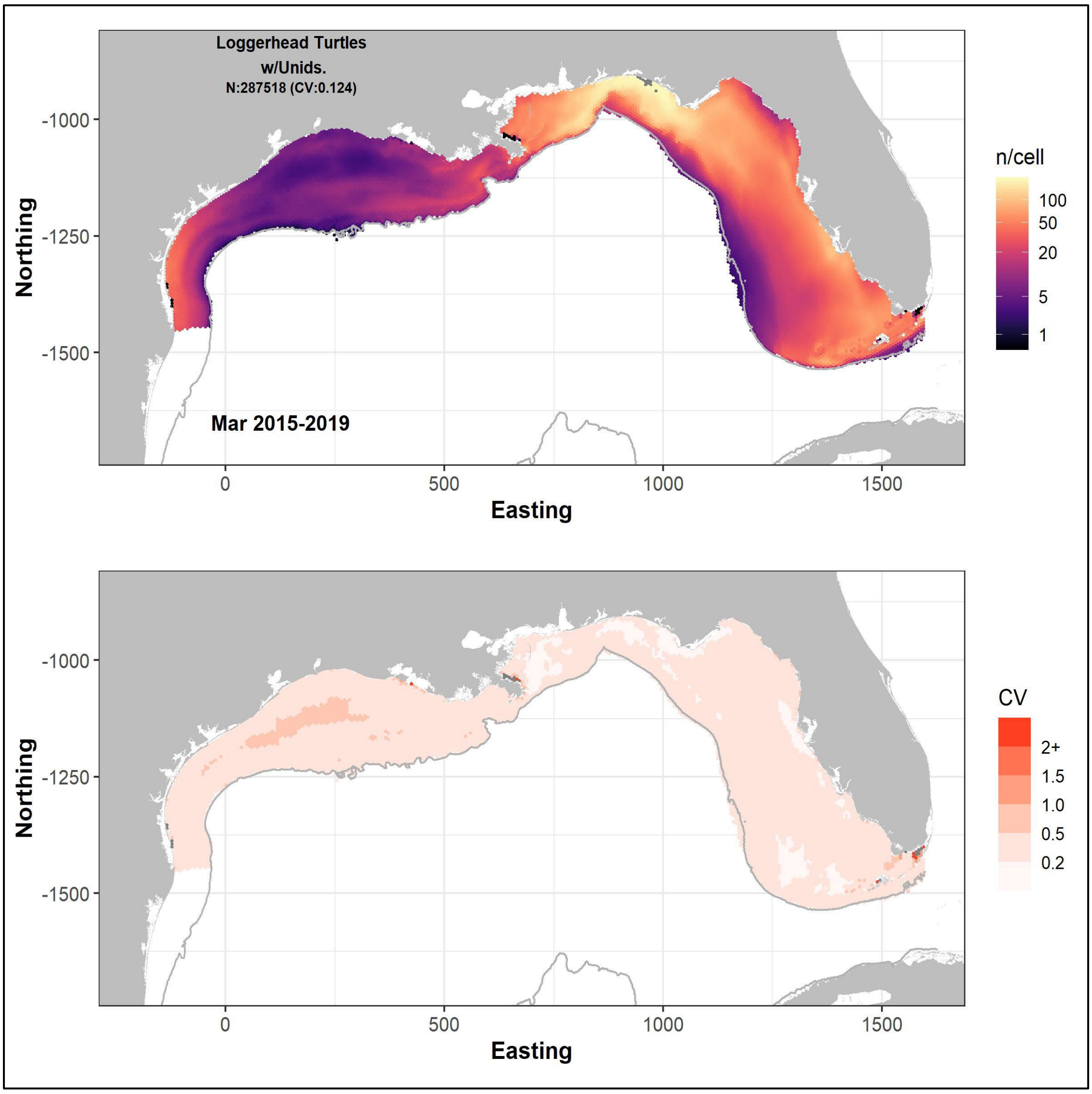

Figure D.4-52. Density model prediction for shelf loggerhead turtles in the NGOM for the months of March 2015–2019.

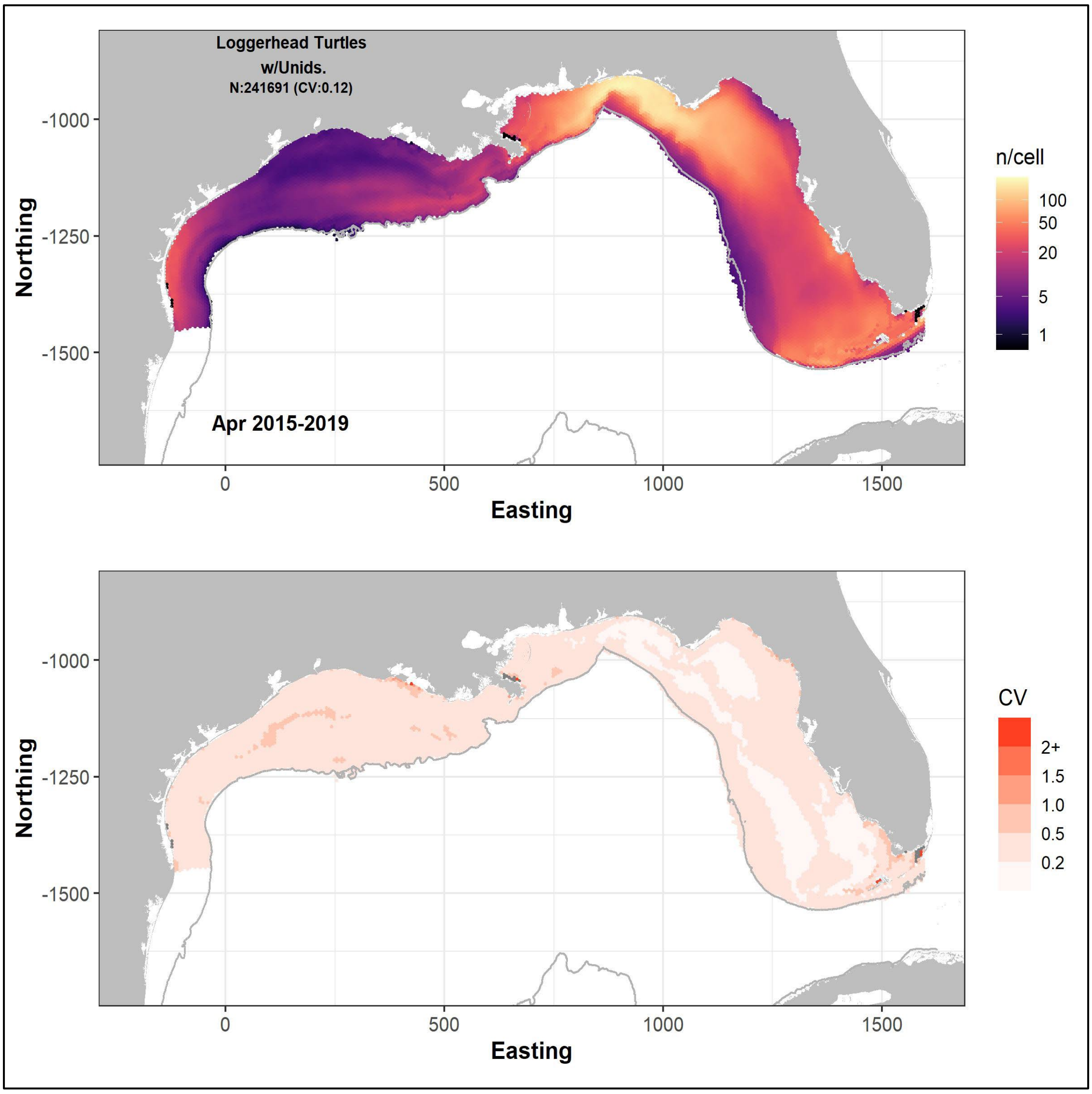

Figure D.4-53. Density model prediction for shelf loggerhead turtles in the NGOM for the months of April 2015–2019.

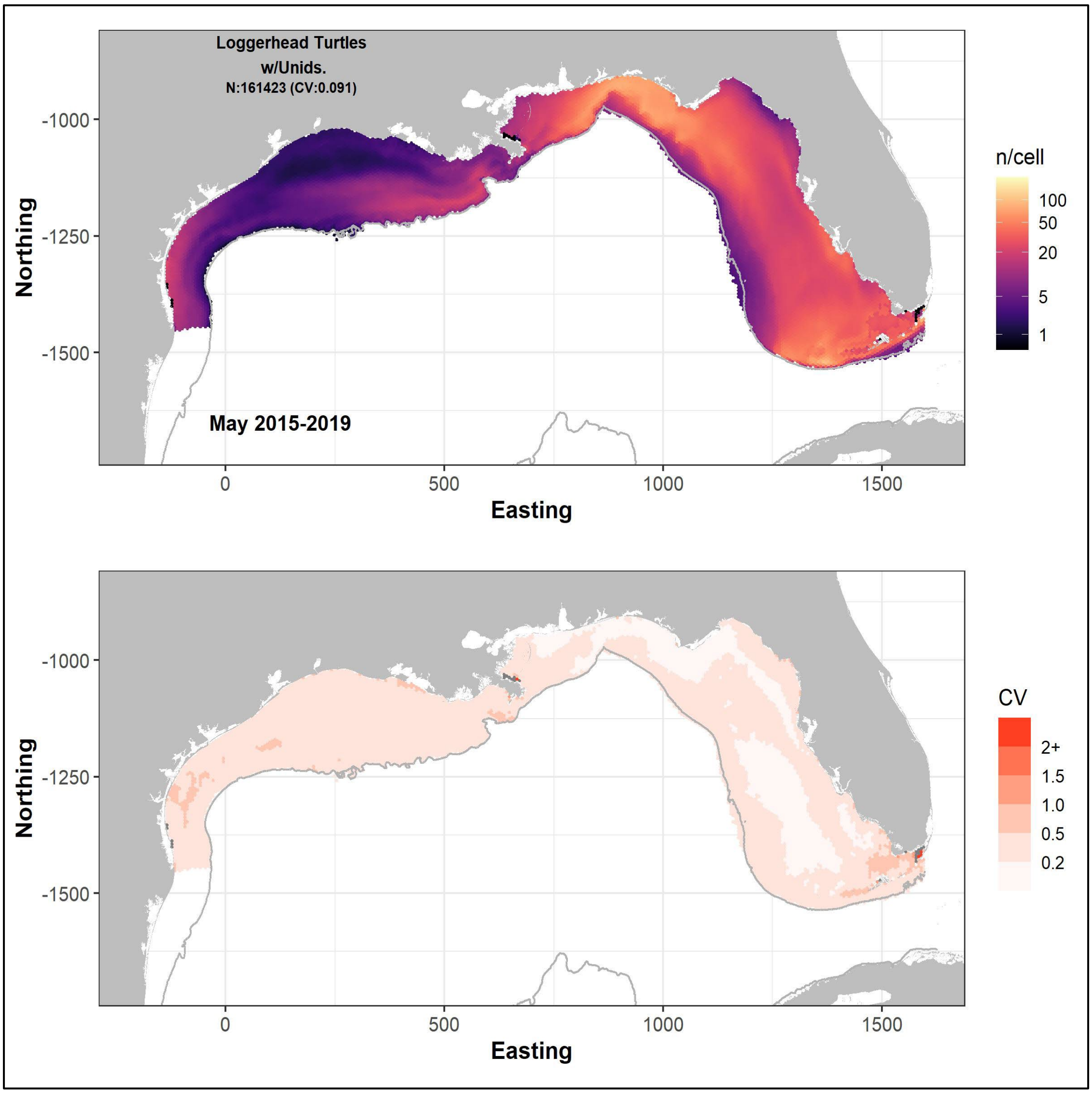

Figure D.4-54. Density model prediction for shelf loggerhead turtles in the NGOM for the months of May 2015–2019.

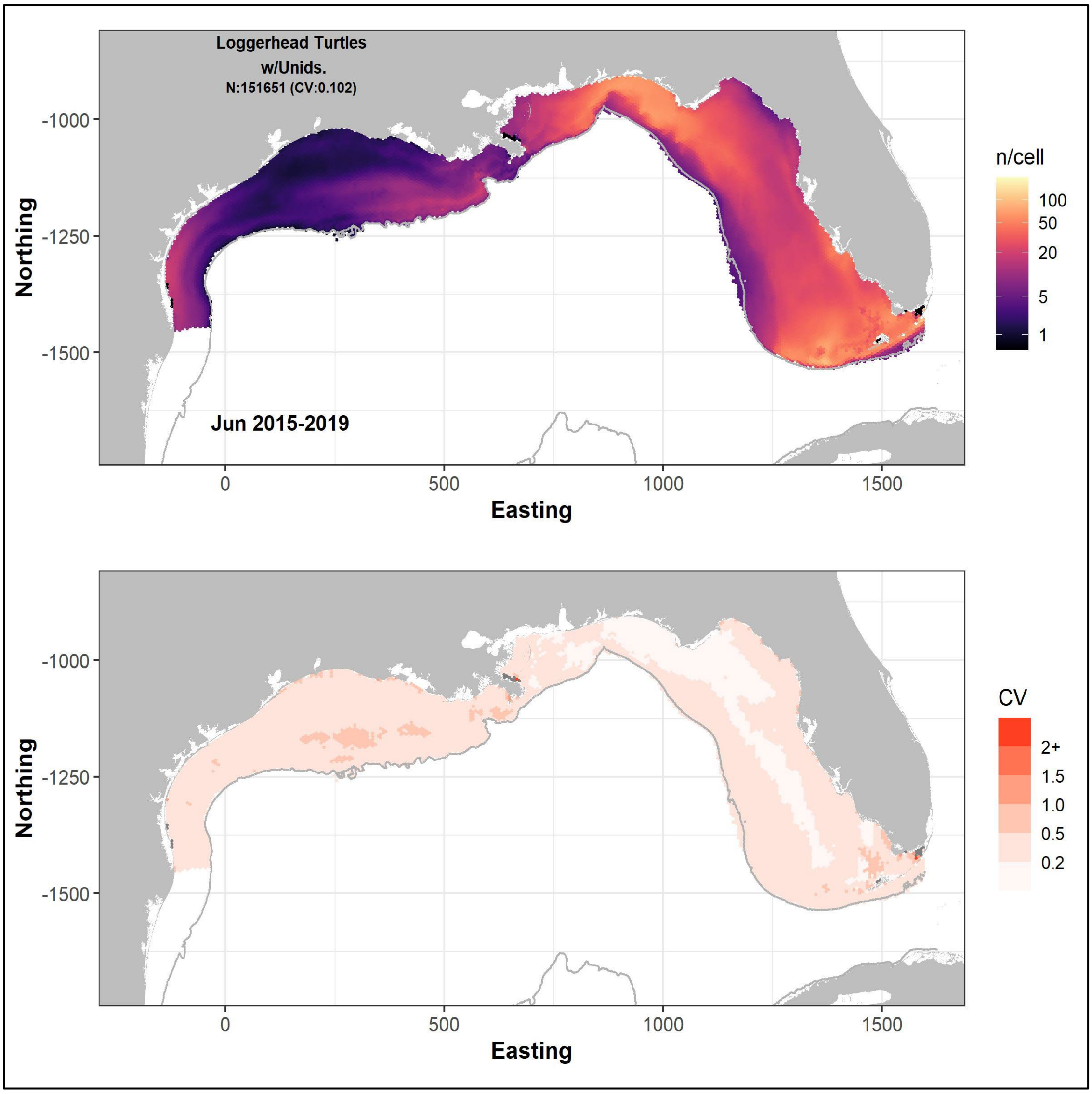

Figure D.4-55. Density model prediction for shelf loggerhead turtles in the NGOM for the months of June 2015–2019.

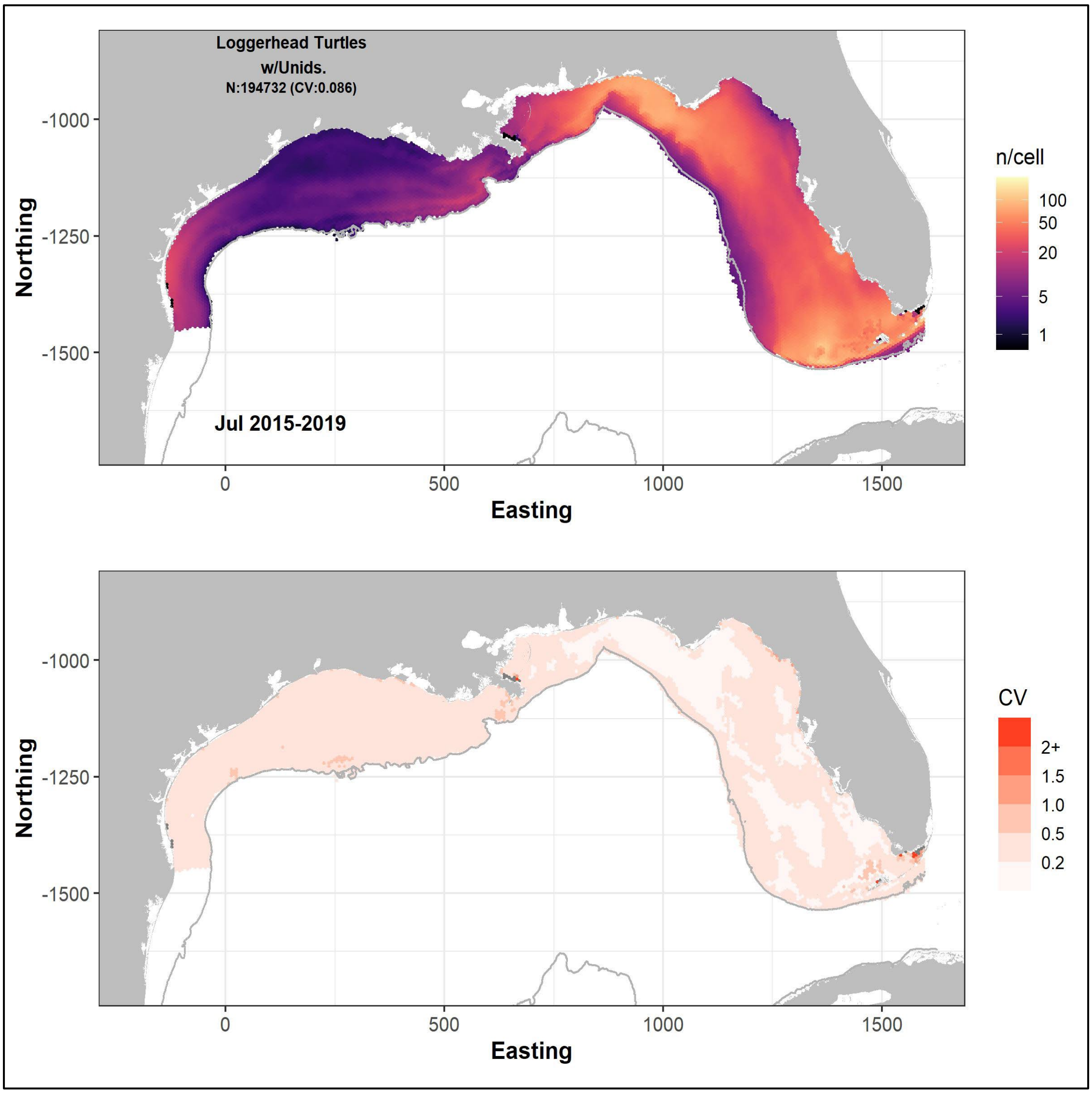

Figure D.4-56. Density model prediction for shelf loggerhead turtles in the NGOM for the months of July 2015–2019.

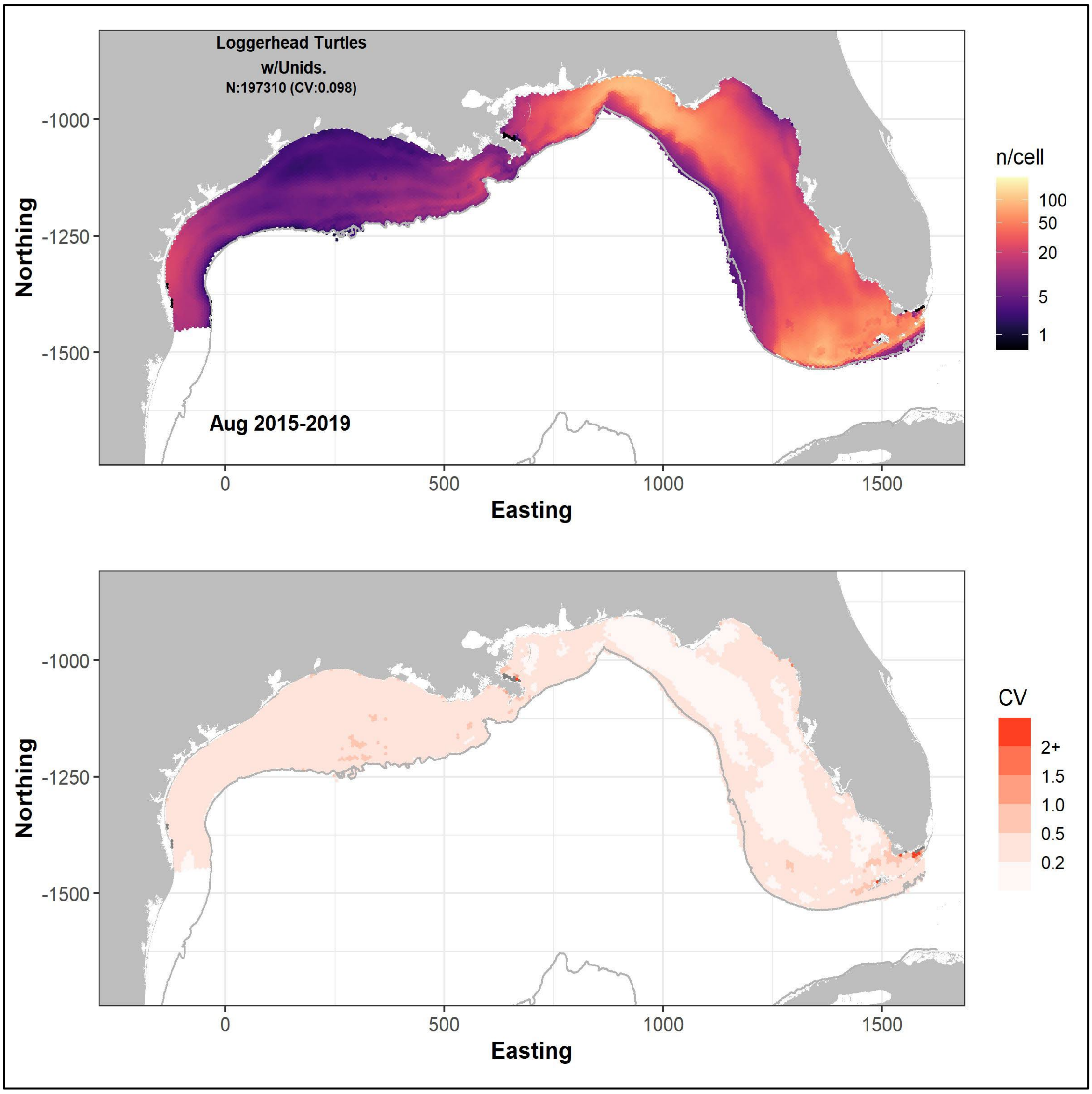

Figure D.4-57. Density model prediction for shelf loggerhead turtles in the NGOM for the months of August 2015–2019.

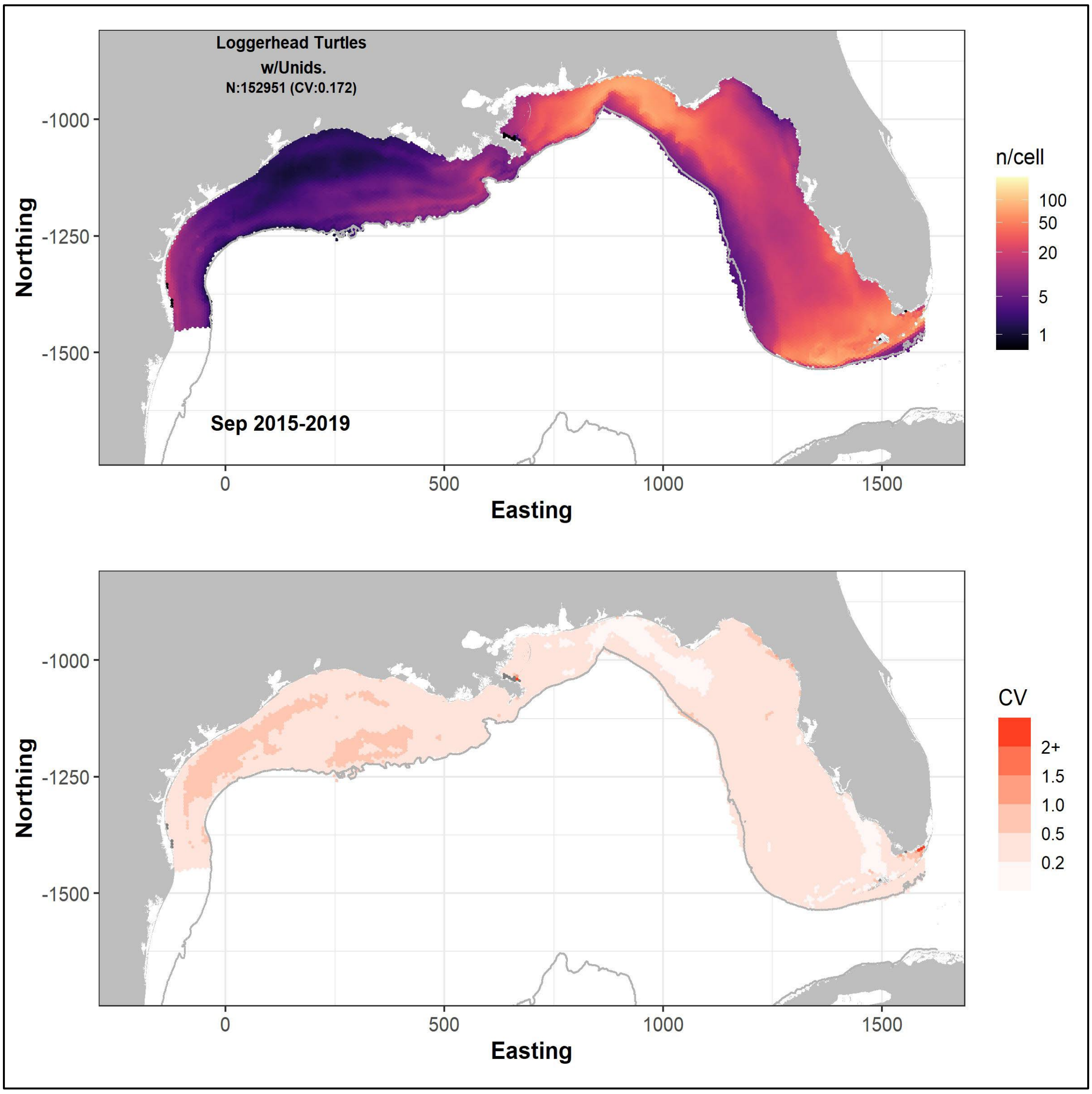

Figure D.4-58. Density model prediction for shelf loggerhead turtles in the NGOM for the months of September 2015–2019.

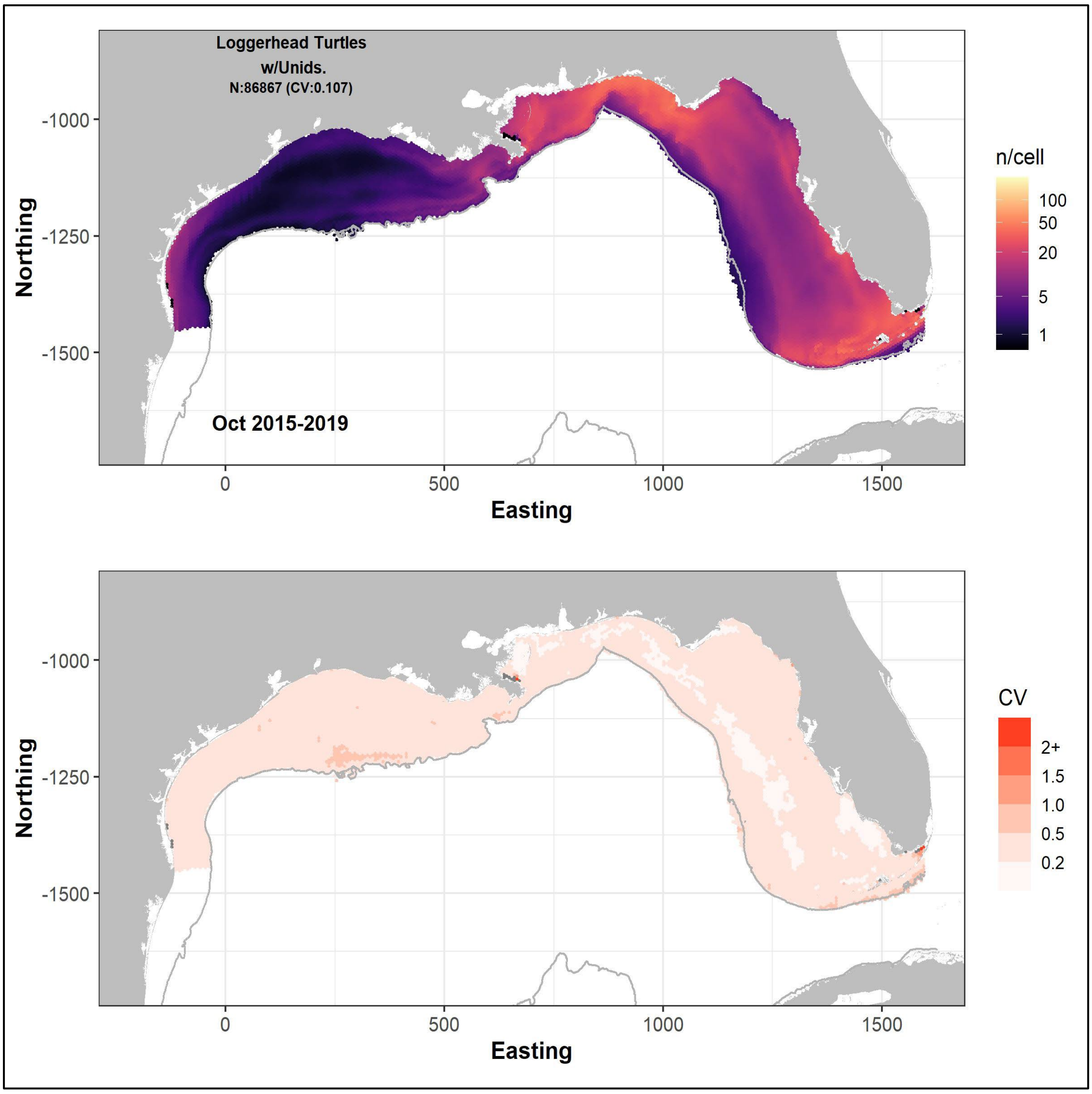

Figure D.4-59. Density model prediction for shelf loggerhead turtles in the NGOM for the months of October 2015–2019.

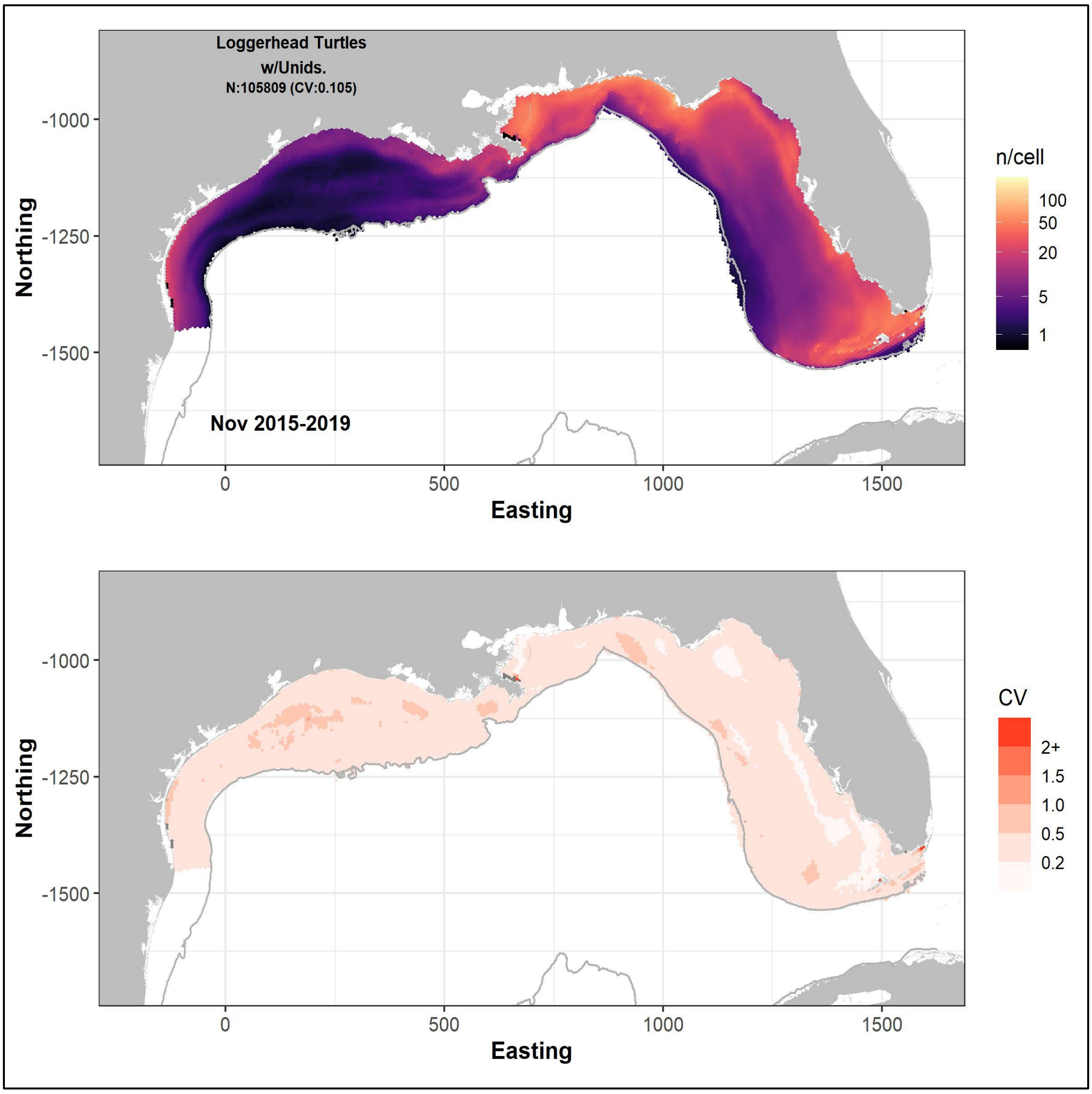

Figure D.4-60. Density model prediction for shelf loggerhead turtles in the NGOM for the months of November 2015–2019.

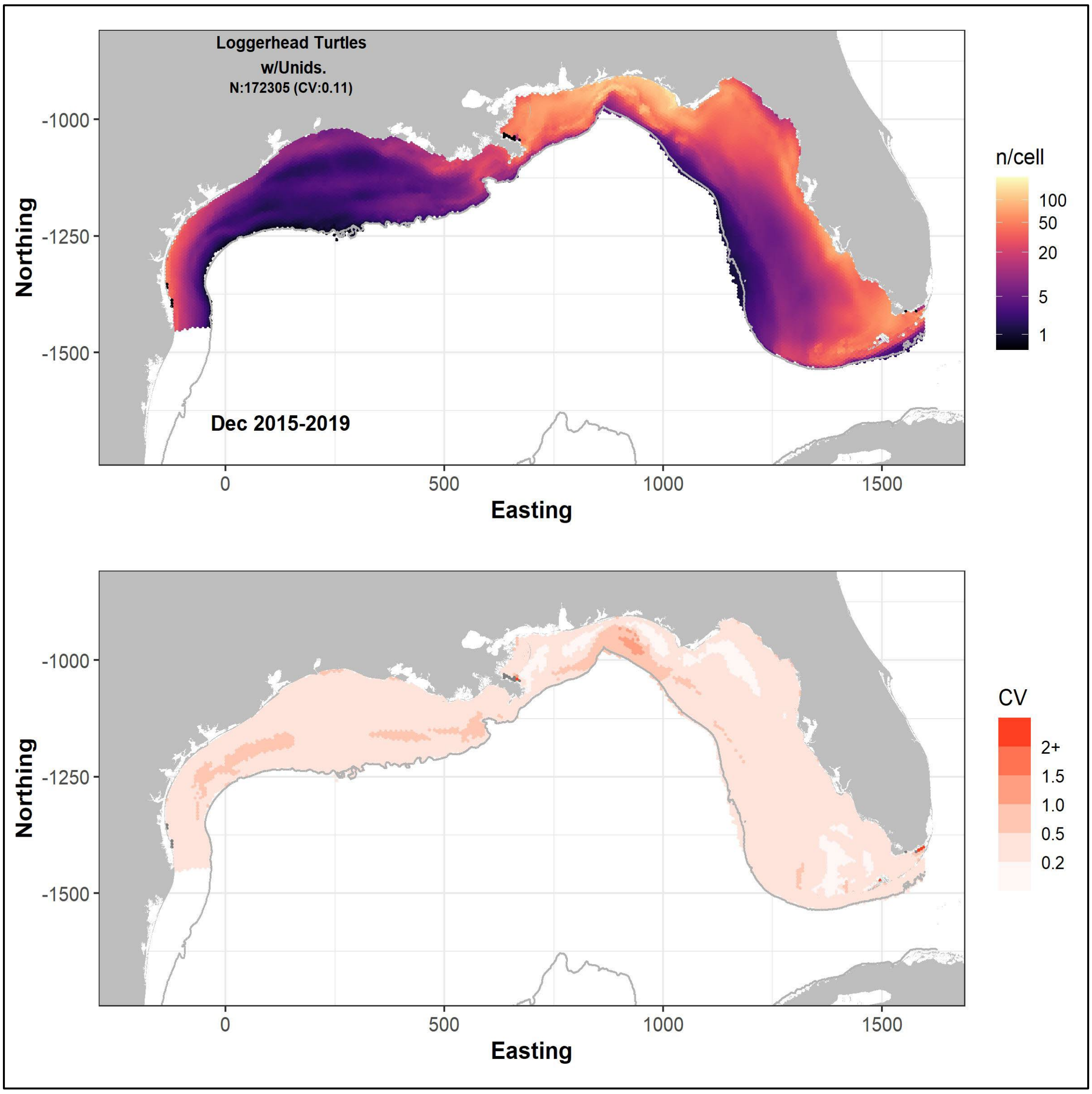

Figure D.4-61. Density model prediction for shelf loggerhead turtles in the NGOM for the months of December 2015–2019.

The density models for loggerhead turtles were summarized seasonally (Winter: Dec–Feb, Spring: Mar–May, Summer: Jun–Aug, Fall: Sep–Nov) and by Bureau of Ocean Energy Management (BOEM) planning area to generate abundance and CVs that reflect uncertainty in both model parameters and inter-annual variation in environmental conditions for each area (Table D.4-6).

Table D.4-6. Seasonal abundance (CV) of loggerhead turtles in US shelf waters during 2015–2019 for BOEM planning areas

Season	Eastern	Central	Western
Winter	125,320 (0.34)	29,617 (0.22)	8,905 (0.36)
Spring	144,202 (0.24)	27,636 (0.3)	9,935 (0.4)
Summer	118,221 (0.16)	16,876 (0.22)	7,665 (0.31)
Fall	65,652 (0.36)	14,535 (0.27)	4,206 (0.36)

D.4.5.5 Gulf-Wide Average Monthly Density: 2015–2019

Prediction maps were generated using monthly environmental parameters for the period of 2015–2019 extrapolating the model for loggerhead turtles throughout the GOM. As noted above, these extrapolations should be treated with caution given the potential for changing species-environment relationships in unsampled areas (Figures D.4-62–D.4-73).

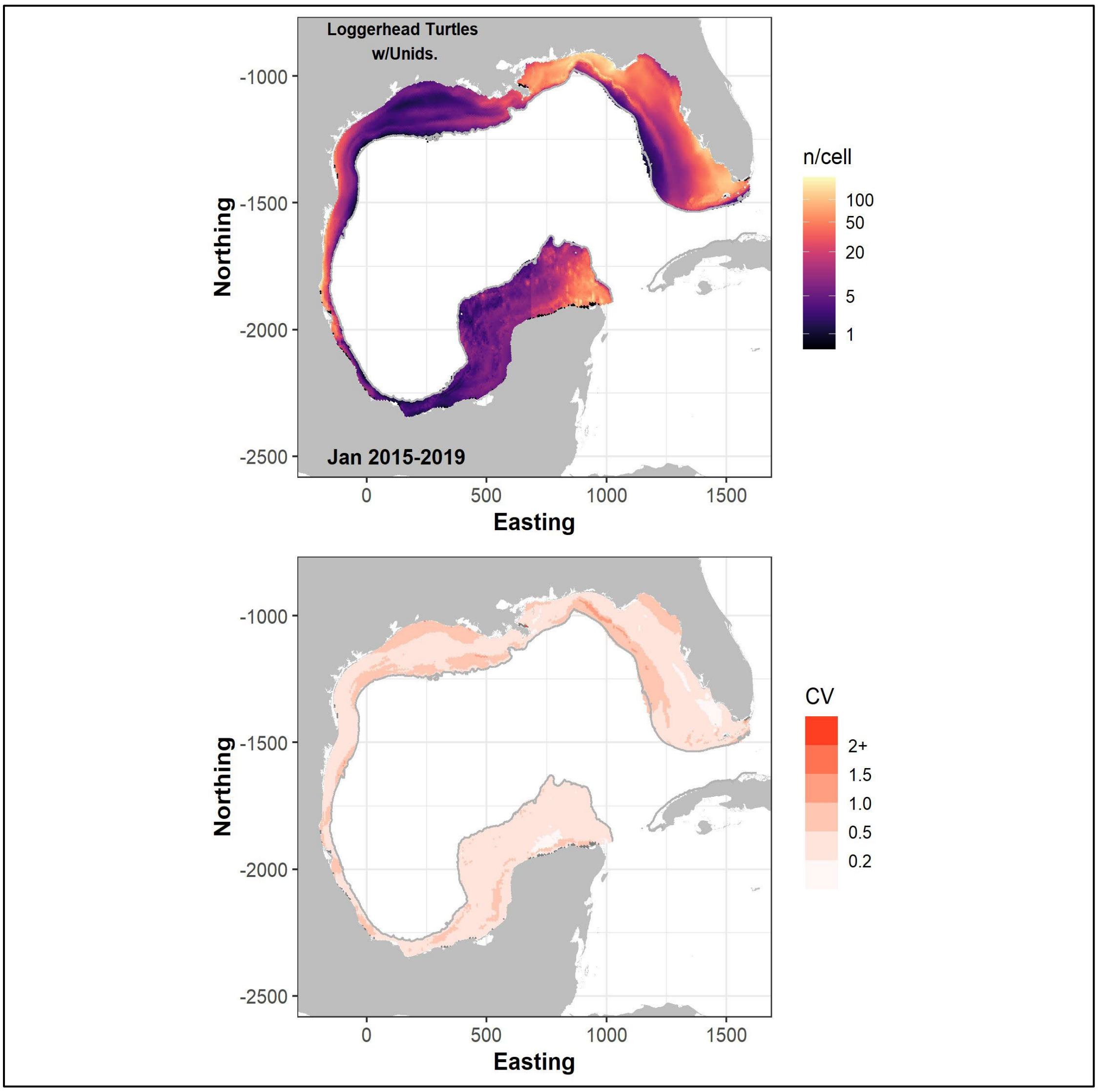

Figure D.4-62. Projected density model for shelf loggerhead turtles in the entire GOM for the months of January 2015–2019.

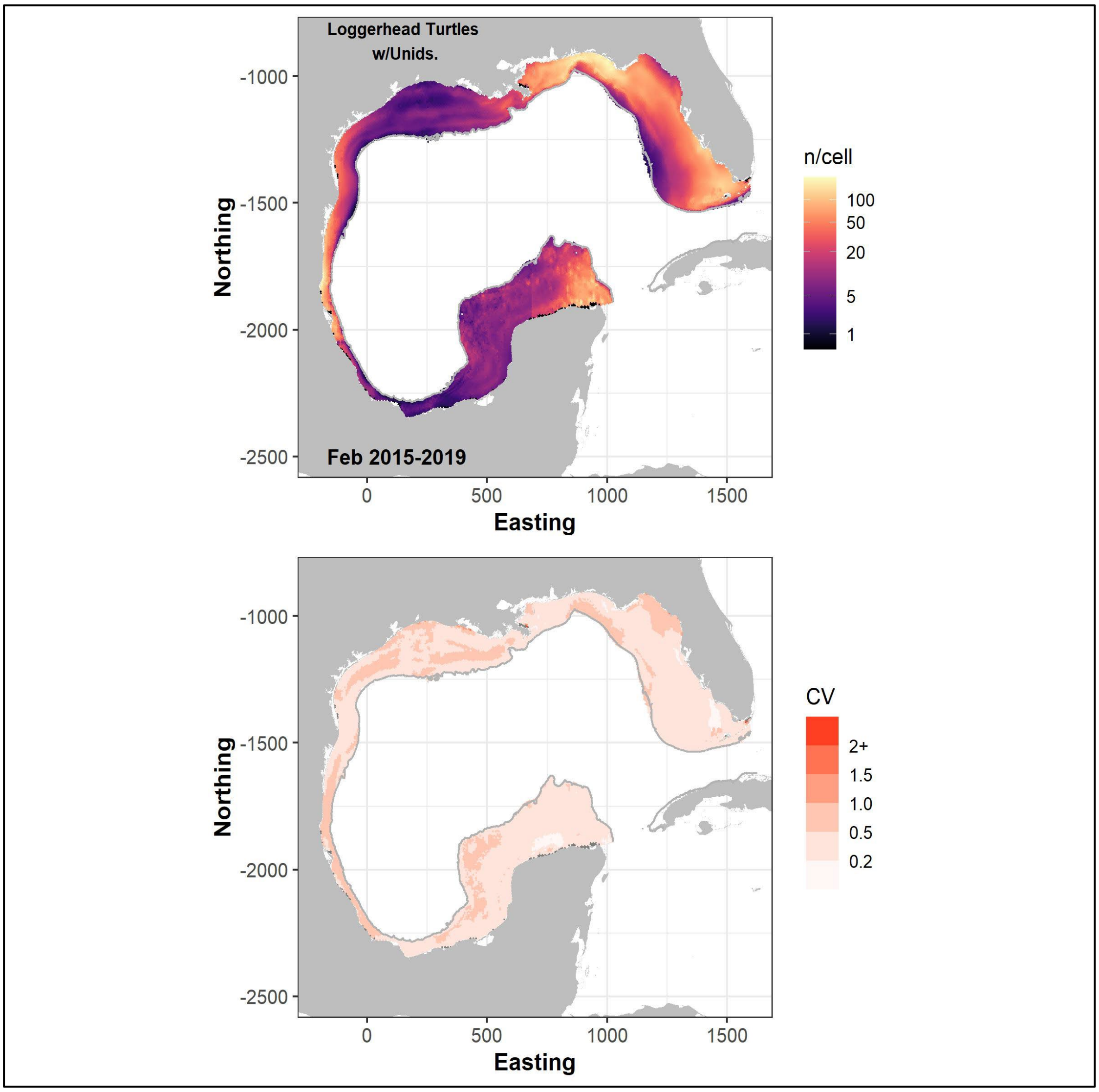

Figure D.4-63. Projected density model for shelf loggerhead turtles in the entire GOM for the months of February 2015–2019.

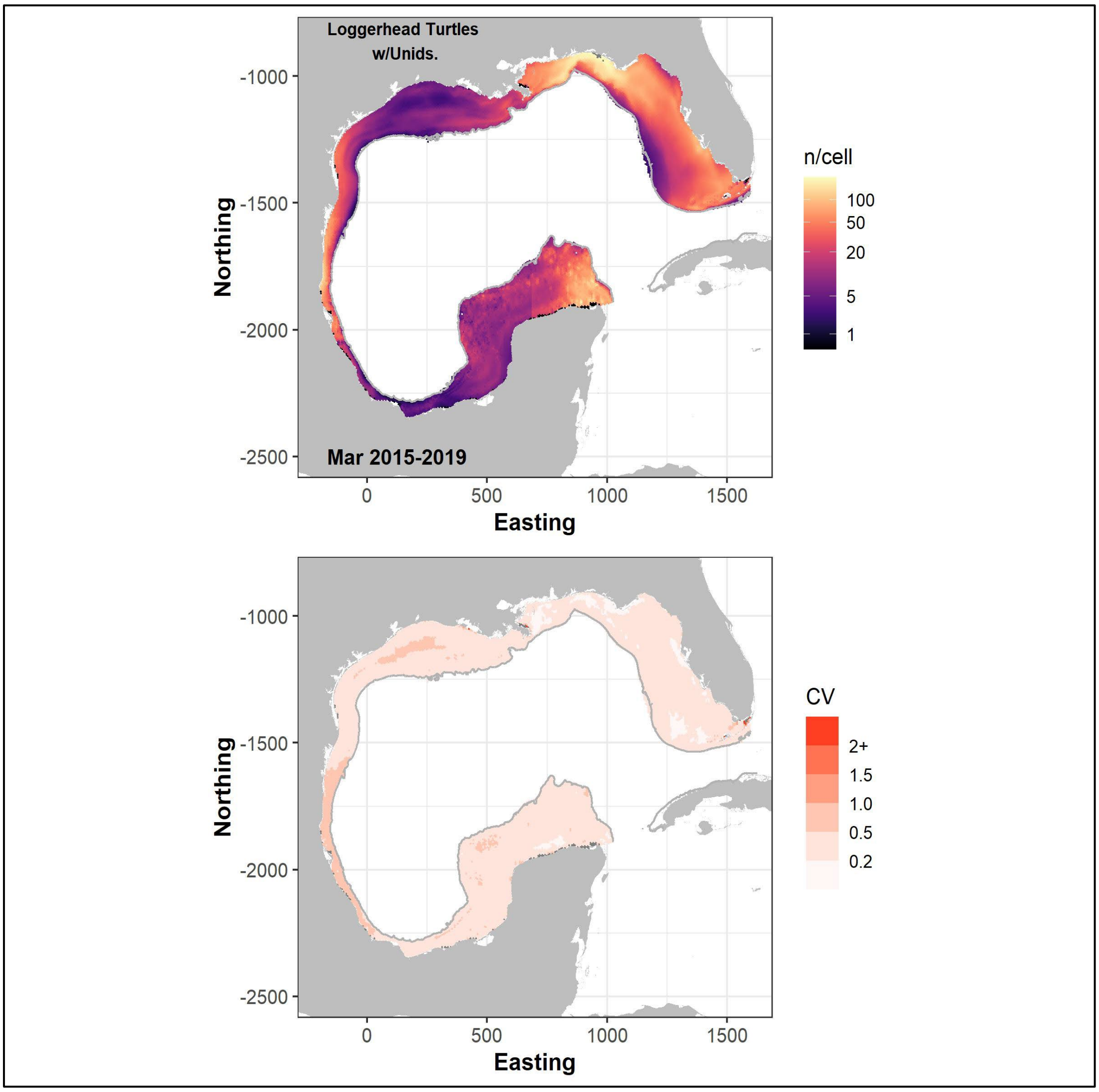

Figure D.4-64. Projected density model for shelf loggerhead turtles in the entire GOM for the months of March 2015–2019.

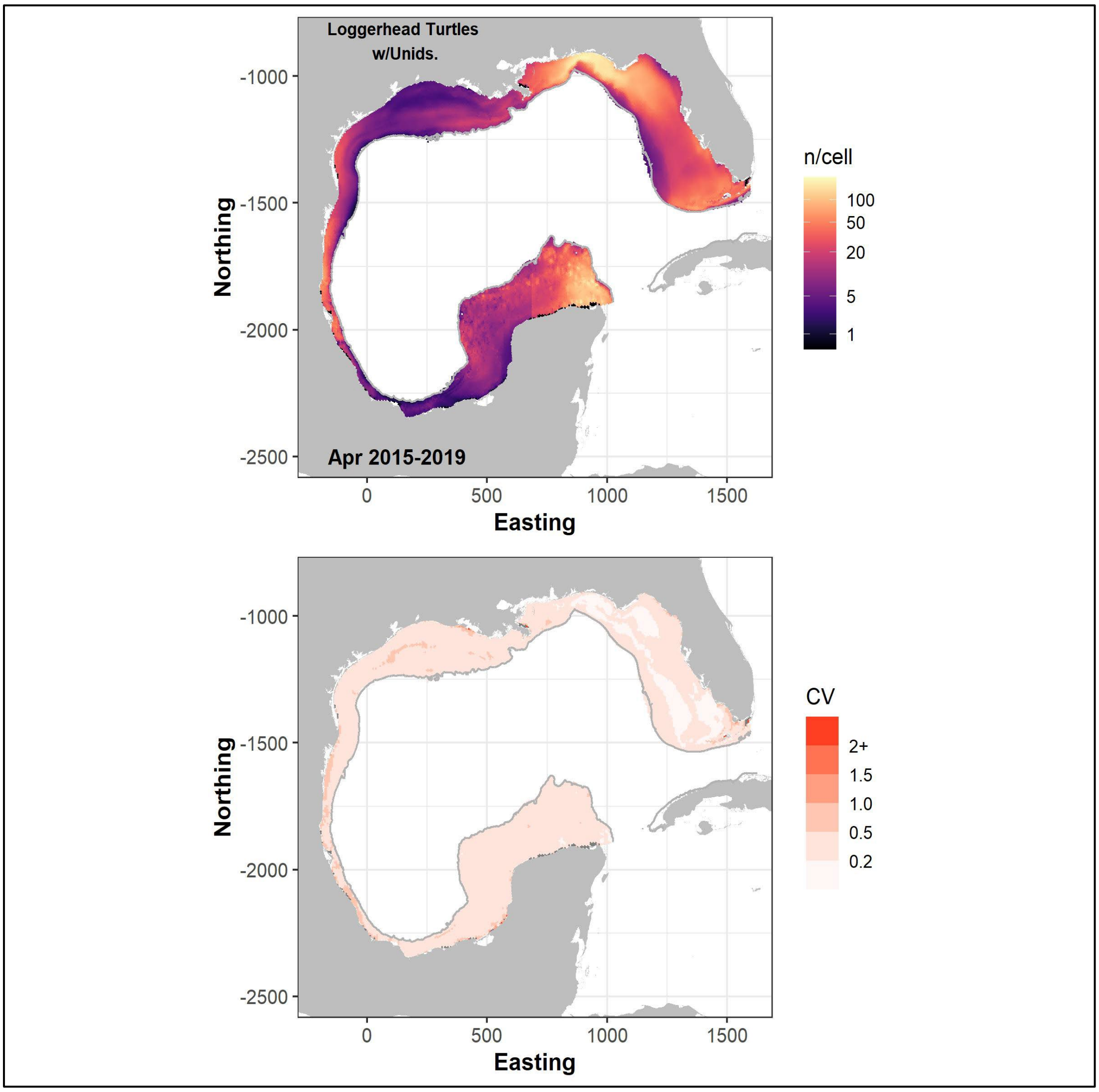

Figure D.4-65. Projected density model for shelf loggerhead turtles in the entire GOM for the months of April 2015–2019.

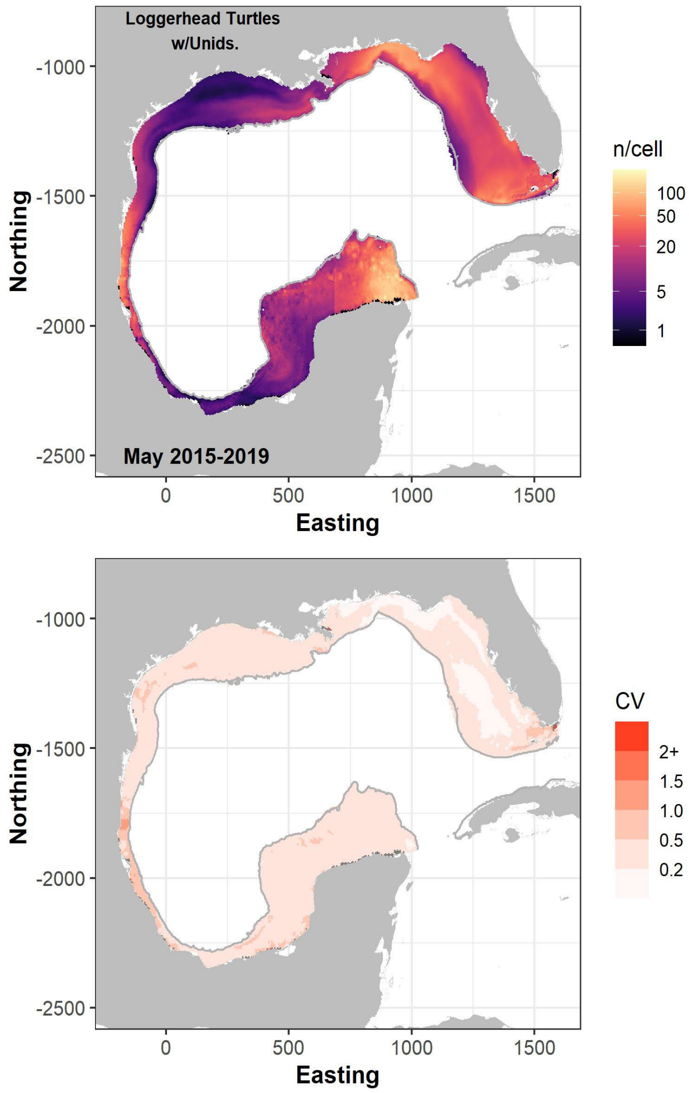

Figure D.4-66. Projected density model for shelf loggerhead turtles in the entire GOM for the months of May 2015–2019.

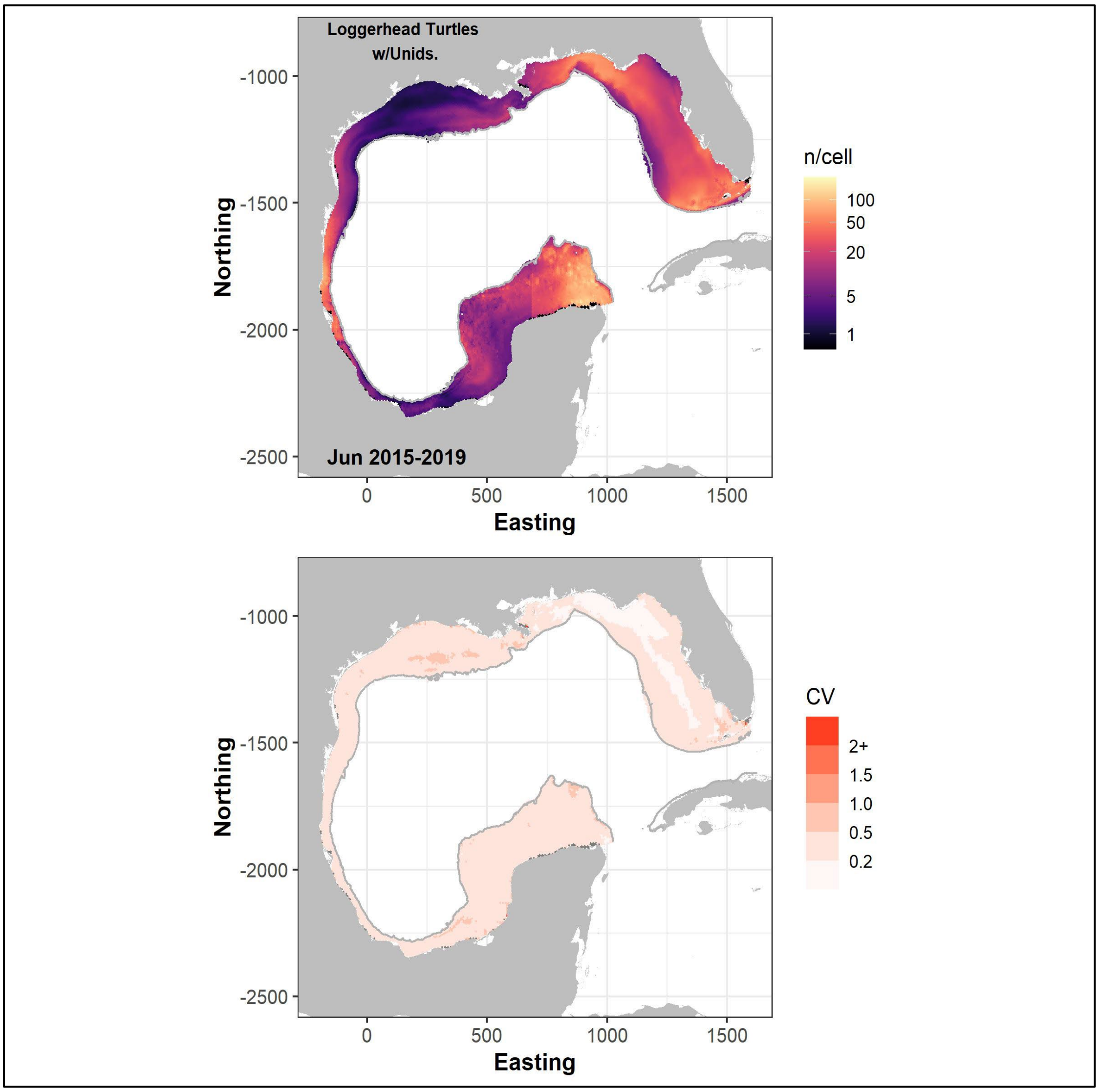

Figure D.4-67. Projected density model for shelf loggerhead turtles in the entire GOM for the months of June 2015–2019.

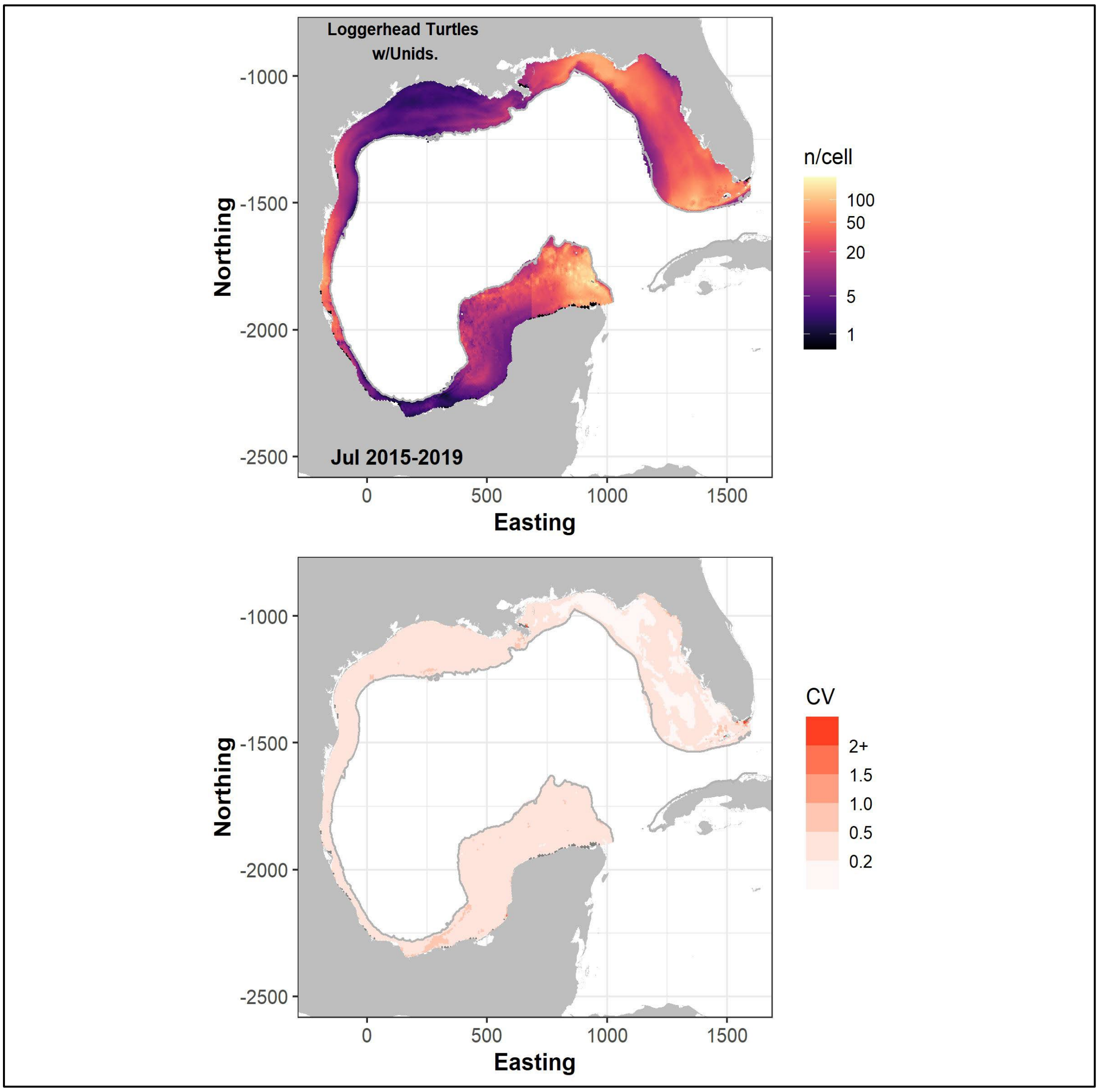

Figure D.4-68. Projected density model for shelf loggerhead turtles in the entire GOM for the months of July 2015–2019.

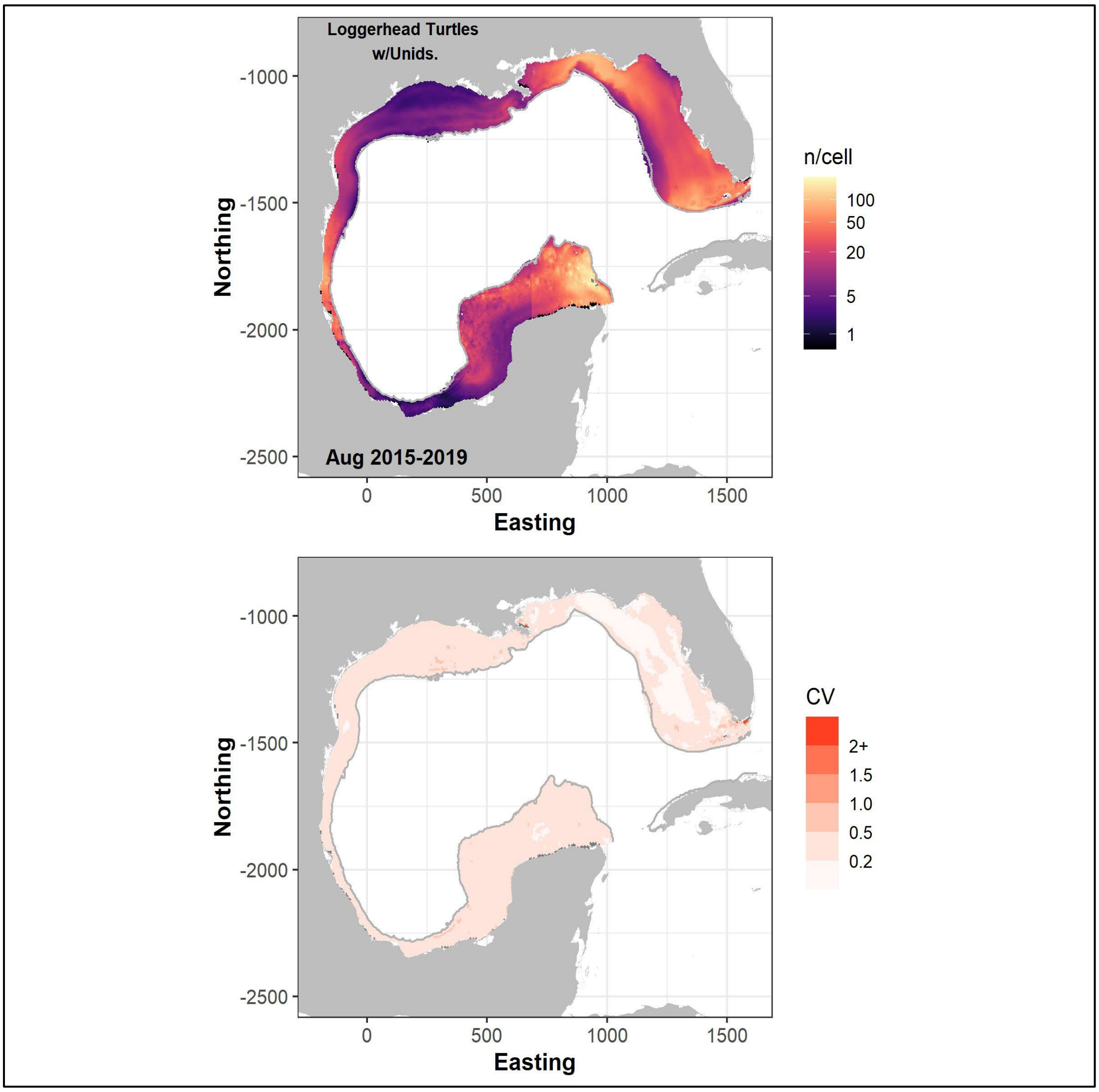

Figure D.4-69. Projected density model for shelf loggerhead turtles in the entire GOM for the months of August 2015–2019.

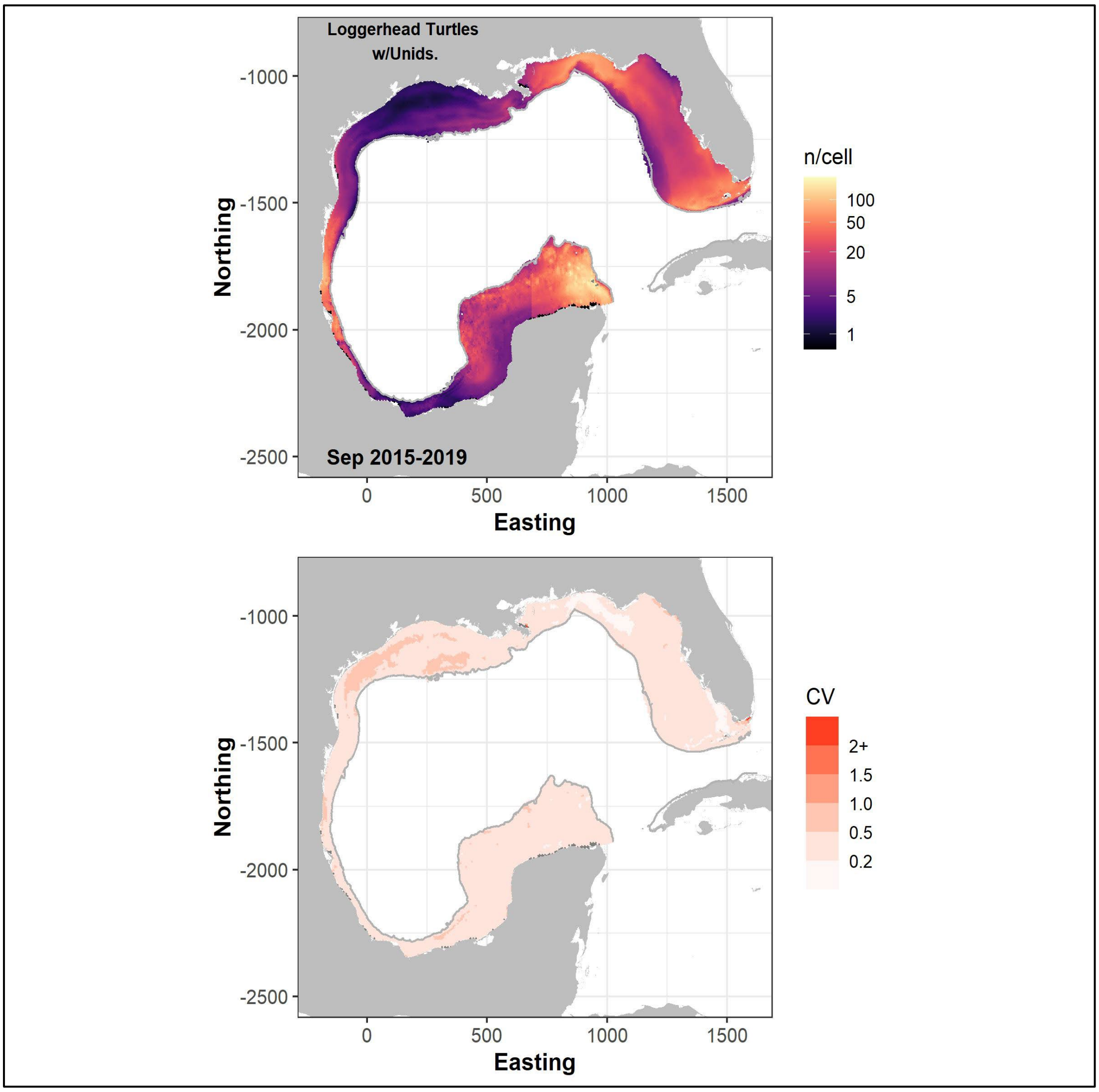

Figure D.4-70. Projected density model for shelf loggerhead turtles in the entire GOM for the months of September 2015–2019.

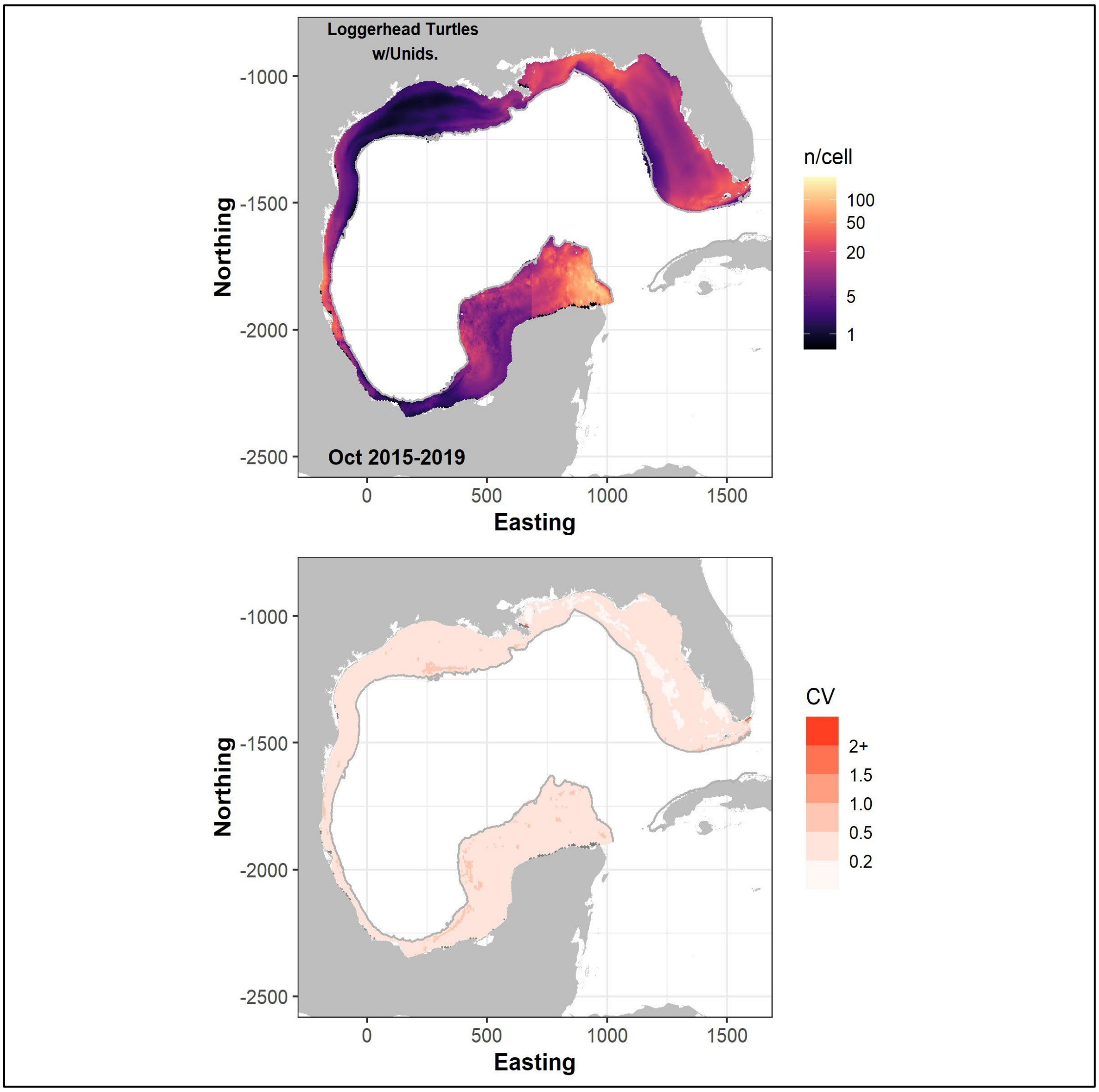

Figure D.4-71. Projected density model for shelf loggerhead turtles in the entire GOM for the months of October 2015–2019.

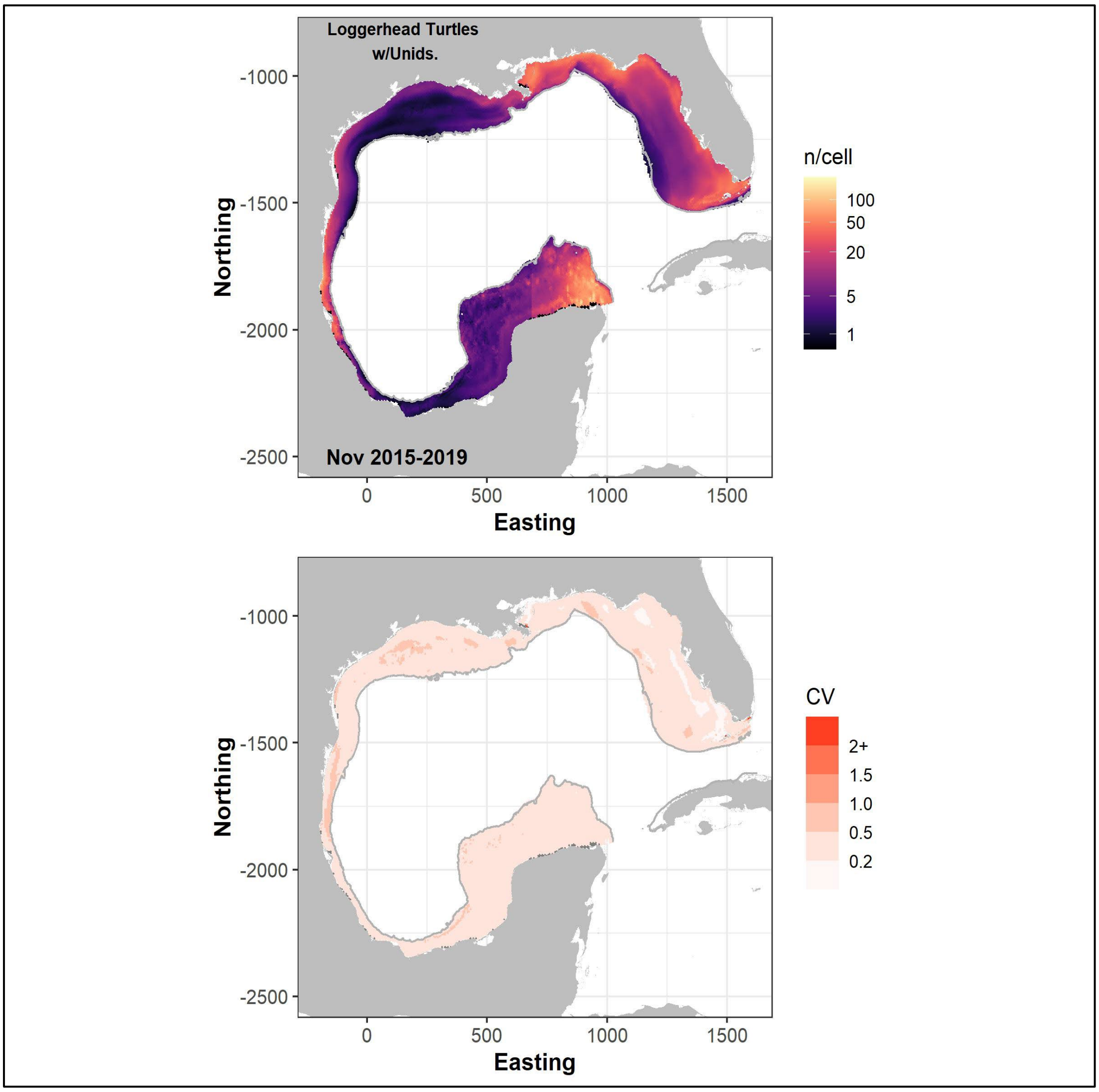

Figure D.4-72. Projected density model for shelf loggerhead turtles in the entire GOM for the months of November 2015–2019.

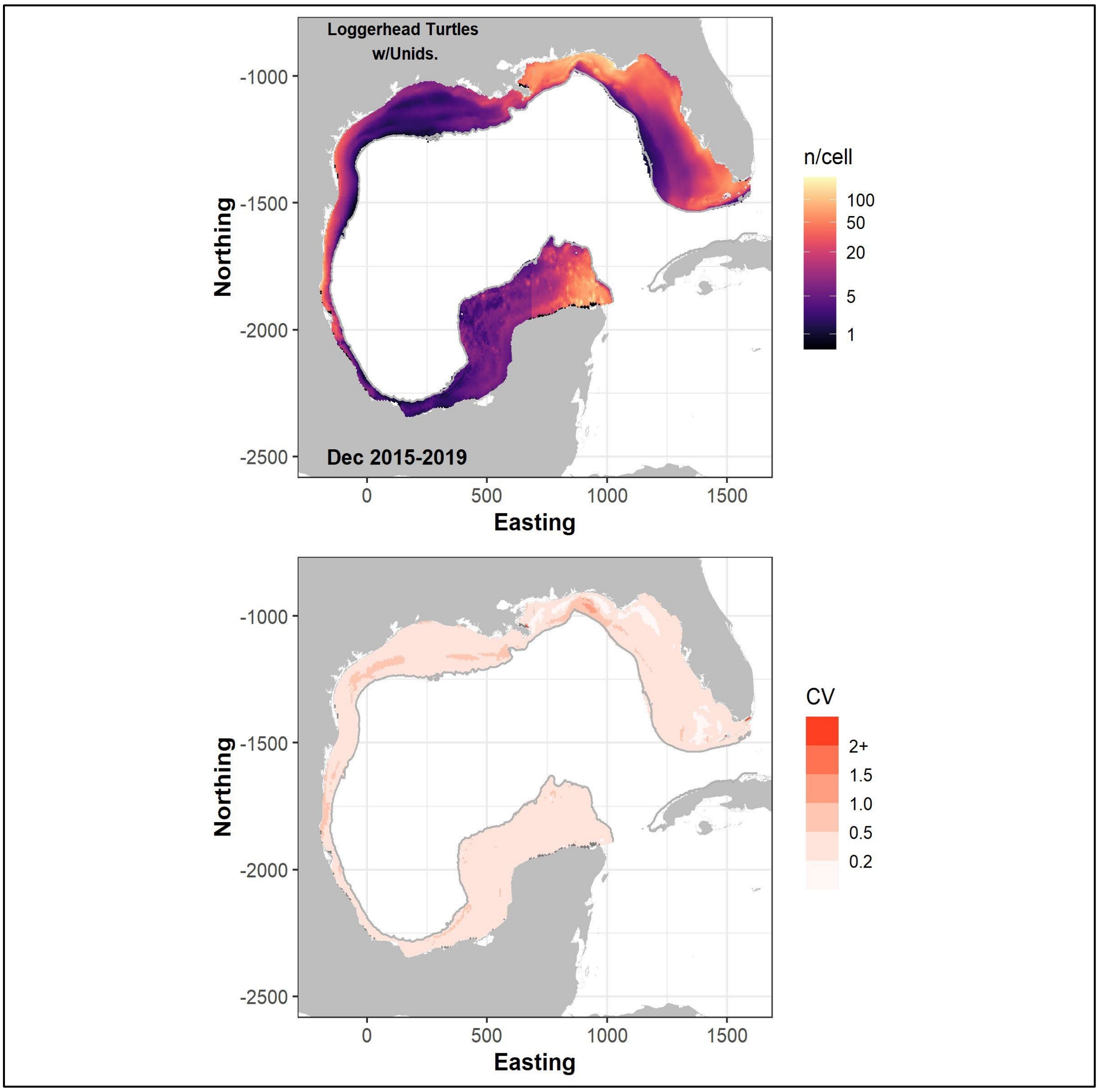

Figure D.4-73. Projected density model for shelf loggerhead turtles in the entire GOM for the months of December 2015–2019.

D.5 Gulf of Mexico Unidentified Hardshell Turtle Density Models

Photo credit: NOAA Fisheries

Sea turtles are difficult to identify reliably from the air, and observers are trained to make positive identification to species only when they feel confident in their identification. In addition, turtles are often observed just below the water surface or diving, making reliable identification impossible. As a result, many of the observed turtles during the aerial surveys were identified only as "hardshell turtles". Incorporating these unidentified observations into density estimates is essential to developing unbiased estimates. To properly apportion unidentified turtles among species, a spatial density model (SDM) was developed for unidentified hardshell turtles. The resulting density of hardshell turtles were partitioned among the identified species based upon the relative predicted density of each species in each spatial cell. This section describes the development of SDMs for unidentified hardshell turtles occurring over the continental shelf based upon seasonal aerial surveys conducted in 2011–2012 and 2017–2018, including average abundance prediction maps generated using monthly environmental parameters for the period of 2015–2019. This section also includes projected density and prediction maps for shelf waters of the entire Gulf of Mexico (GOM).

D.5.1 Survey Data and Sightings

Aerial line-transect surveys were conducted over the continental shelf of the northern Gulf of Mexico (NGOM) in a survey region extending from the shoreline to the shelf break (approximately the 200 m isobath) between Key West, Florida and the US/Mexico border near Brownsville, TX. Each survey was conducted in a NOAA Twin Otter flying at a survey altitude of 183 m (600 ft) and an approximate speed of 100 knots. Survey tracklines were spaced approximately 20 km apart and were oriented so as to be perpendicular to the shoreline. The aircraft was equipped with two large bubble windows in the forward portion of the aircraft (left and right sides) and one right bubble window and a belly window in the aft portion of the aircraft to allow effective visualization of the trackline (see Figure 2 in the GoMMAPPS project final report). Surveys were conducted using two independent teams to allow estimation of detection probability in within the surveyed strip and on the trackline using Mark Recapture Distance Sampling (MRDS) approaches. Aerial surveys were conducted in spring 2011, summer 2011, fall 2011, and winter 2012 as part of the Natural Resources Damage Assessment associated with the *Deepwater Horizon* oil spill. Additional surveys were conducted in the summer of 2017, winter 2018, and fall 2018 as part of the GoMMAPPS project. Additional details about the survey design and execution are contained in Garrison et al. (2022). The total number of unidentified hardshell turtle groups sighted is shown in Table D.5-1.

Table D.5-1. Unidentified hardshell turtles observed for each survey included in this analysis

Survey	Groups	Individuals
TOSE11F	312	393
TOSE11Sp	369	422
TOSE11Su	317	350
TOSE12W	549	644
TOSE17Su	430	492
TOSE18F	132	137
TOSE18W	450	606

During summer and fall, unidentified hardshell turtles were observed primarily in the central NGOM and in the northwestern GOM at intermediate depths over the continental shelf. During winter months, high densities of unidentified hardshell turtles were also observed off the northwestern coast of Florida (Figure D.5-1).

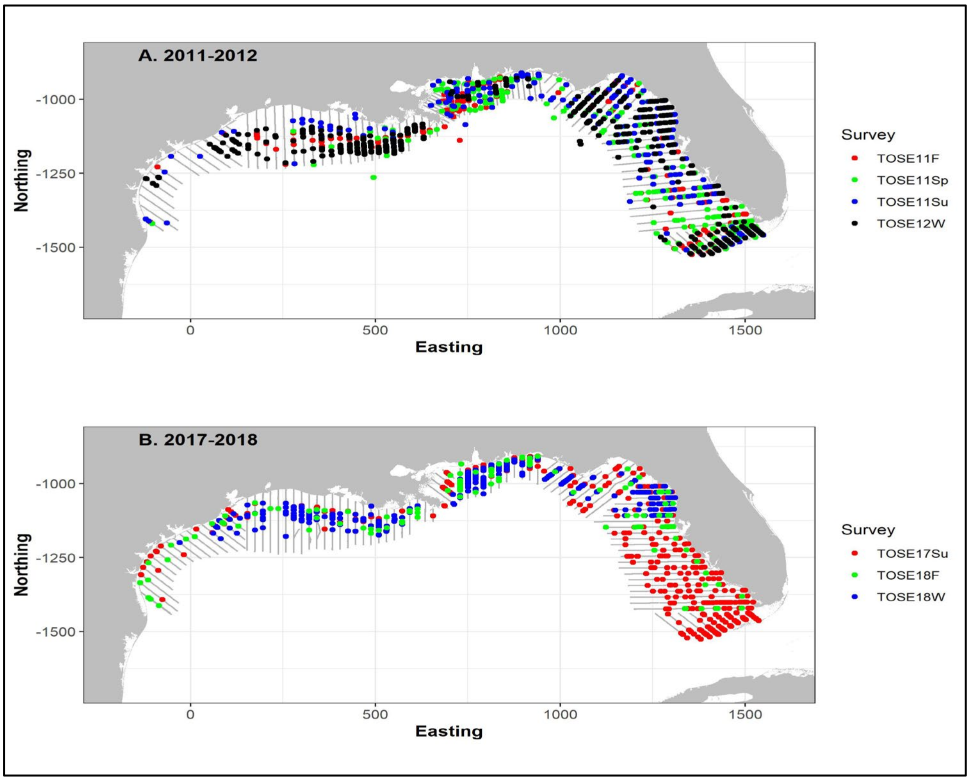

Figure D.5-1. Survey effort and unidentified hardshell turtle sightings during (A) 2011–2012 and (B) 2017–2018.

D.5.2 Distribution of Sightings and Physical Oceanography during Each Survey

The distribution of unidentified hardshell turtle sightings and surface temperature and chlorophyll-a concentrations are shown in Figures D.5-2–D.5-8.

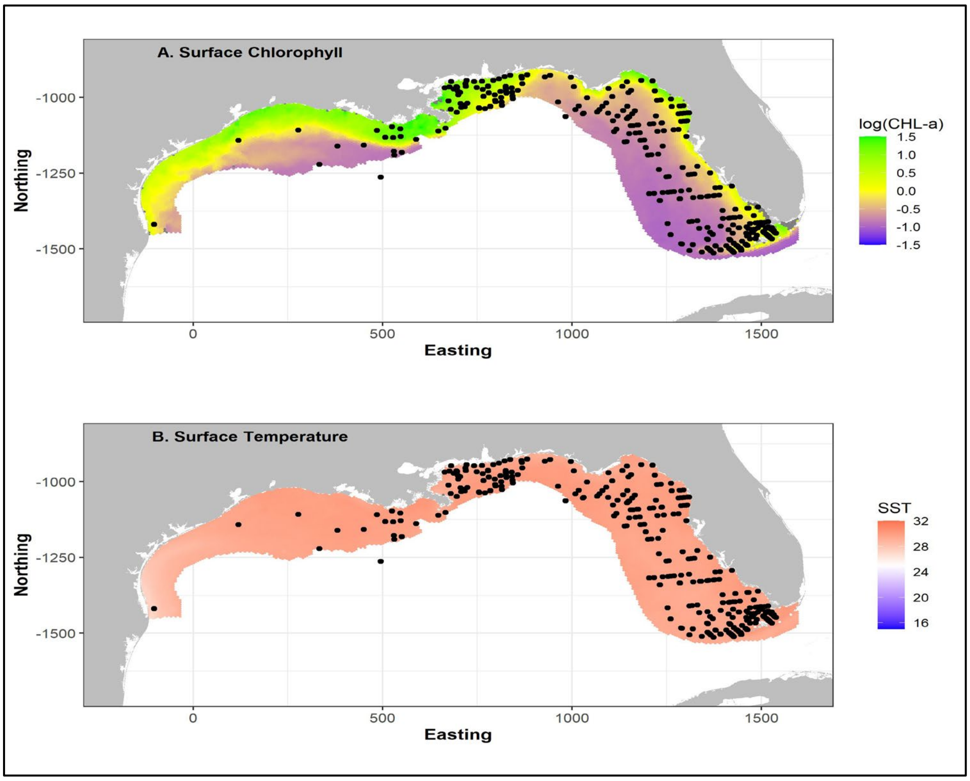

Figure D.5-2. Unidentified hardshell turtle sightings during spring 2011.

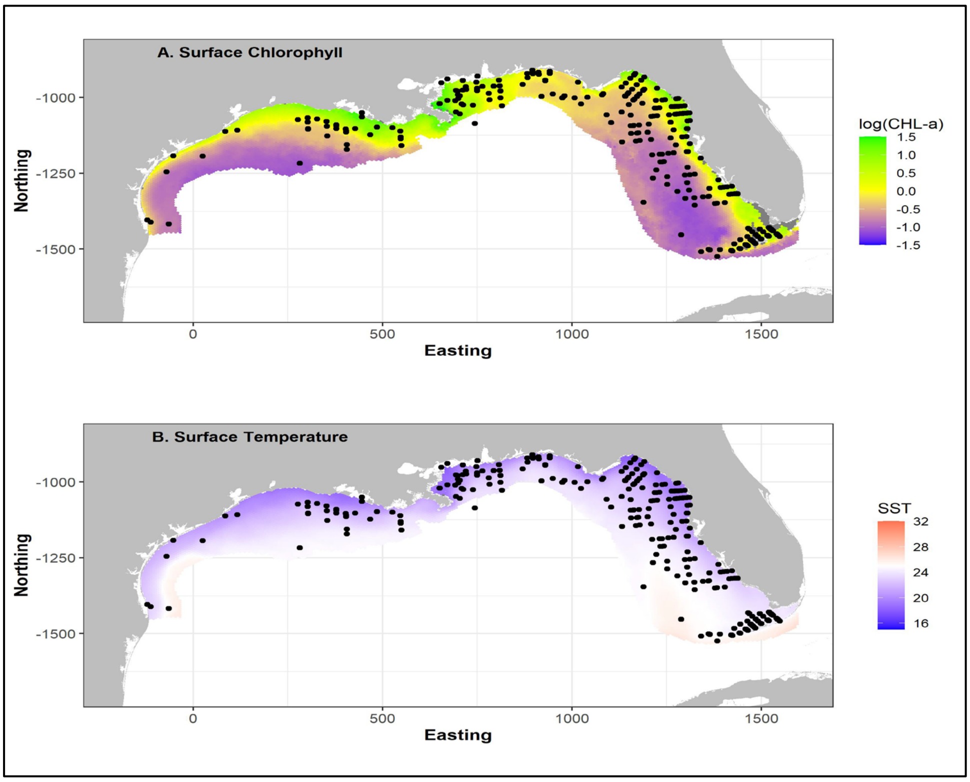

Figure D.5-3. Unidentified hardshell turtle sightings during summer 2011.

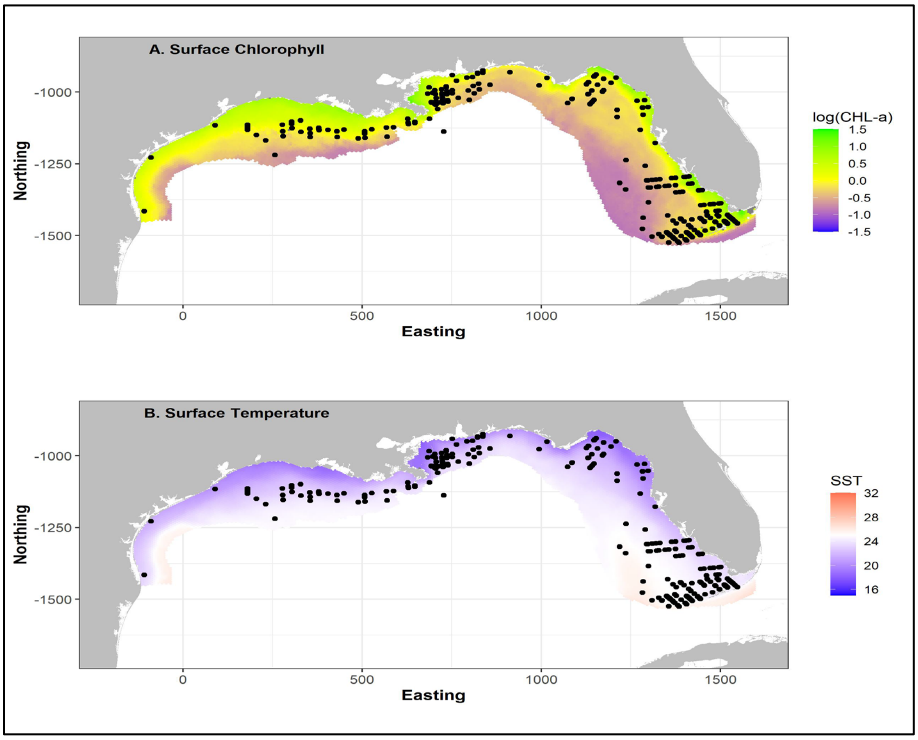

Figure D.5-4. Unidentified hardshell turtle sightings during fall 2011.

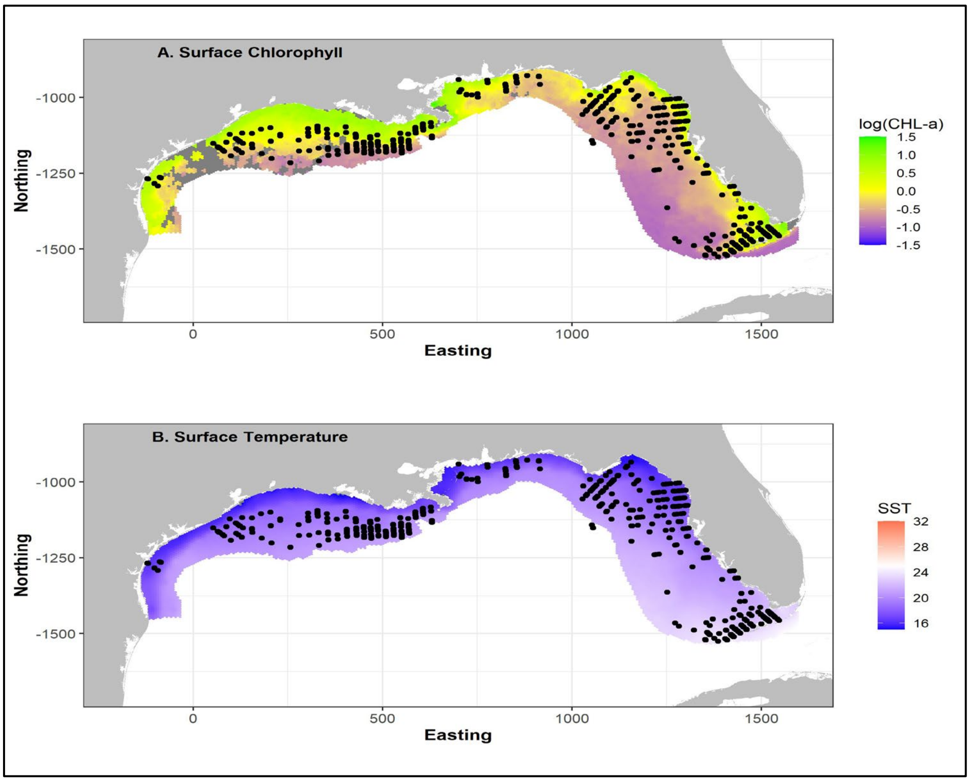

Figure D.5-5. Unidentified hardshell turtle sightings during winter 2012.

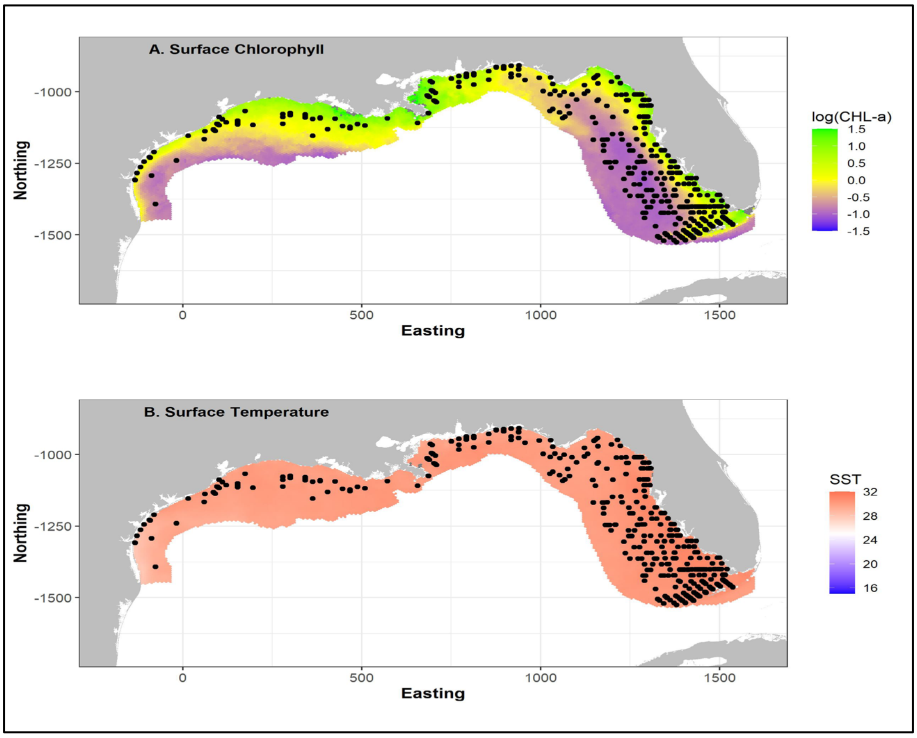

Figure D.5-6. Unidentified hardshell turtle sightings during summer 2017.

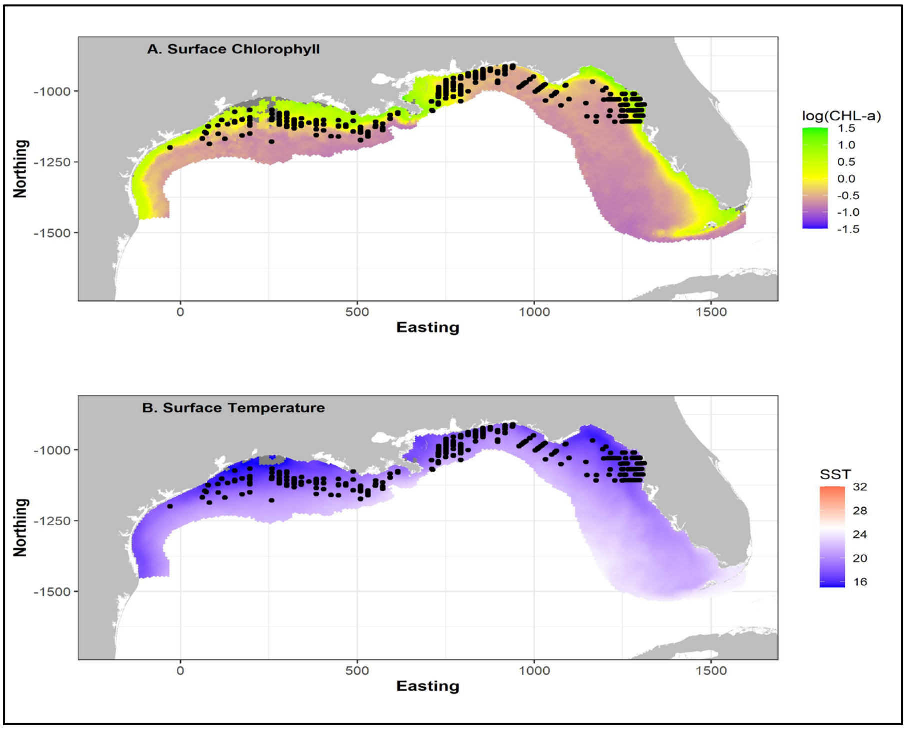

Figure D.5-7. Unidentified hardshell turtle sightings during winter 2018. Note that survey effort was incomplete in the northeastern GOM during this survey.

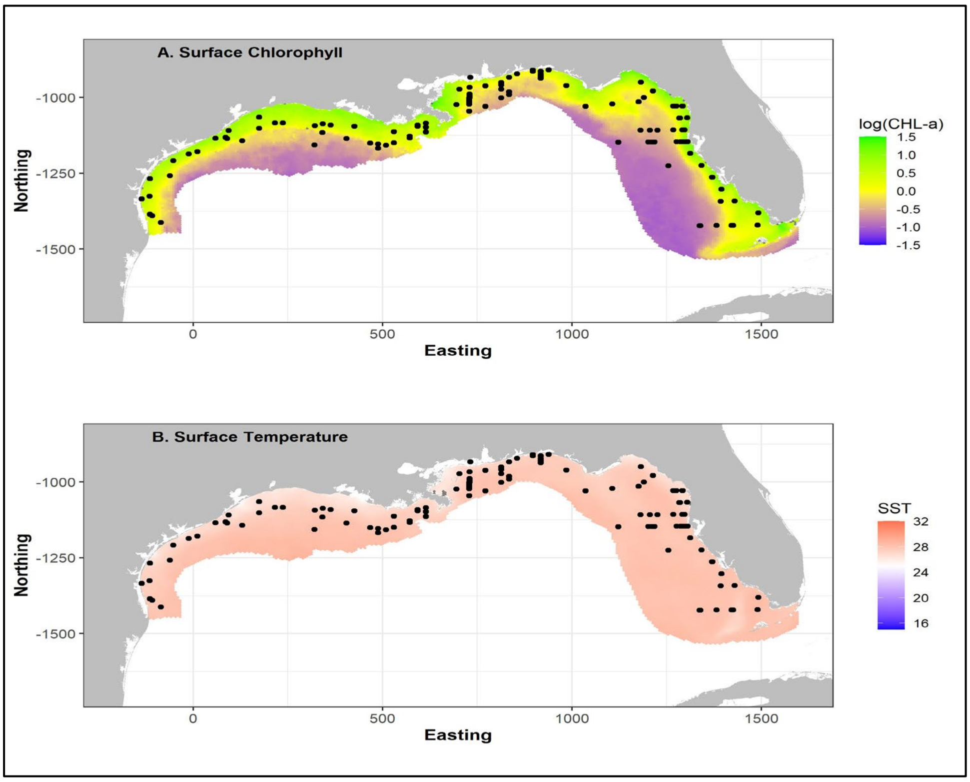

Figure D.5-8. Unidentified hardshell turtle sightings during fall 2018.

D.5.3 Distance Analysis and Detection Probability

Detection probability within the surveyed strip was estimated using MRDS approaches. Covariates considered for inclusion in the detection function included sea state, cloud cover, water turbidity, and sun penetration. In addition, the correlation between ln(group size) and perpendicular sighting distance (PSD) was examined, but there was no relationship between group size and detection distances, so group size was not considered for inclusion in the model.

The best model was selected by first examining the distribution of PSD and selecting an appropriate right truncation distance and key function. Then, all combinations of detection covariates were considered for both the detection function and mark-recapture portion of the model, and the model with the lowest Akaike's Information Criterion (AIC) was selected. The best model included a hazard-rate key function with a right truncation distance of 300 m. Sea State, Cloud Cover, and Turbidity were included as covariates in the distance component of the model. Sea state, Turbidity, Weather Condition, and an interaction term with observer position were included in the mark-recapture component of the model (Table D.5-2).

Table D.5-2. Parameters included in the detection probability function

(MCDS = Multiple covariate distance sampling)

Model	Parameter	Estimate	SE
MCDS	MCDS Intercept	4.3682	0.1534
MCDS	Sea State	0.0773	0.0361
MCDS	Sun Penetration	0.1755	0.0670
MRDS	MRDS Intercept	-1.4419	0.3871
MRDS	Distance	0.0036	0.0014
MRDS	Observer	-0.5354	0.0826
MRDS	Sun Penetration	0.3577	0.1507
MRDS	Turbidity	0.1986	0.1326
MRDS	Distance x Observer	-0.0010	0.0007

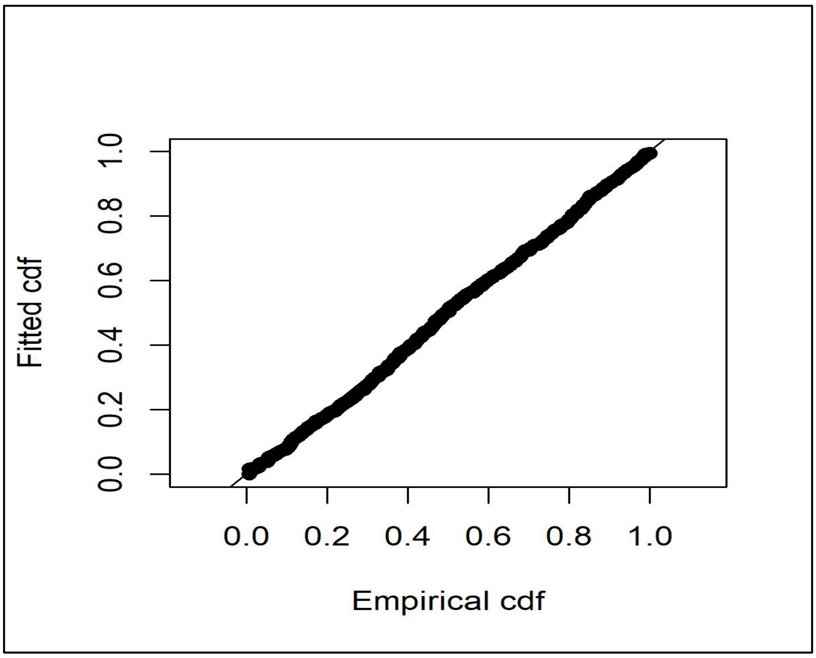

Figure D.5-9. MRDS detection function Q-Q plot (cdf = cumulative distribution function).

The resulting detection probability function had a good overall fit as indicated by the linear Quantile-Quantile (Q-Q) plot (Figure D.5-9). The Chi-square goodness of fit test p-value was 0 (Chi-square = 51.42, df = 7) indicating some deviation from the expected model especially in the mark-recapture component at high PSD. However, the Cramer-von Mises test p-value was 0.207 (test statistic = 0.236) suggesting an adequate model fit overall.

The estimated detection probability on the trackline is shown in Table D.5-3, and the detection probability function is shown in Figure D.5-10.

Table D.5-3. Estimated detection probability and number of detections in the surveyed area from Multiple Covariate Distance function

Parameter	Estimate	SE	CV
Detection probability	0.560	0.014	0.025
Team 1 p(0)	0.259	0.024	0.093
Team 2 p(0)	0.170	0.016	0.094
Combined p(0)	0.384	0.030	0.078
Overall Avg. Detection Prob.	0.215	0.018	0.084

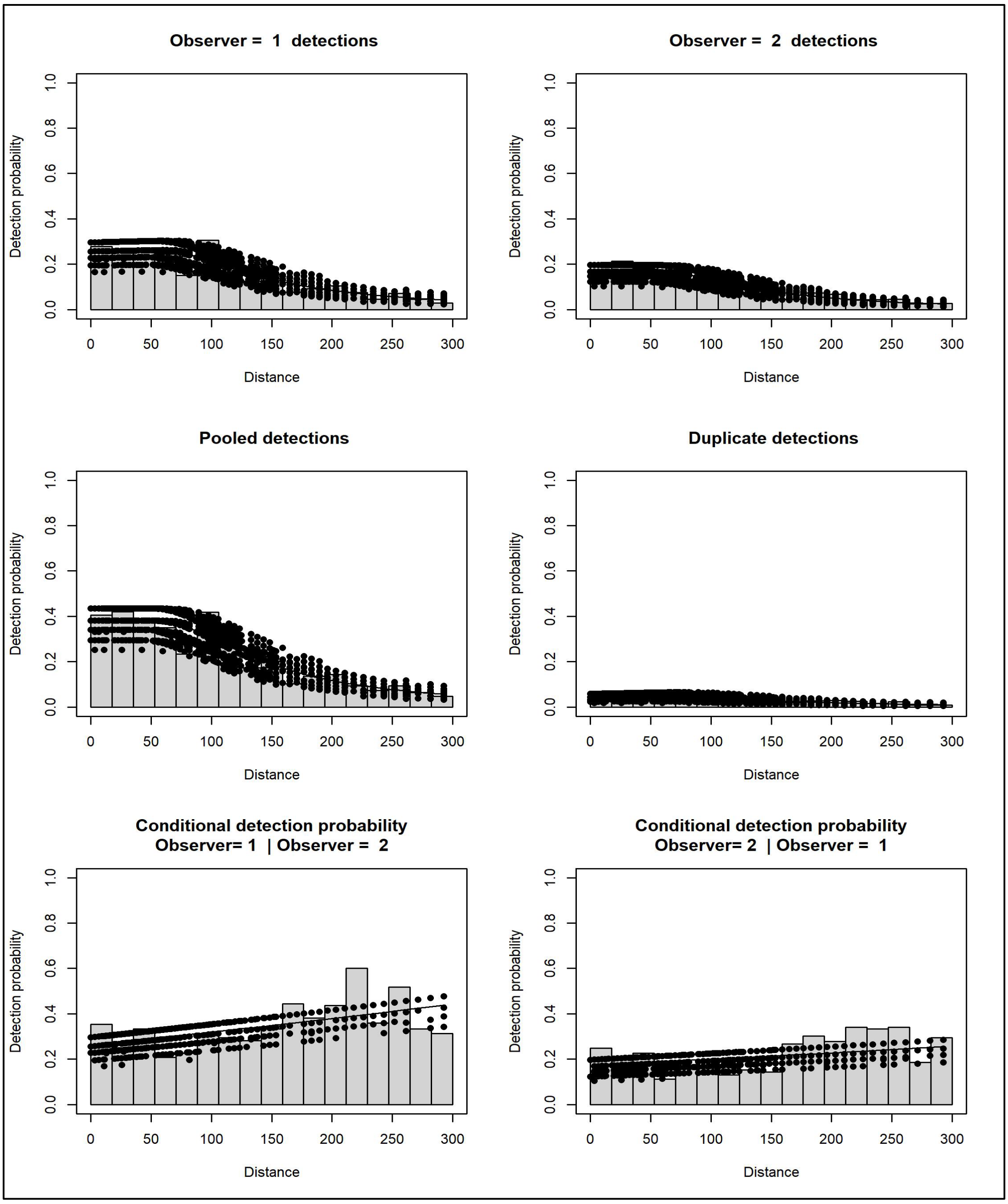

Figure D.5-10. Mark-recapture distance sampling detection probability.

D.5.3.1 Estimating Availability Bias

Sea turtles spend a significant amount of time underwater where they are not available to be counted by aerial observers. The amount of time below the surface varies both spatially and temporally as a function of the behavioral state of the turtles (e.g., feeding vs. traveling) and in response to environmental conditions. To account for availability bias, we applied generalized additive models (GAMs) of sea turtle occurrence in the upper 2 meters of the water column based upon an extensive database of telemetry tag data for loggerhead, Kemp's Ridley, and green turtles (Roberts et al. 2022).

This GAM used environmental variables to predict the probability that turtles would be near the surface and available to the aerial survey team. These models included environmental predictors of availability such as season, sea surface temperature, distance from the shelf break, water depth, salinity, the occurrence of fronts, and spatial location. For each hardshell turtle observed, we used the weighted average of the predicted probability that the turtle was near the surface from the three identified species models based upon the environmental conditions at the time of observation. The average was weighted by the number of sightings of each species in a given survey. The median probability that a unidentified hardshell turtle was at the surface was 0.326 (Inter-quartile range: 0.240–0.390; Figure D.5-11). The number of turtles observed at the location was divided by the estimated probability to account for availability to the survey. This corrected number was the response variable in the spatial density model.

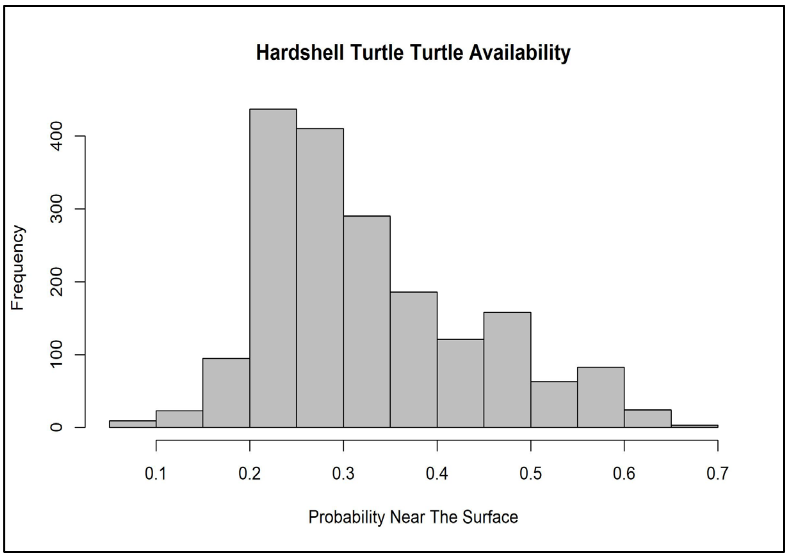

Figure D.5-11. Probability that unidentified hardshell turtles observed during the aerial surveys were near the surface based upon a generalized additive model accounting for spatial and temporal variability in turtle dive behavior.

(Roberts et al. 2022).

D. 5.4 Spatial Density Model Selection

A GAM was used to develop a spatial density model to describe the effect of habitat variables on the density and abundance of unidentified hardshell turtles in the NGOM. Survey effort (kilometers of survey trackline) was partitioned into segments within a grid of hexagonal cells of 40 km^2 area and matched to physical oceanographic parameter values within each cell. Each resulting segment was considered a sampling unit within the GAM, and the number of animals observed on the segments was the response variable in a log count model assuming a Tweedie error distribution to account for overdispersed count data. An offset term (ln[strip area]) was included in the model to account for the effective area surveyed within each spatial cell based upon the detection probability function described above and covariates during the survey.

An initial GAM model was fit using all available oceanographic and physiographic variables. A reduced model was the selected including only model terms with p-value < 0.2. This reduced model was compared to the full model using AIC to ensure selection of the best fitting, most parsimonious model. Model fit was assessed through the examination of randomized quantile residuals and the associated Q-Q plot for deviance residuals.

For unidentified hardshell turtles, the selected model included Average Depth (AvgDepth), Sea Surface Temperature (Avg_SST), Distance from Shore (Dist2Shore), Distance from Canyons (Dist2Canyo), distance from the shelf break (Dist2Shelf), log(chlorophyll-a concentration) (lAvg_Chl), Mixed Layer Depth (Avg_CMEMS_MLD) (Avg_CMEMS_MLD), and the East-West spatial coordinate (Easting) (Table D.5-4). In addition, a factor variable (YrClass) was included in the model to reflect the overall higher density of unidentified hardshell turtles in recent years compared to prior years. The model fit to the data was good with a generally linear Q-Q plot and few outlier residual values (Figure D.5-12).

Table D.5-4. Parameter estimates for the selected Generalized Additive Model

(EDF = effective degrees of freedom)

Term	EDF	Max..EDF	F.Statistic	P.value
s(AvgDepth)	1.144	9	5.083	< 0.001
s(Dist2Shelf)	5.586	9	6.845	< 0.001
s(Dist2Canyo)	5.712	9	4.671	< 0.001
s(lAvg_Chl)	5.23	9	5.368	< 0.001
s(Avg_SST)	6.431	9	34.949	< 0.001
s(Easting)	8.094	9	23.343	< 0.001
s(Avg_CMEMS_MLD)	0.988	9	3.517	< 0.001

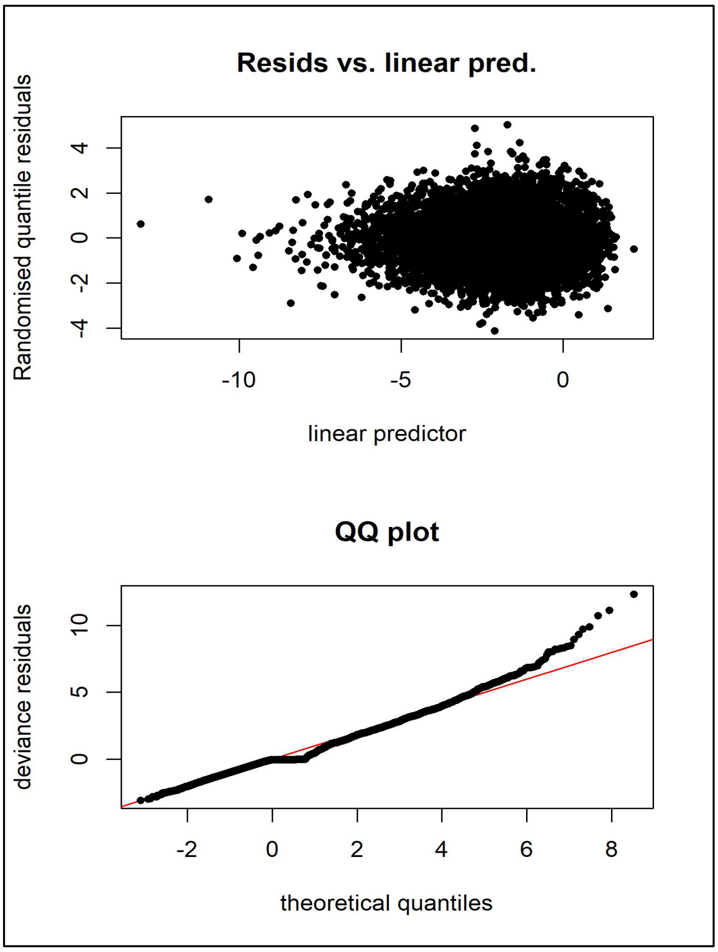

Figure D.5-12. GAM residual plots.

The selected model indicated that unidentified hardshell turtle density was highest at intermediate water depths. Density declined rapidly in waters greater than 150 m depth. The sea surface temperature effect reflects higher densities observed in winter months (Figure D.5-13). The year effect also indicated that observed densities were higher during recent surveys (2017–2018) compared to prior years (2011–2012).

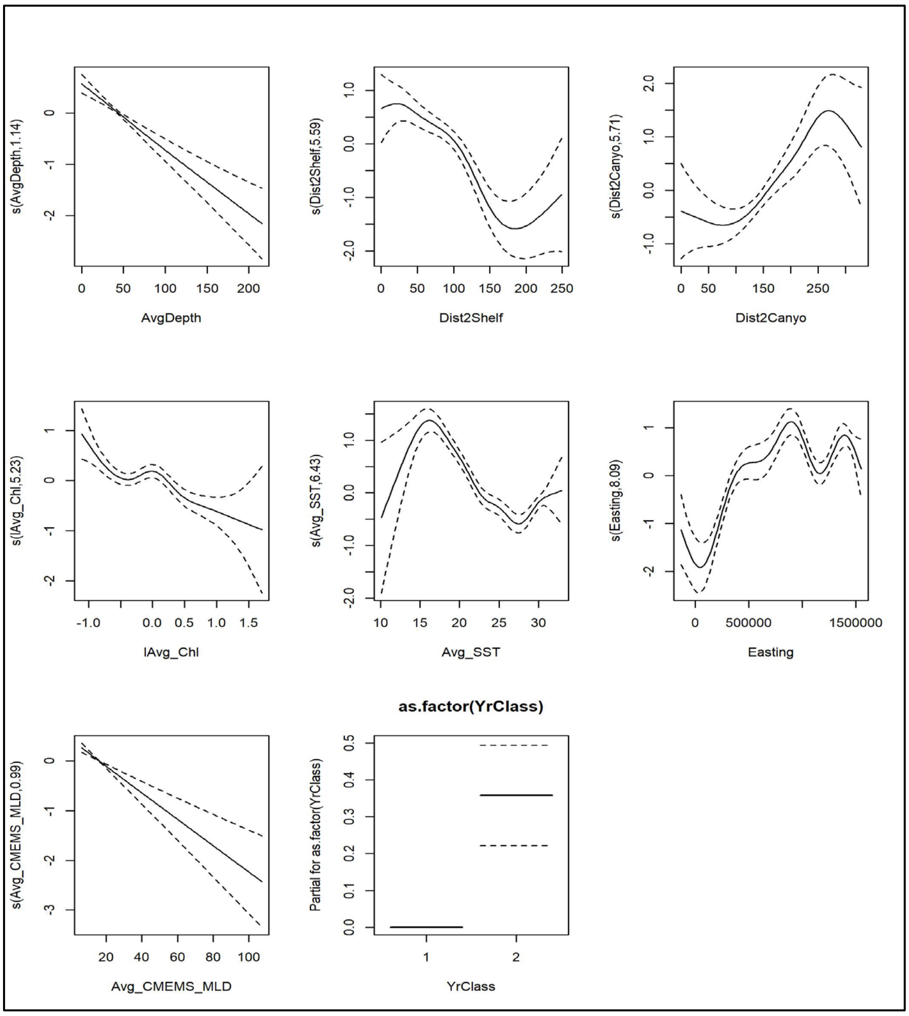

Figure D.5-13. GAM partial plots.

D.5.5 Spatial Density Model Prediction Maps and Model Output

Based upon the selected model, prediction maps were developed based upon monthly average oceanographic variable values for 2018. The estimated uncertainty (coefficient of variation [CV]) reflects only uncertainty in the GAM model fit and does not account for uncertainty in the detection probability function.

D.5.5.1 Northern Gulf of Mexico

Monthly prediction maps demonstrate variability in animal density resulting from variability in the underlying physical oceanography (Figures D.5-14–D.5-25).

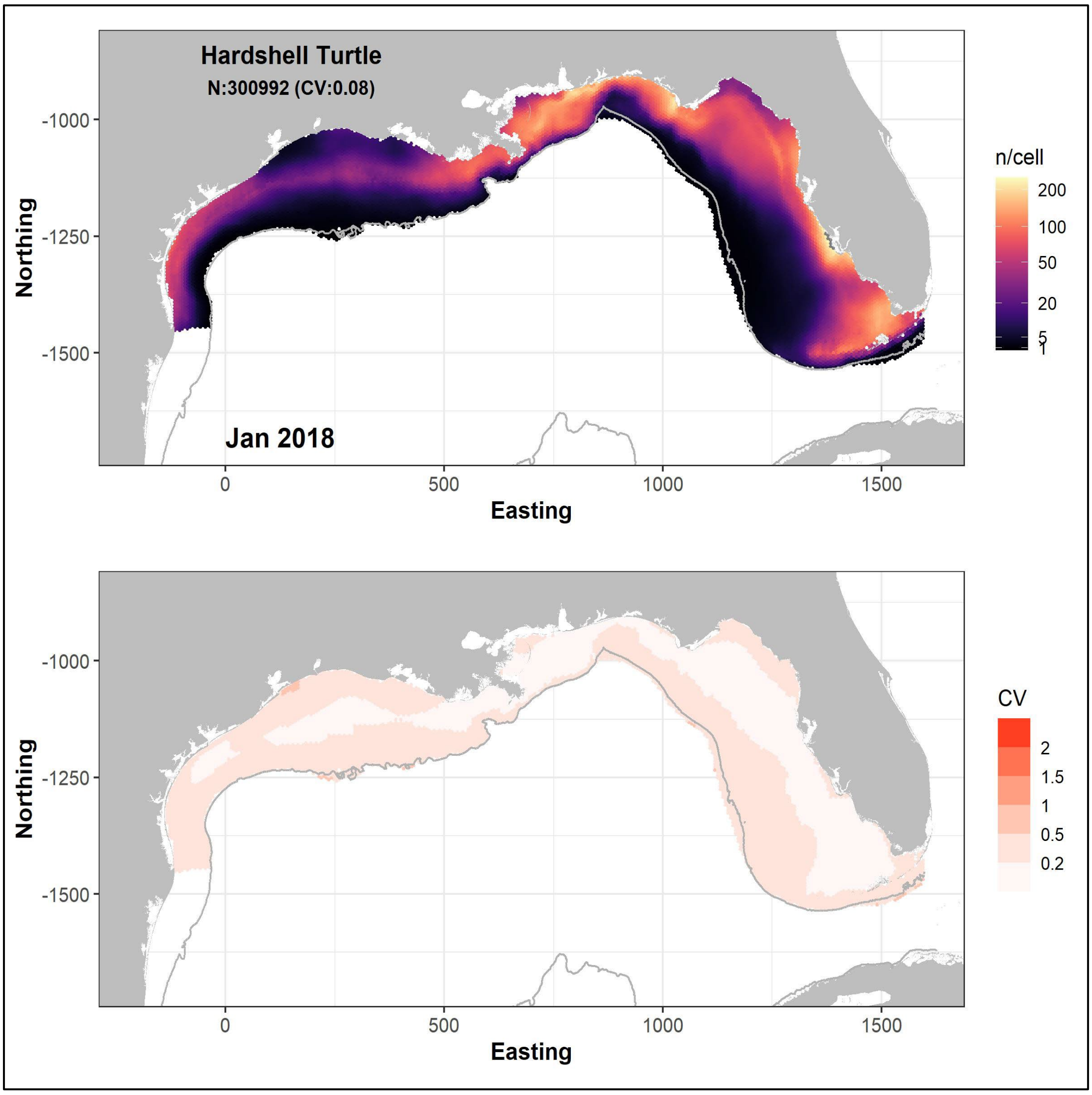

Figure D.5-14. Density model prediction for shelf unidentified hardshell turtles in the NGOM in January 2018.

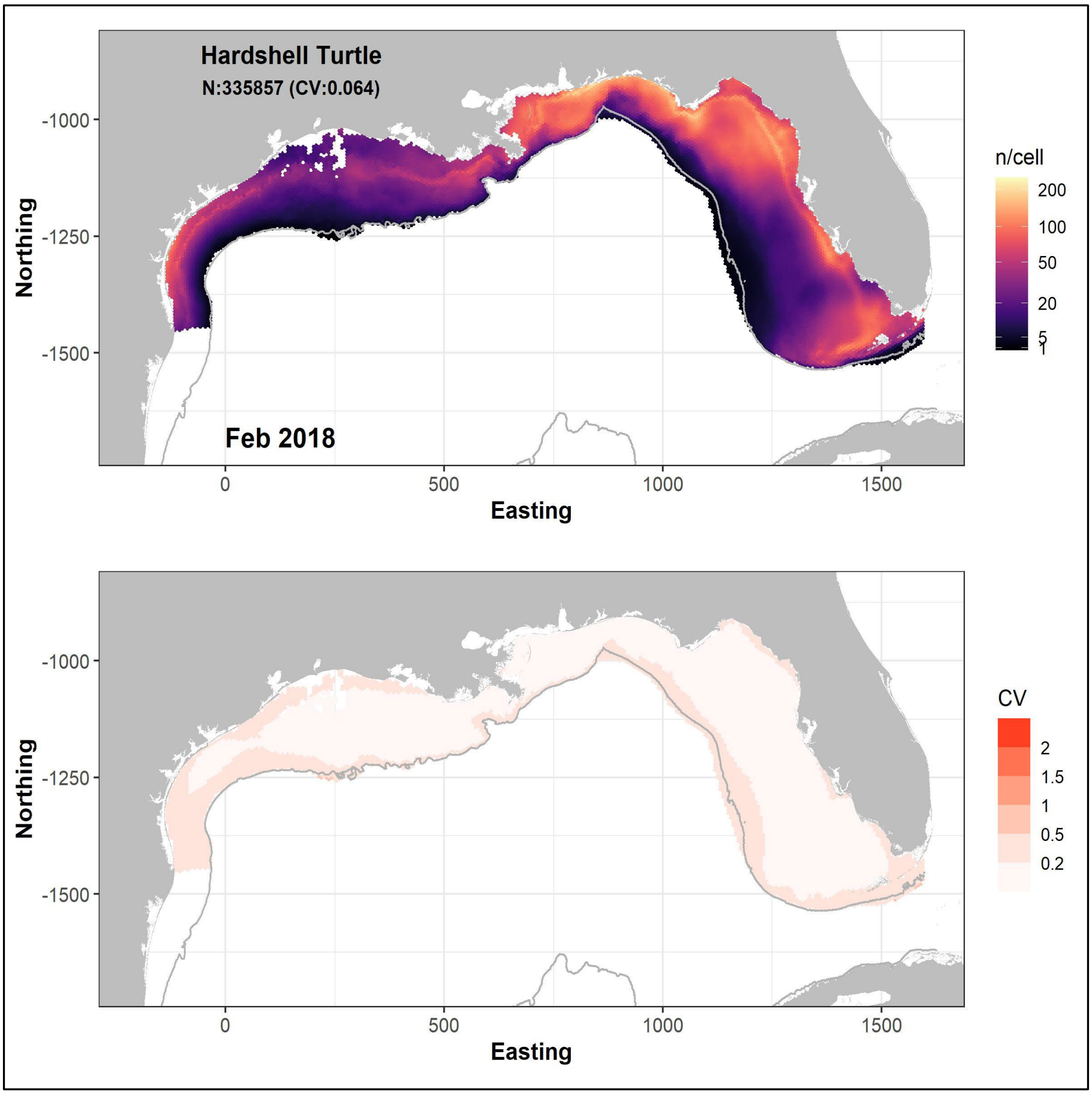

Figure D.5-15. Density model prediction for shelf unidentified hardshell turtles in the NGOM in February 2018.

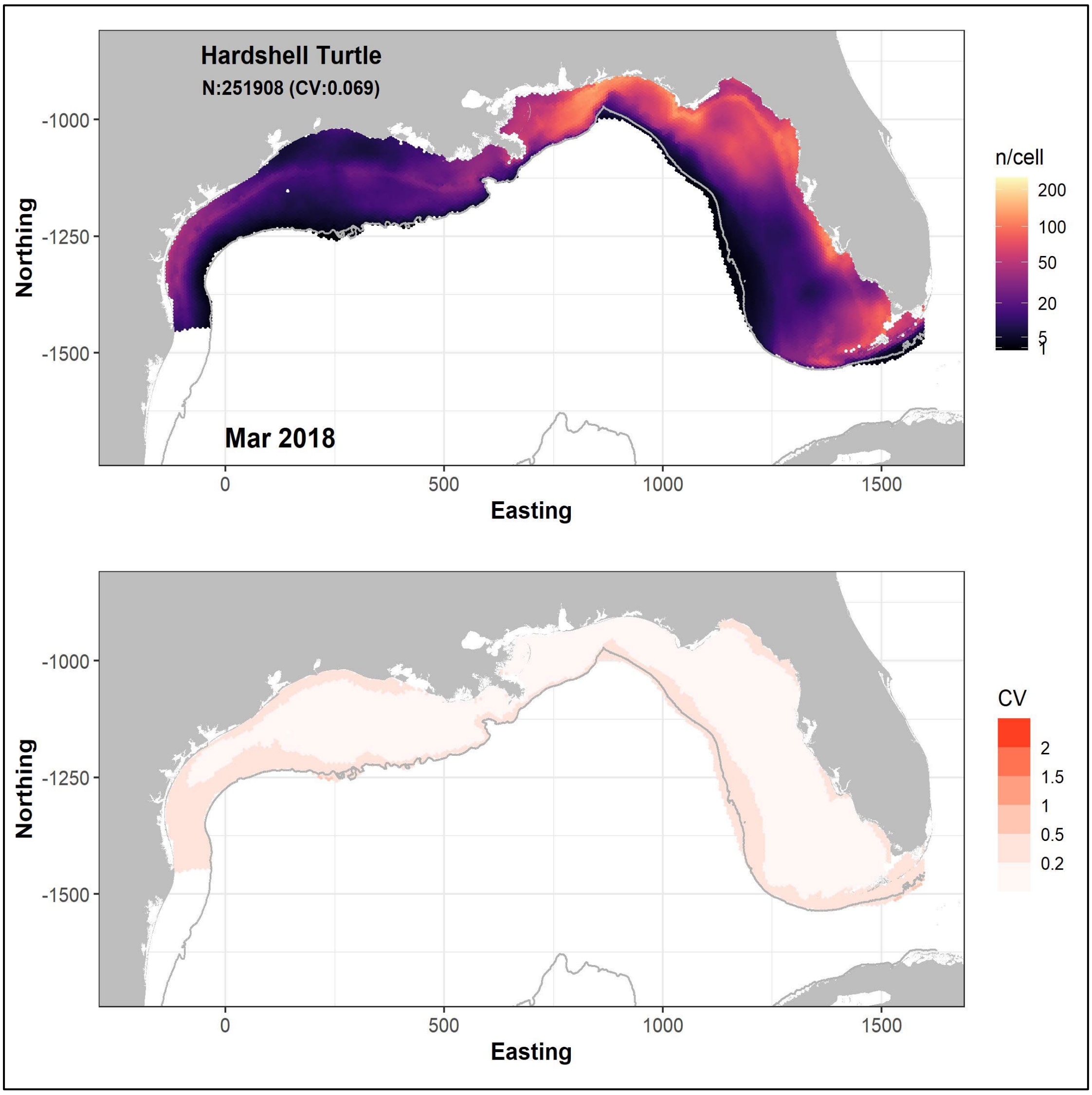

Figure D.5-16. Density model prediction for shelf unidentified hardshell turtles in the NGOM in March 2018.

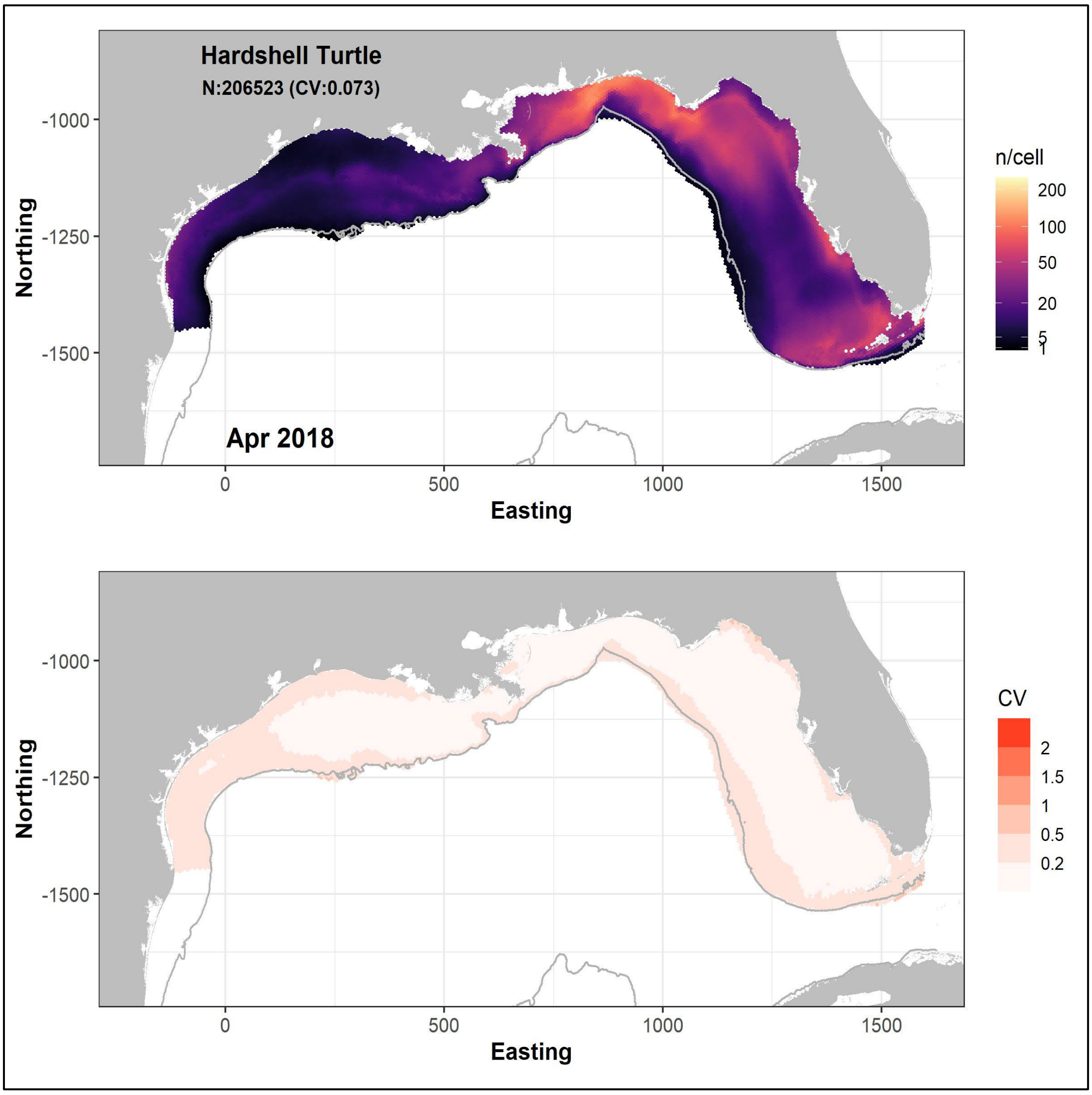

Figure D.5-17. Density model prediction for shelf unidentified hardshell turtles in the NGOM in April 2018.

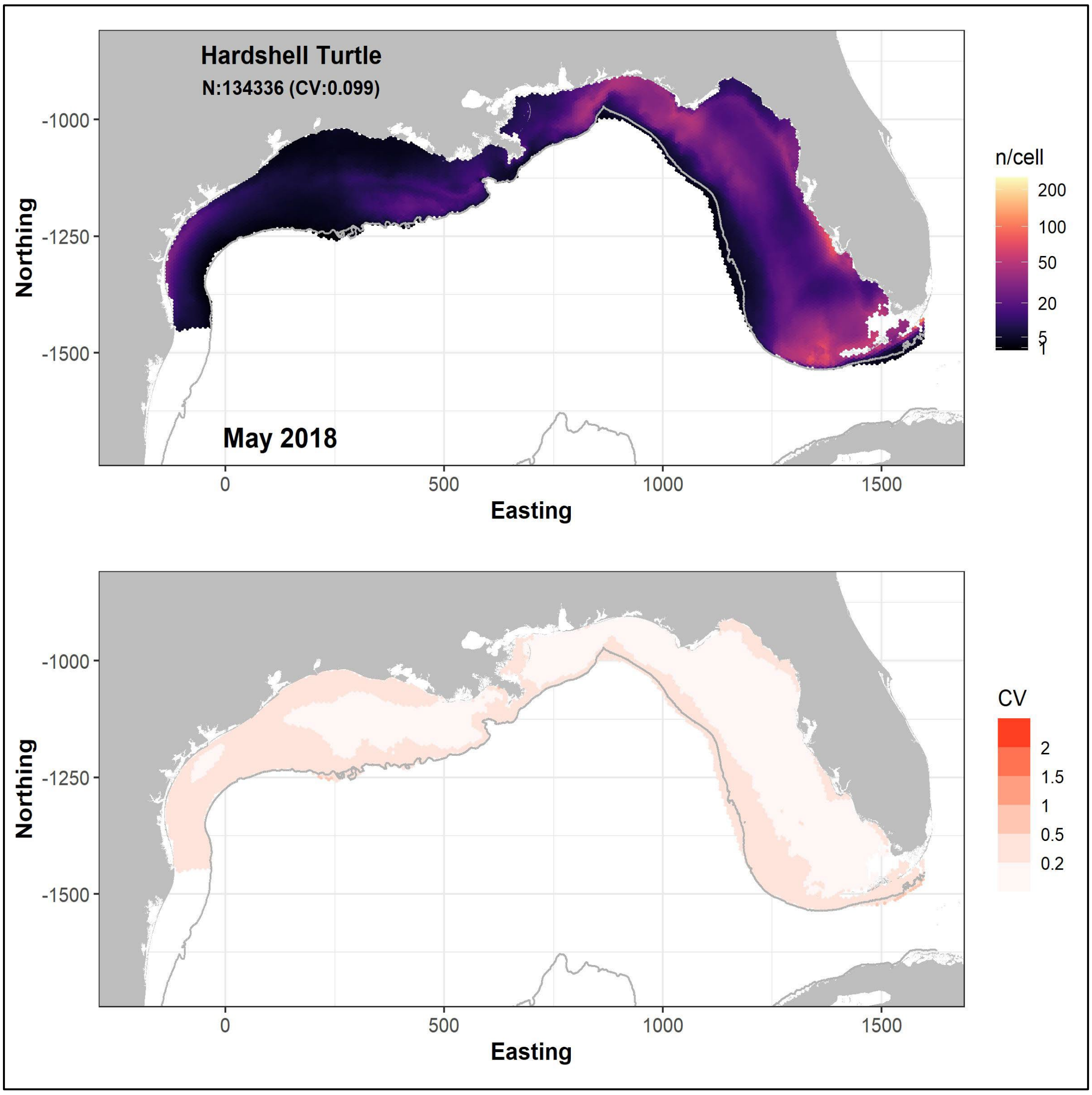

Figure D.5-18. Density model prediction for shelf unidentified hardshell turtles in the NGOM in May 2018.

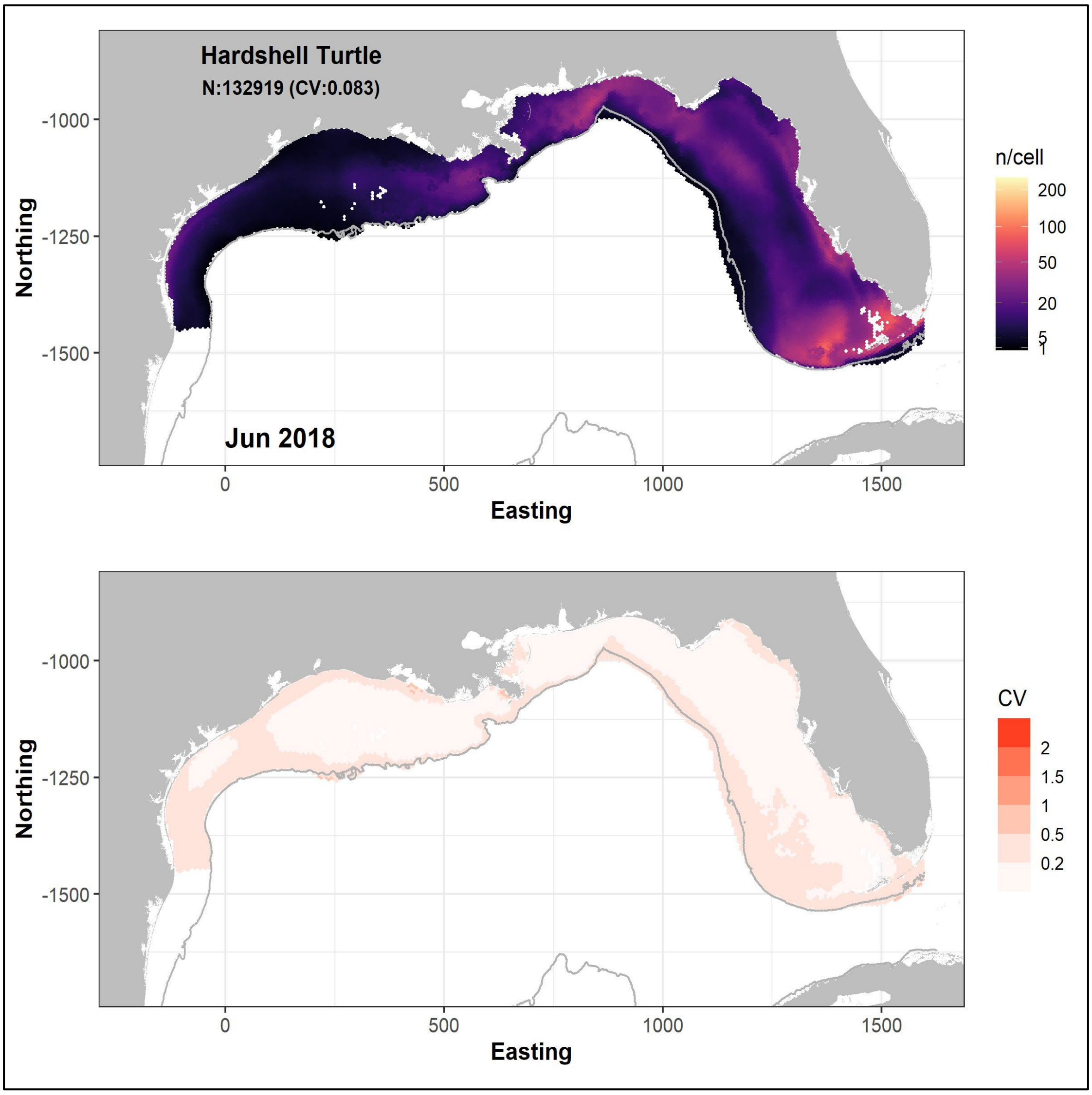

Figure D.5-19. Density model prediction for shelf unidentified hardshell turtles in the NGOM in June 2018.

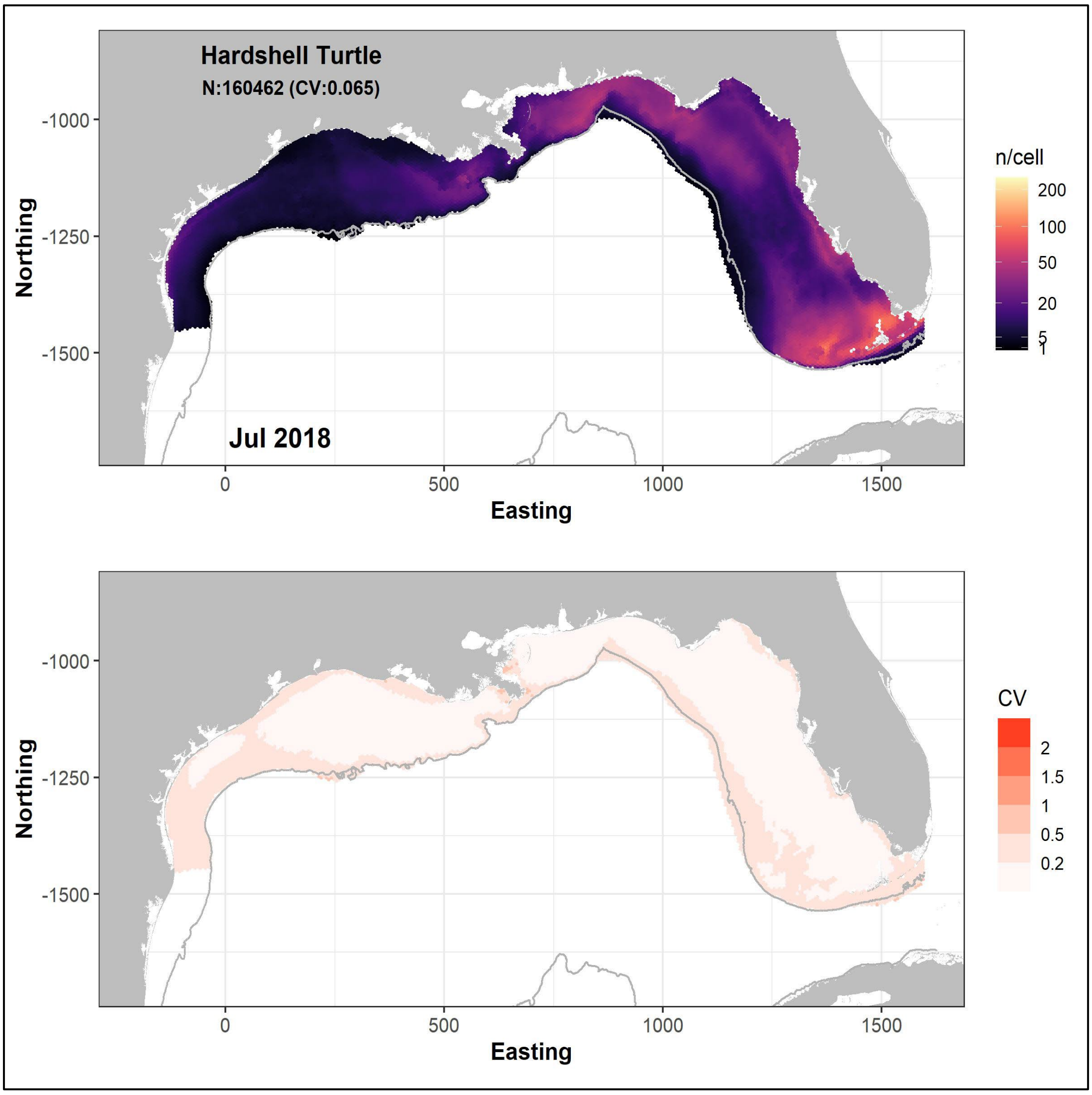

Figure D.5-20. Density model prediction for shelf unidentified hardshell turtles in the NGOM in July 2018.

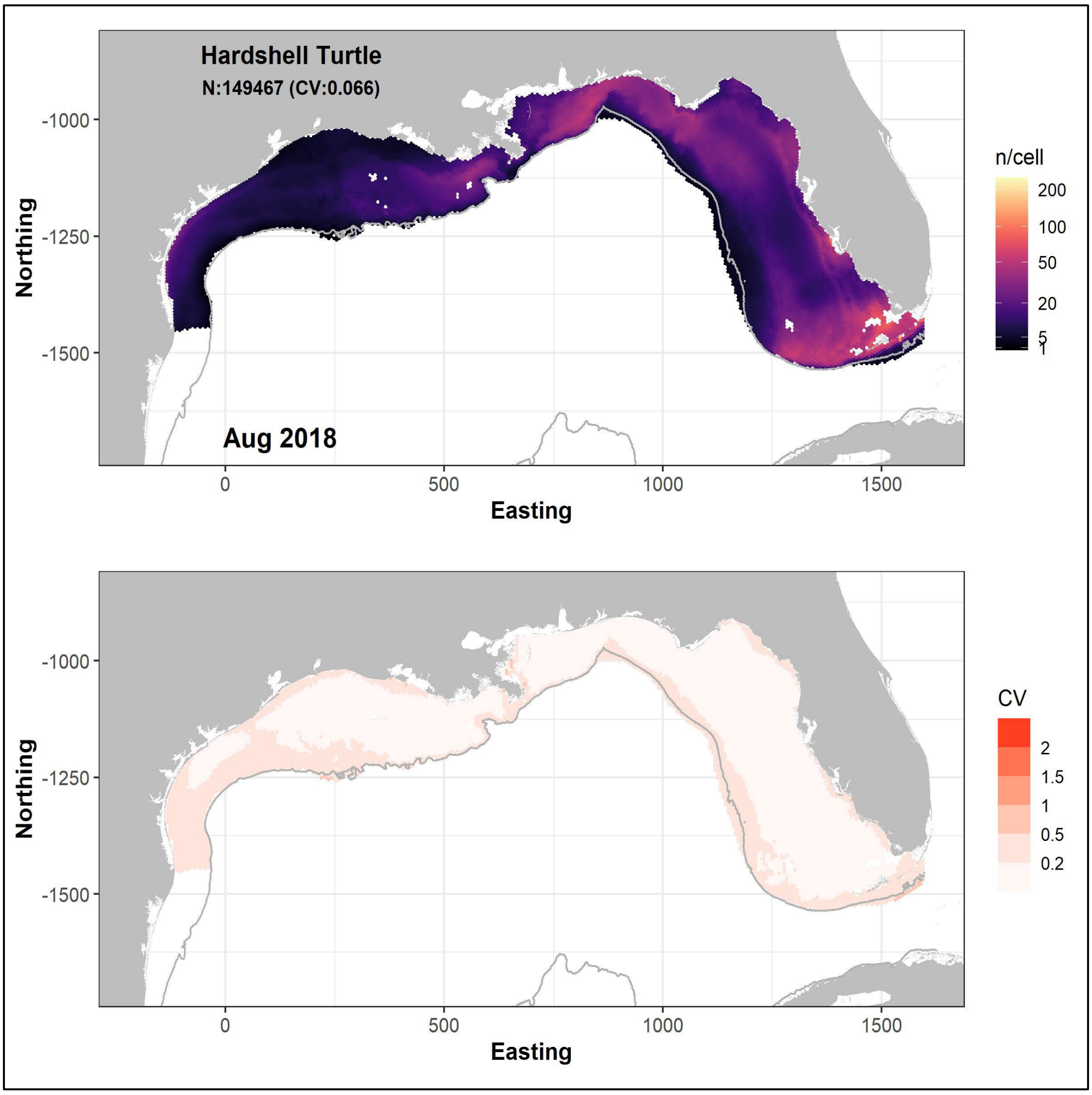

Figure D.5-21. Density model prediction for shelf unidentified hardshell turtles in the NGOM in August 2018.

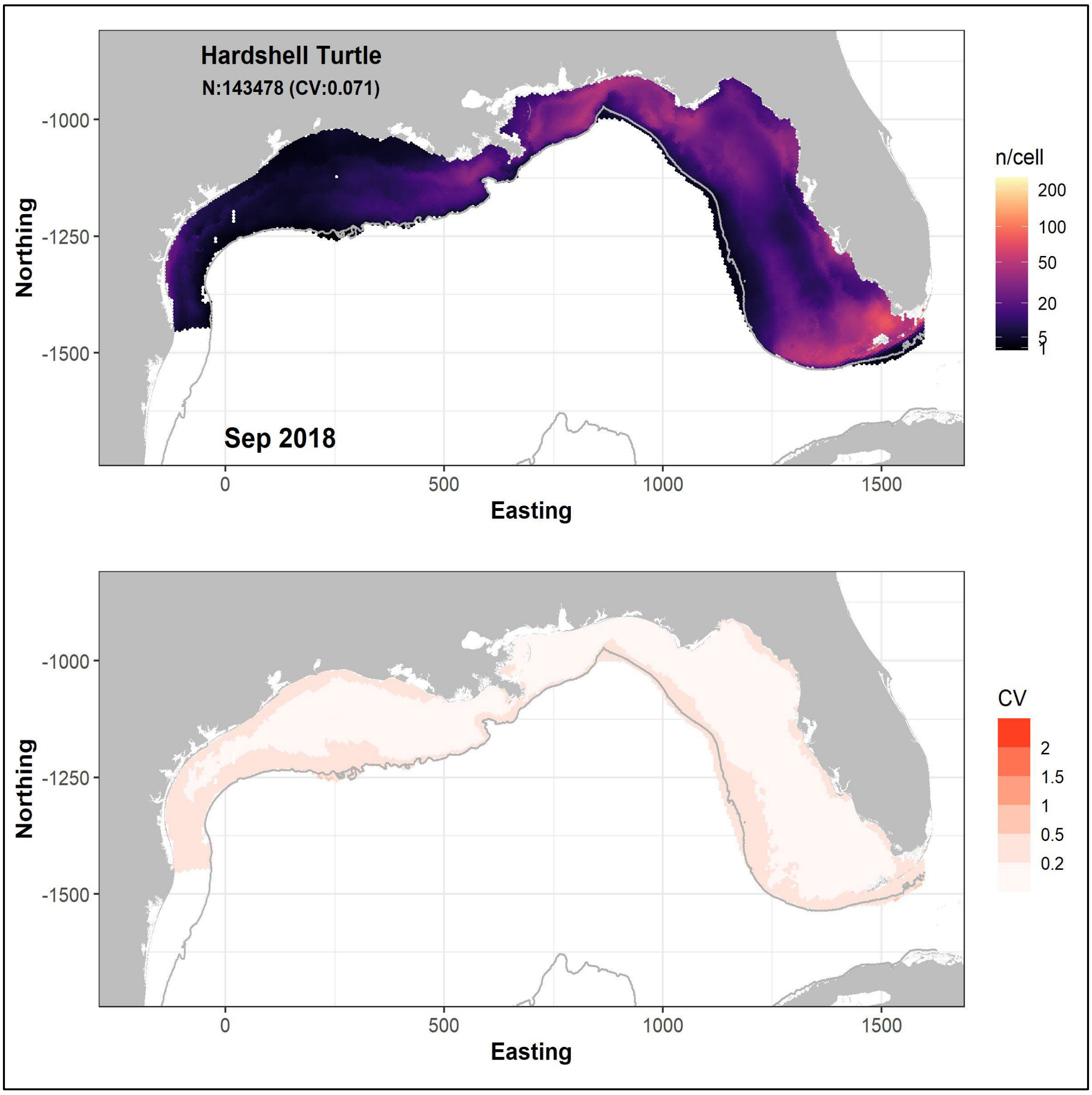

Figure D.5-22. Density model prediction for shelf unidentified hardshell turtles in the NGOM in September 2018.

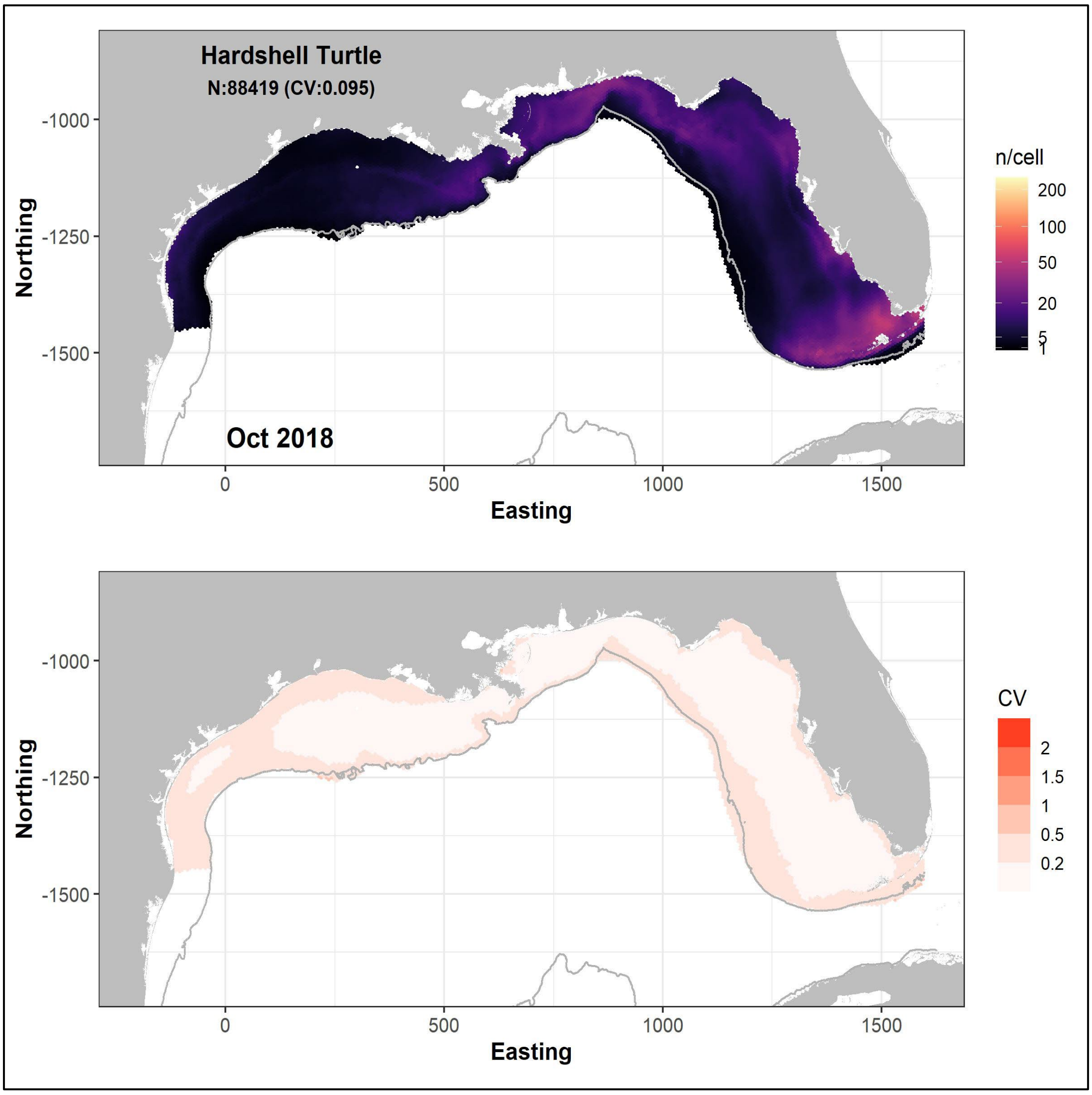

Figure D.5-23. Density model prediction for shelf unidentified hardshell turtles in the NGOM in October 2018.

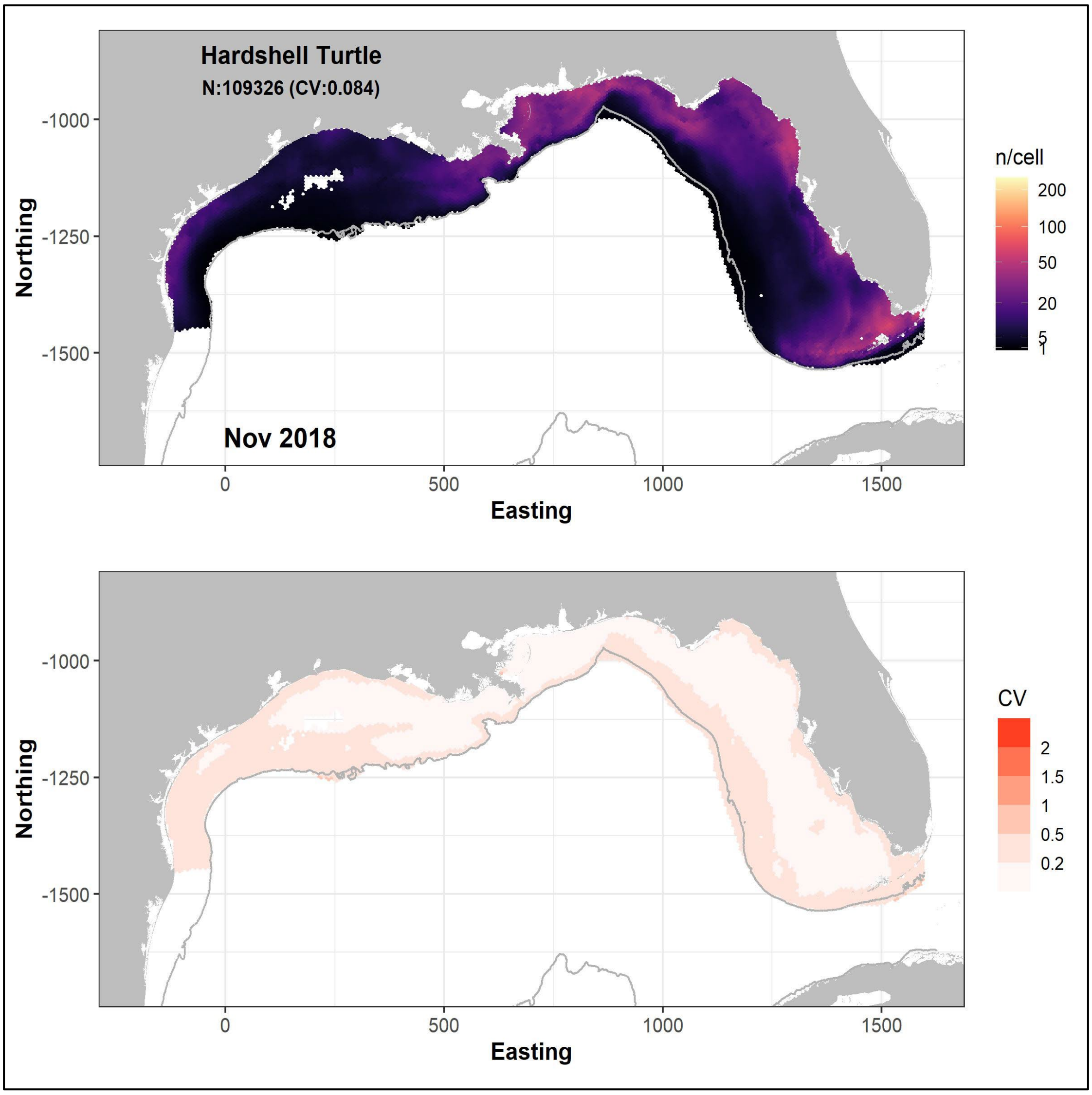

Figure D.5-24. Density model prediction for shelf unidentified hardshell turtles in the NGOM in November 2018.

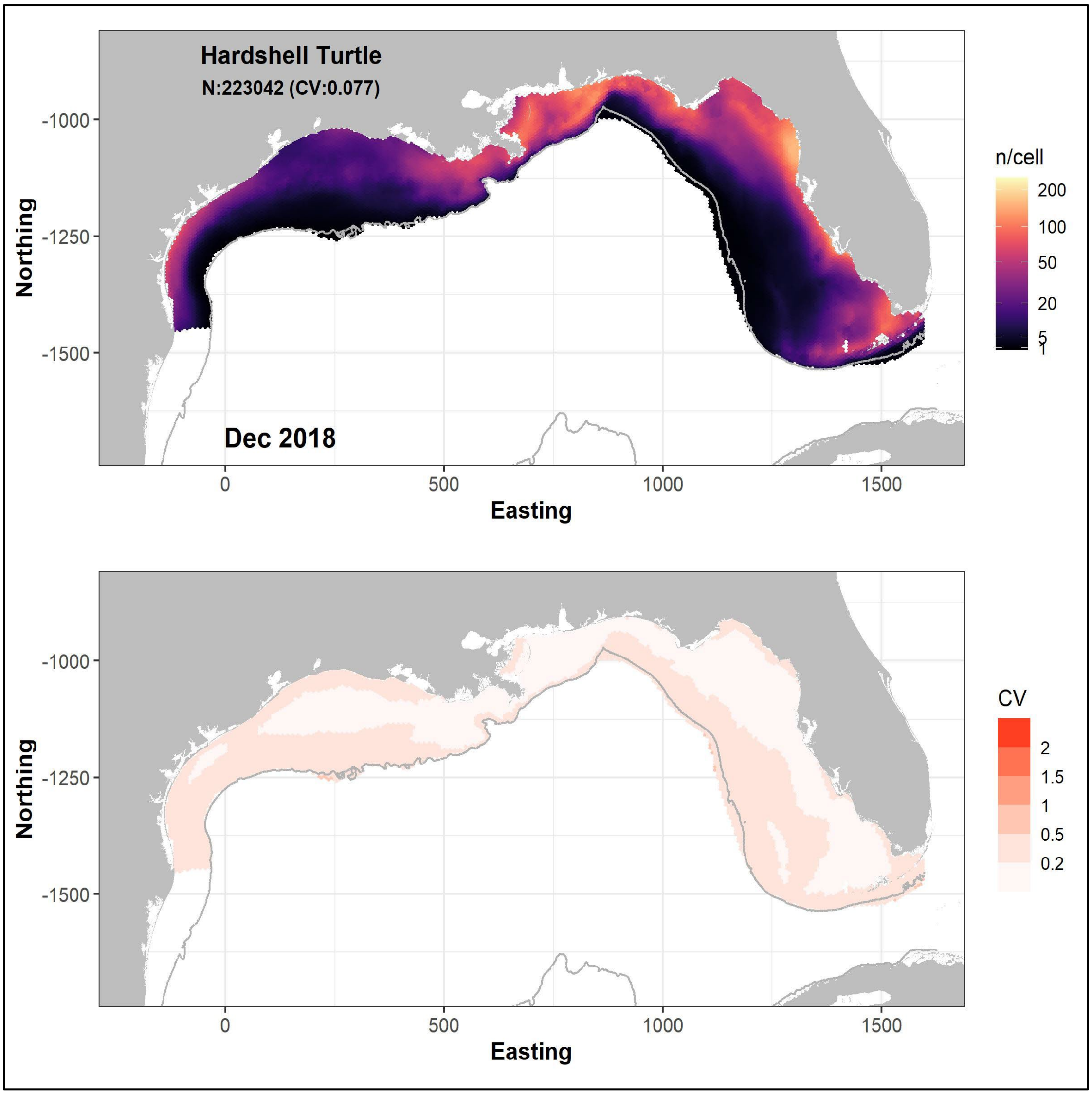

Figure D.5-25. Density model prediction for shelf unidentified hardshell turtles in the NGOM in December 2018.

D.5.5.2 Projected Density throughout the Gulf of Mexico

While aerial survey effort was restricted to the NGOM, turtles occur throughout the northern and southern GOM. The projection of the resulting SDM beyond the NGOM assumes that species-habitat relationships are consistent, and it is unknown if this assumption is reliable. To evaluate the potential density of hardshell turtles outside of the US Economic Exclusive Zone (EEZ), the SDM was projected throughout the GOM. These results should be interpreted with caution given the extrapolation outside of the surveyed area (Figures D.5-26–D.5-37).

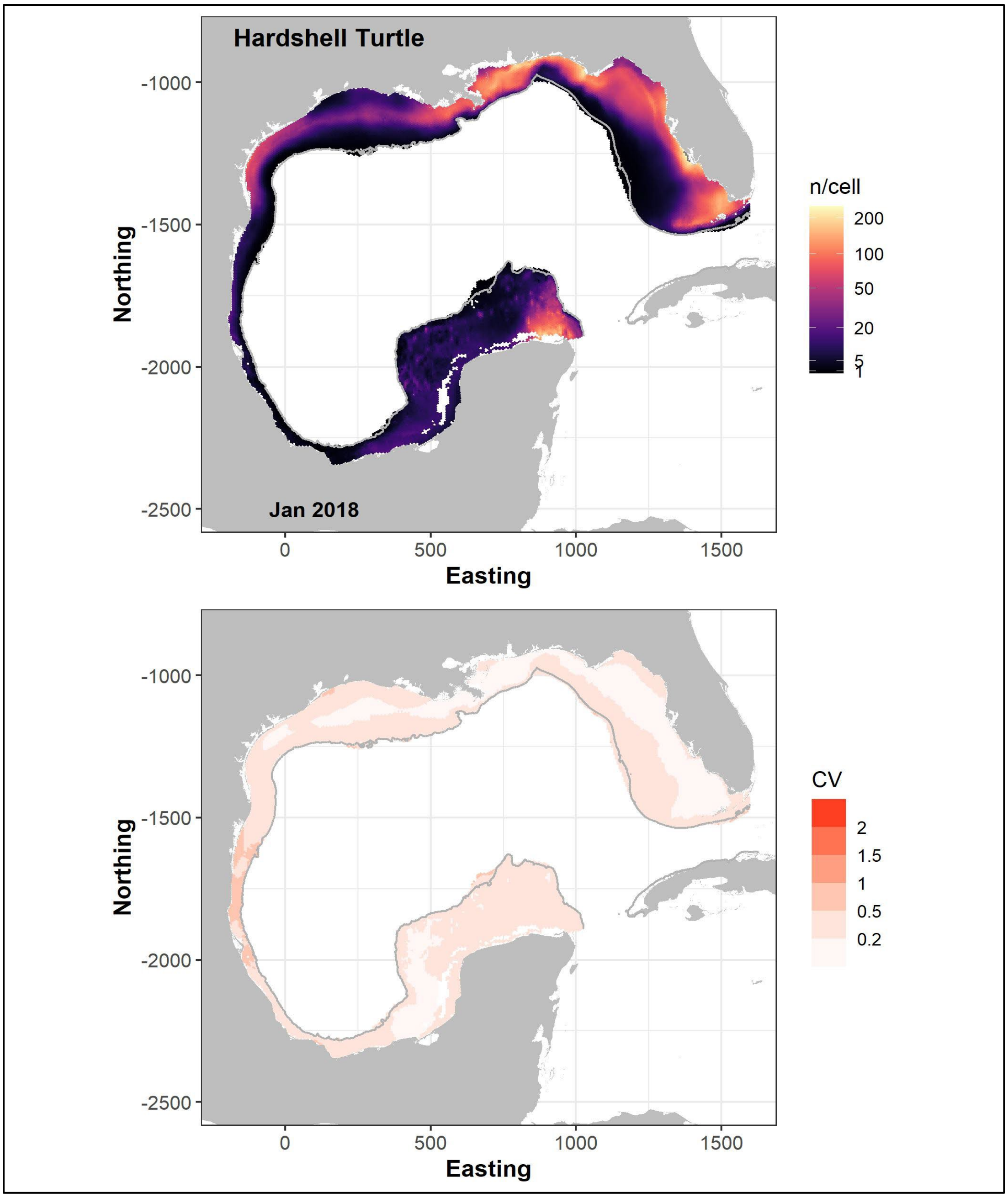

Figure D.5-26. Projected density model for shelf unidentified hardshell turtles in the entire GOM for January 2018.

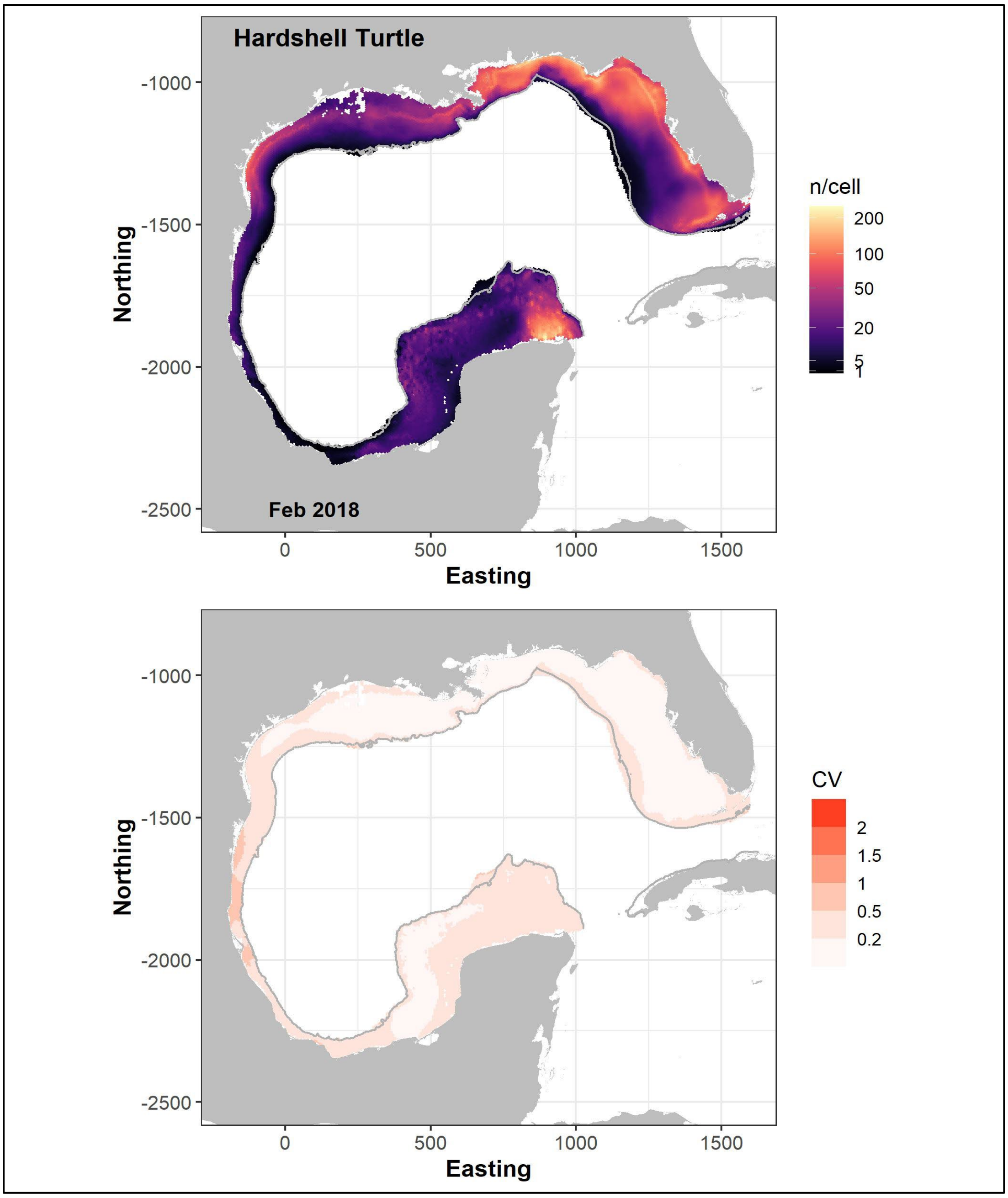

Figure D.5-27. Projected density model for shelf unidentified hardshell turtles in the entire GOM for February 2018.

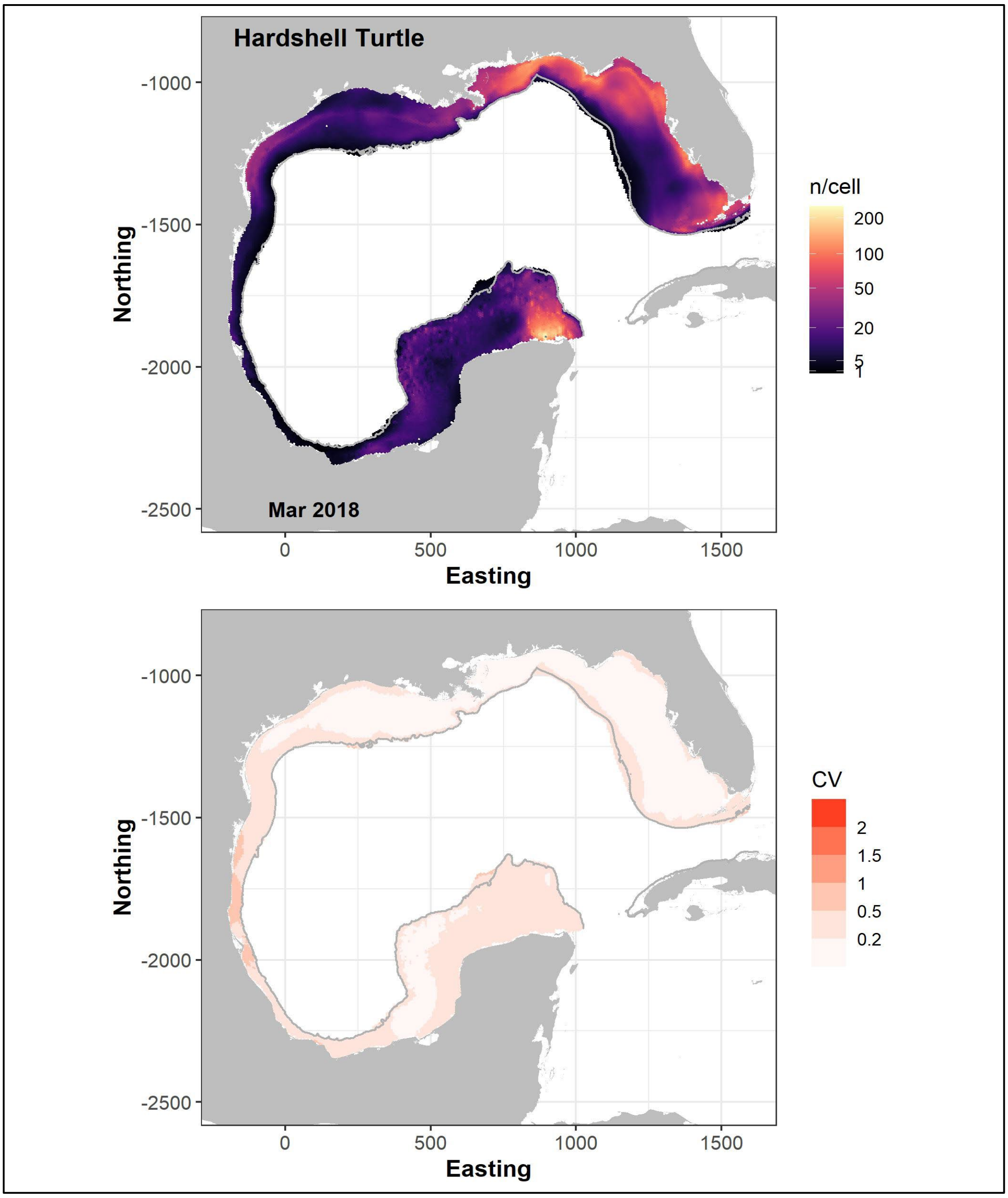

Figure D.5-28. Projected density model for shelf unidentified hardshell turtles in the entire GOM for March 2018.

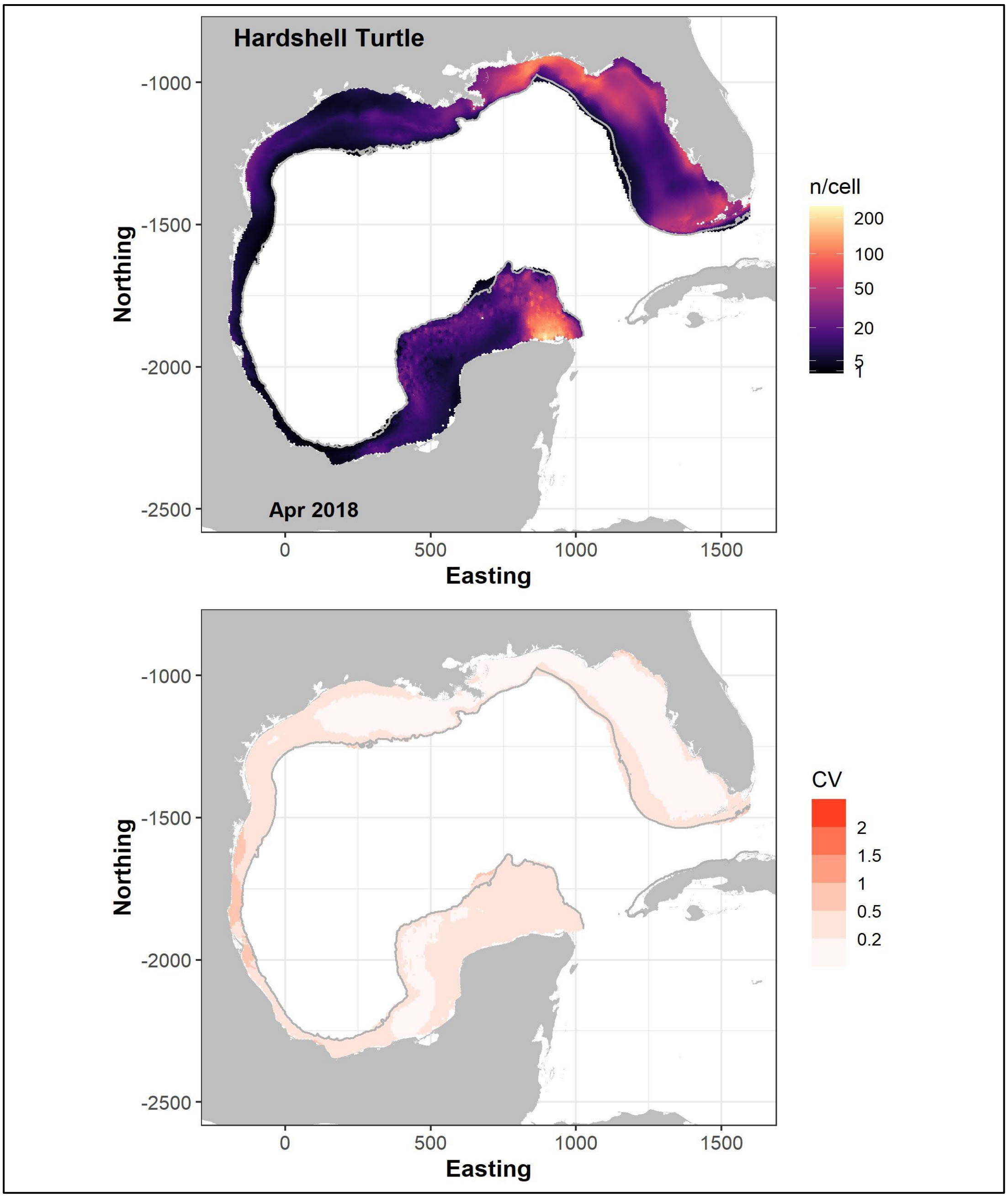

Figure D.5-29. Projected density model for shelf unidentified hardshell turtles in the entire GOM for April 2018.

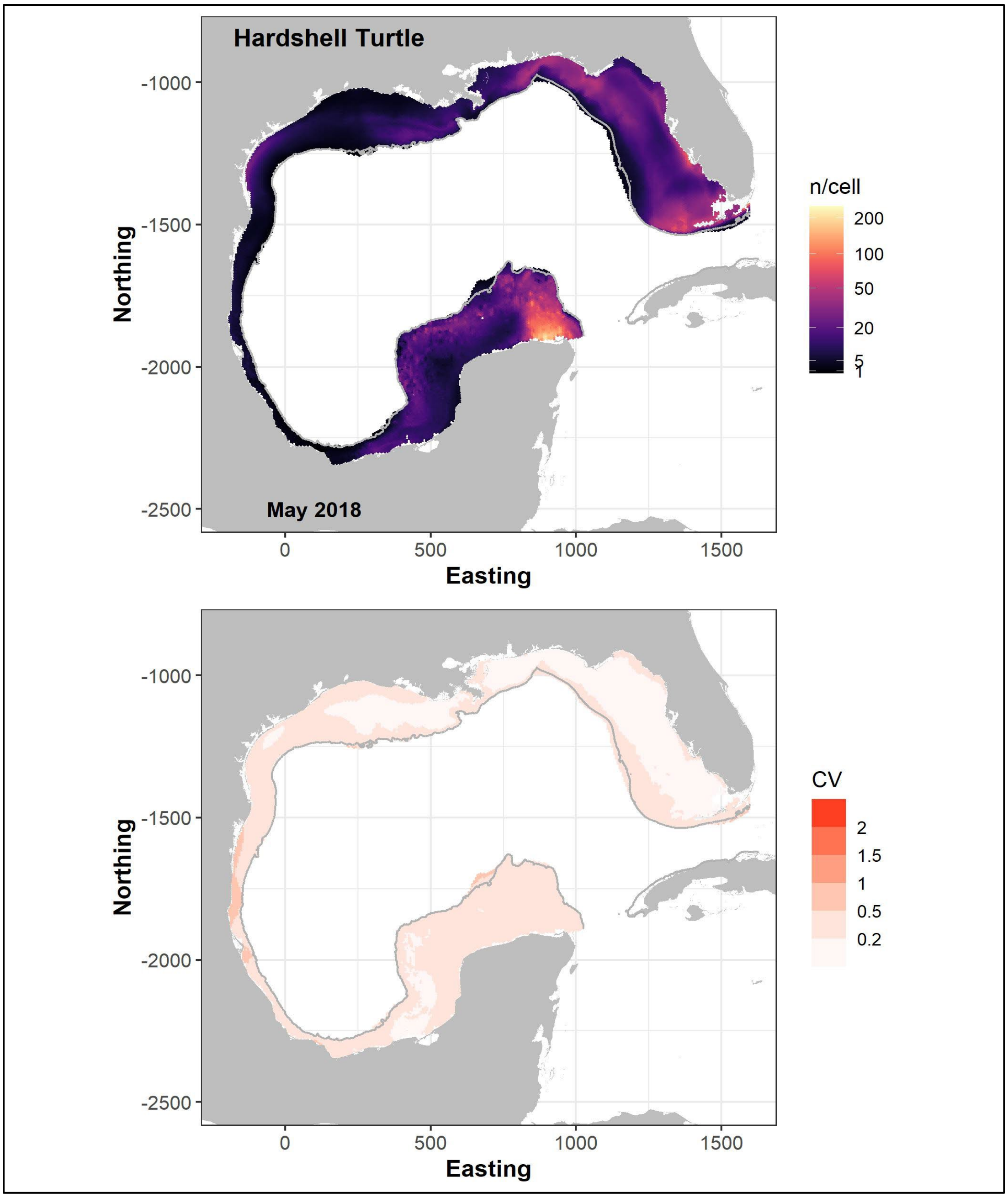

Figure D.5-30. Projected density model for shelf unidentified hardshell turtles in the entire GOM for May 2018.

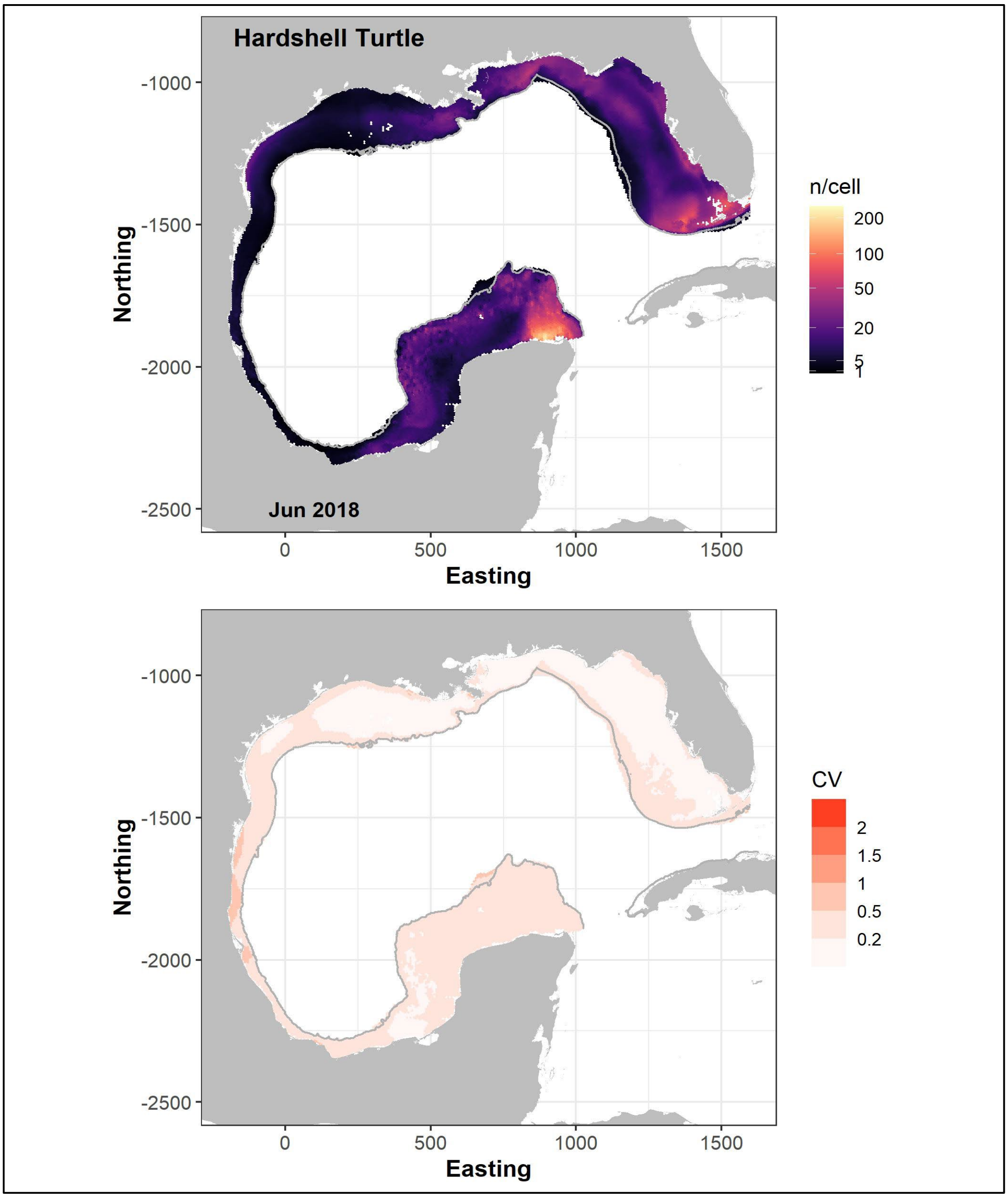

Figure D.5-31. Projected density model for shelf unidentified hardshell turtles in the entire GOM for June 2018.

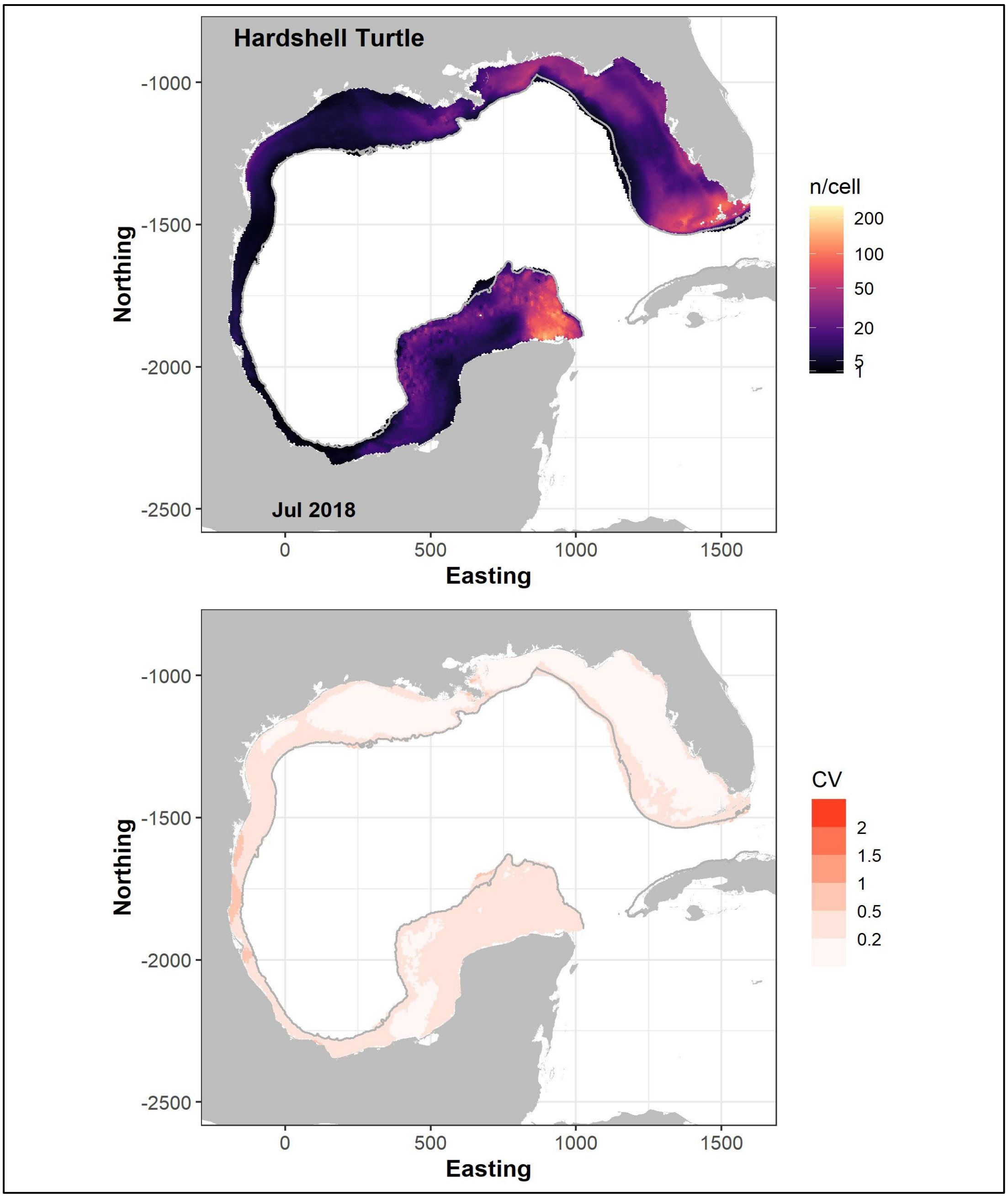

Figure D.5-32. Projected density model for shelf unidentified hardshell turtles in the entire GOM for July 2018.

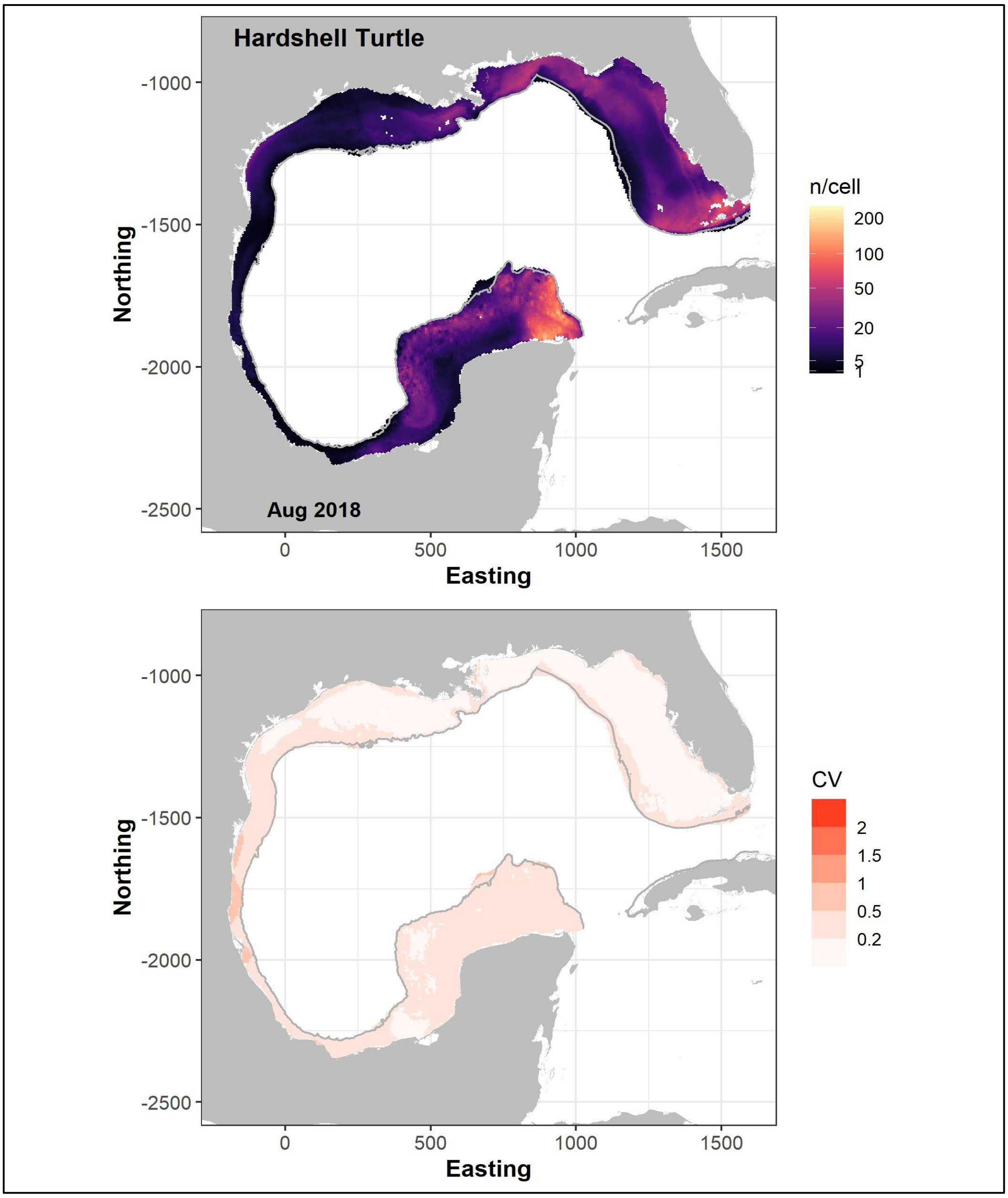

Figure D.5-33. Projected density model for shelf unidentified hardshell turtles in the entire GOM for August 2018.

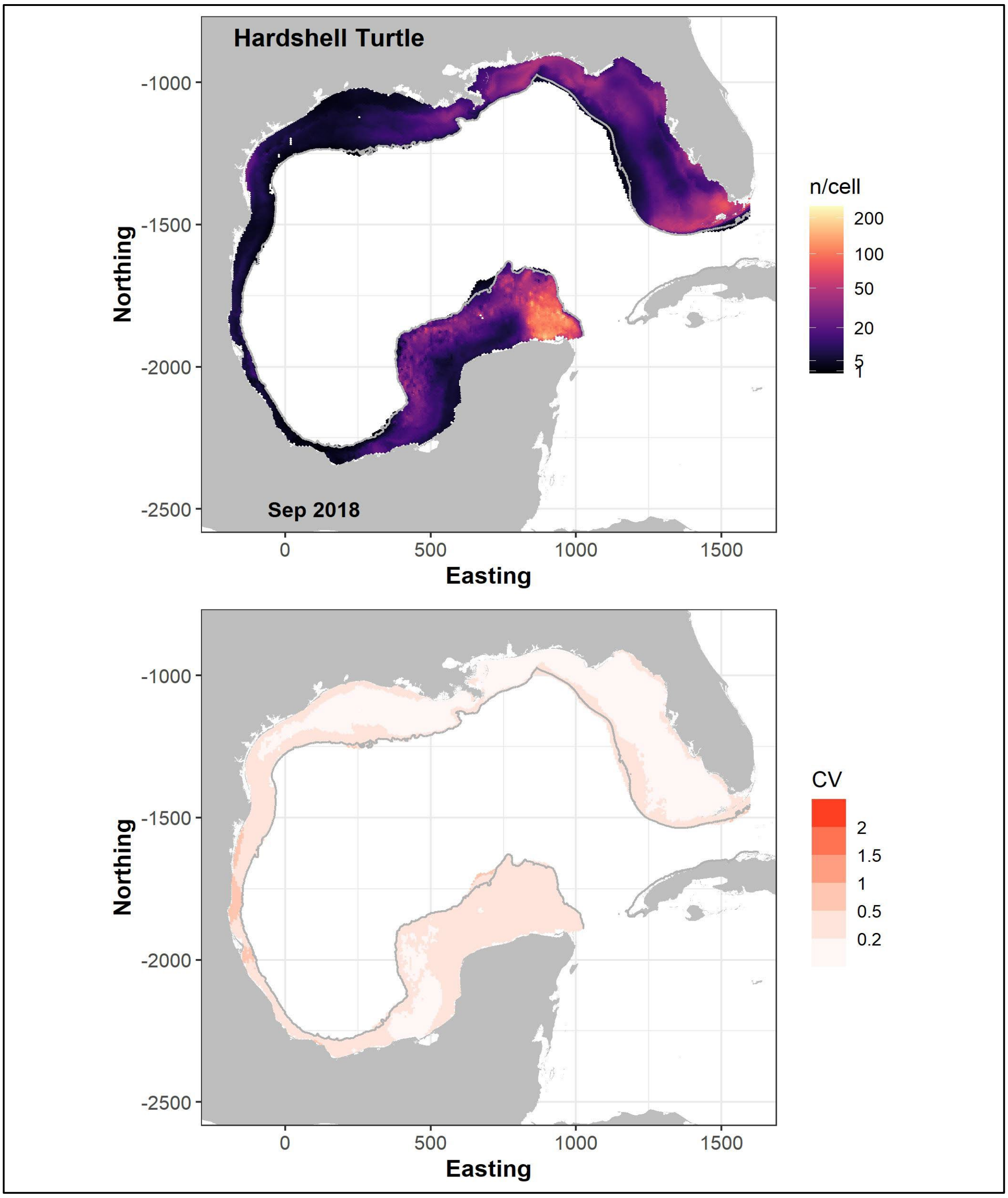

Figure D.5-34. Projected density model for shelf unidentified hardshell turtles in the entire GOM for September 2018.

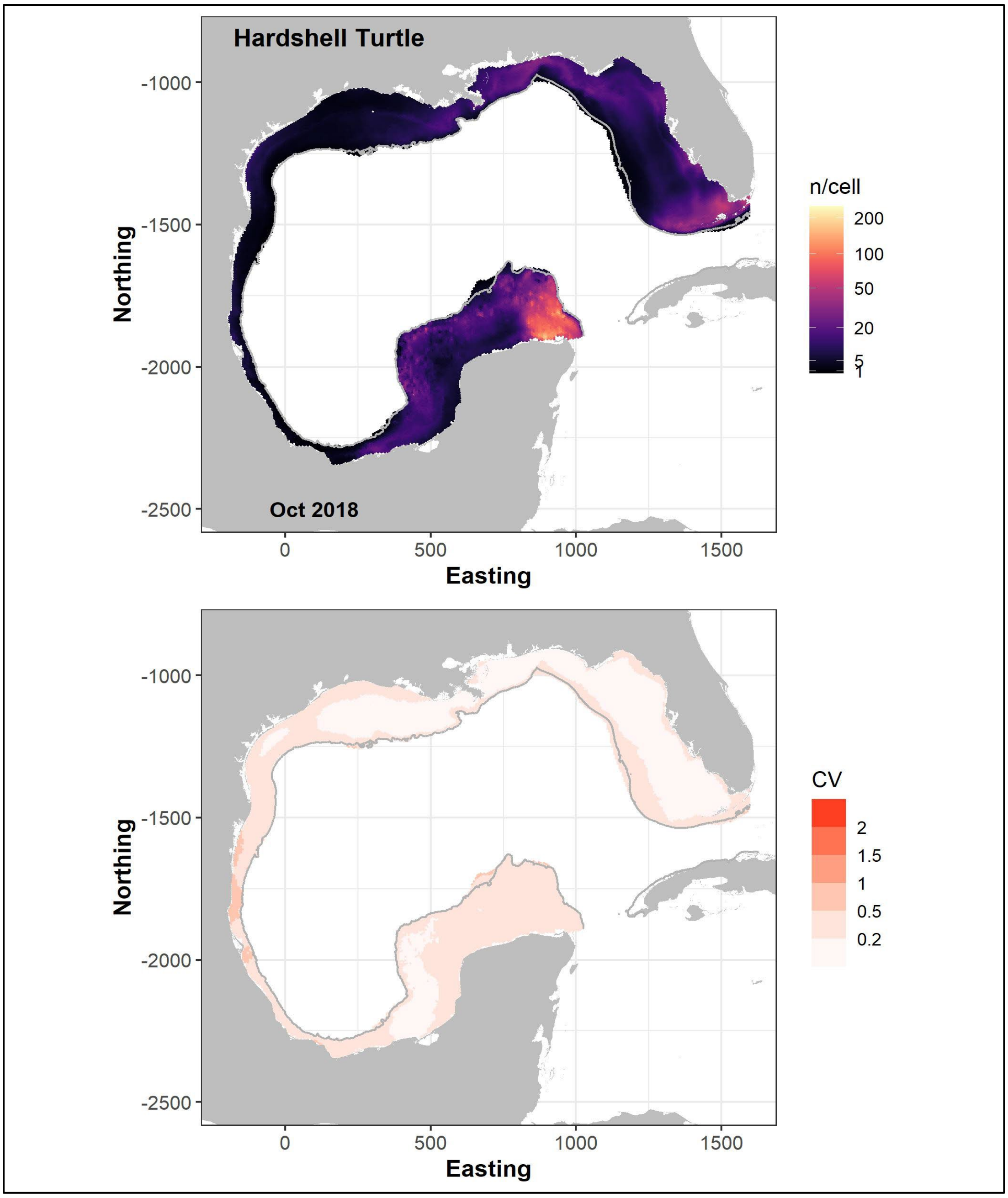

Figure D.5-35. Projected density model for shelf unidentified hardshell turtles in the entire GOM for October 2018.

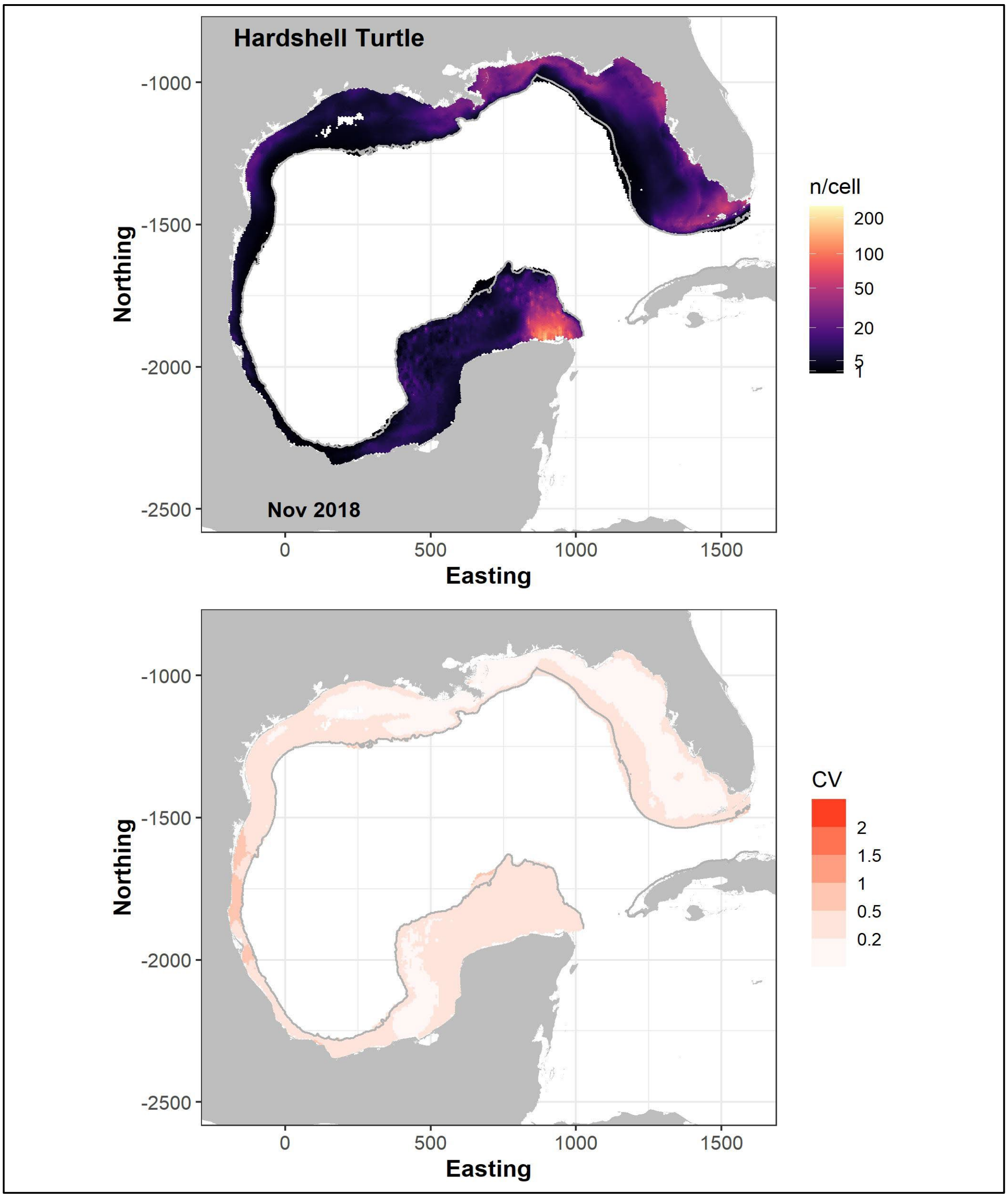

Figure D.5-36. Projected density model for shelf unidentified hardshell turtles in the entire GOM for November 2018.

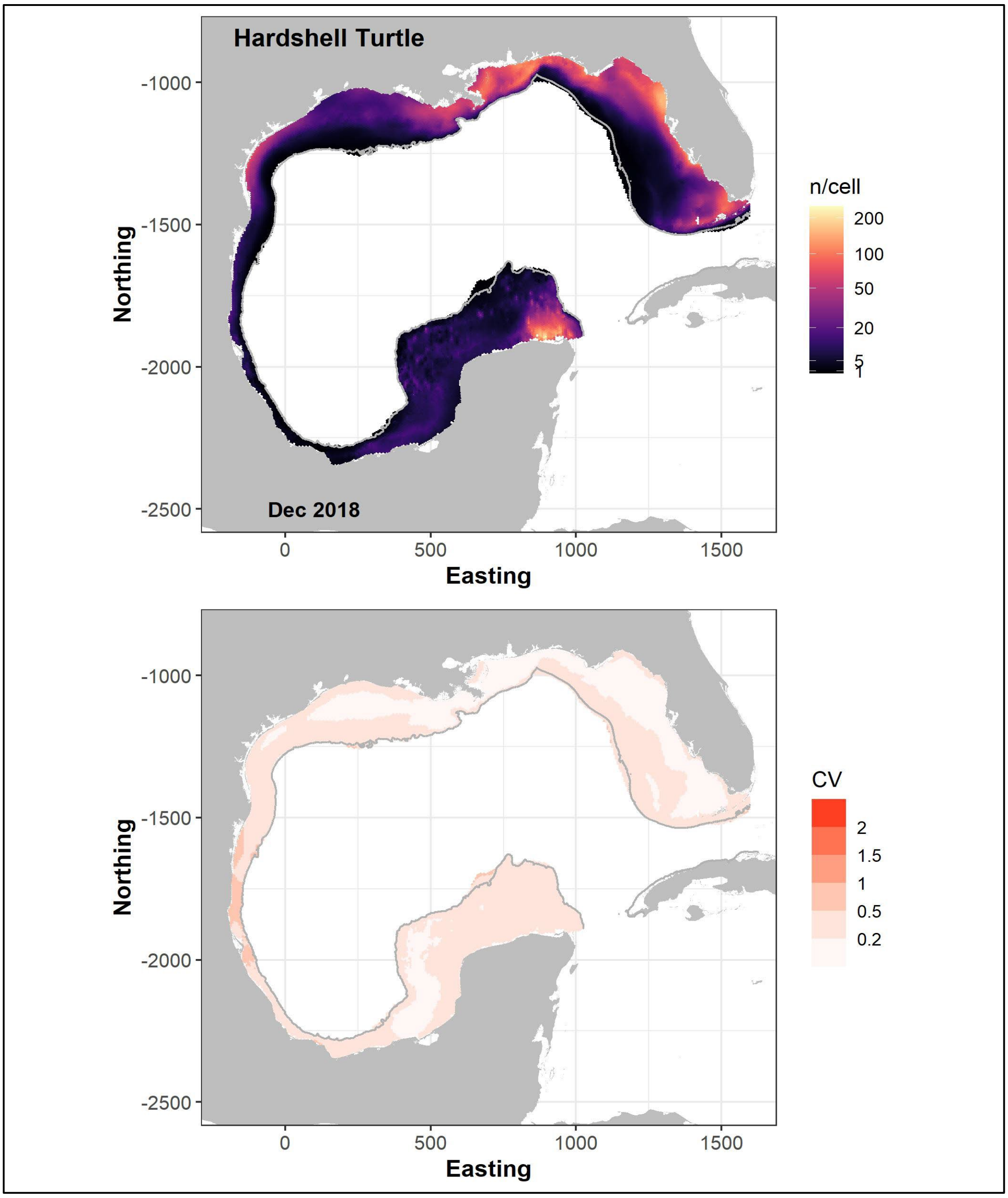

Figure D.5-37. Projected density model for shelf unidentified hardshell turtles in the entire GOM for December 2018.

D.5.5.3 Average Monthly Density: 2015–2019

Prediction maps were generated using monthly environmental parameters for the period of 2015–2019. The posterior distribution of the GAM parameters was sampled 1,000 times to generate a distribution of model coefficients that reflect the statistical uncertainty in the parameter estimation. Predictions of animal density were generated for each month in the 2015–2019 period based on each of these 1,000 parameter sets. In this way, both inter-annual variability in environmental conditions and model uncertainty were included in the resulting samples. The monthly predictions were examined to identify sampled parameters that generated extreme predicted densities, and these extreme values

were excluded from the bootstrap sample before variance estimation. These extreme values, associated with density predictions many orders of magnitude higher than the observed median, reflect projection of the model predictions into poorly sampled parameter space. It was not necessary to trim the bootstrap iterations for unidentified hardshell turtles. The resulting distribution of realizations was used to summarize predicted average densities by month and to calculate metrics of uncertainty (Figures D.5-38–D.5-49).

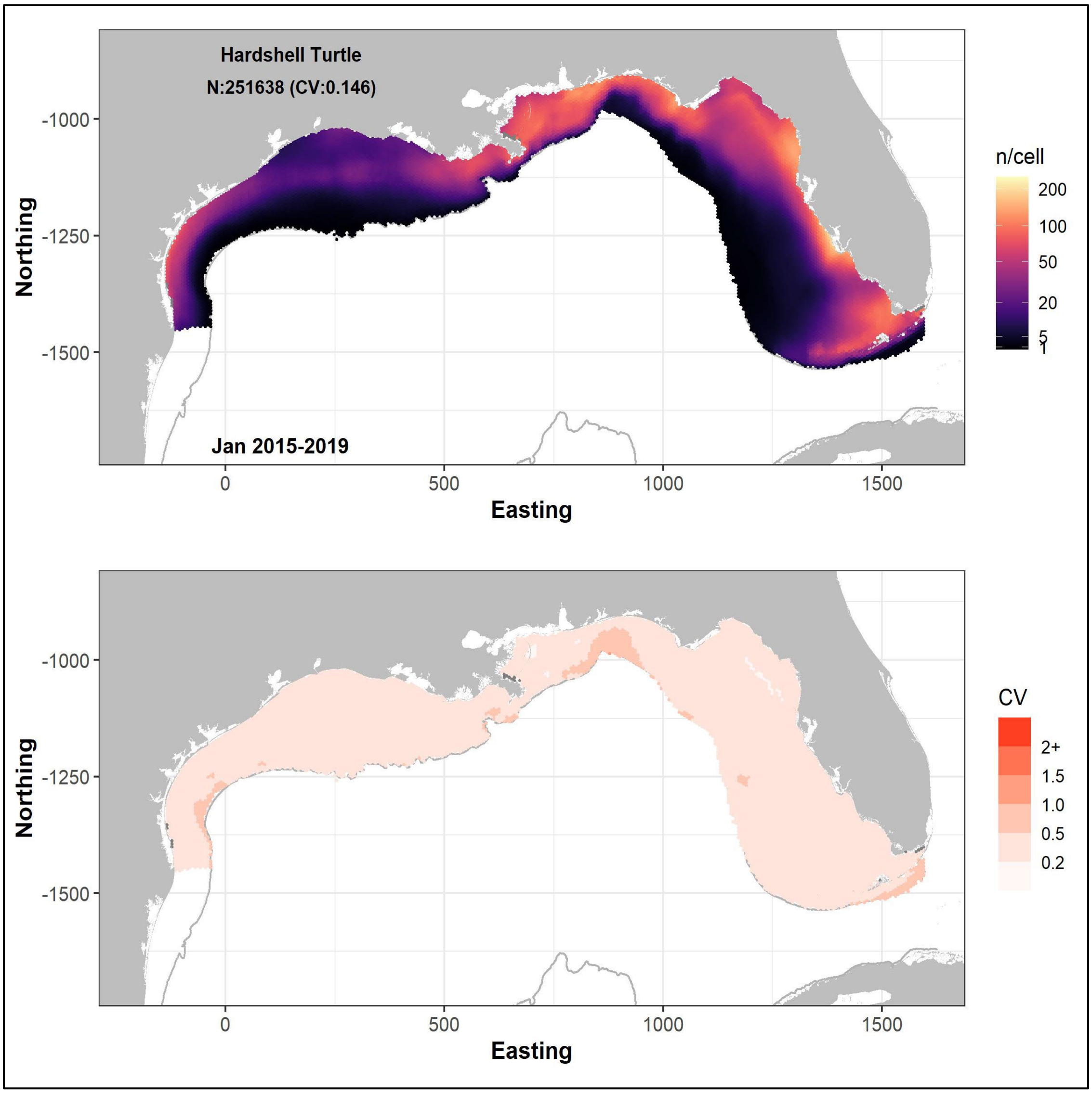

Figure D.5-38. Density model prediction for shelf unidentified hardshell turtles in the NGOM for the months of January 2015–2019.

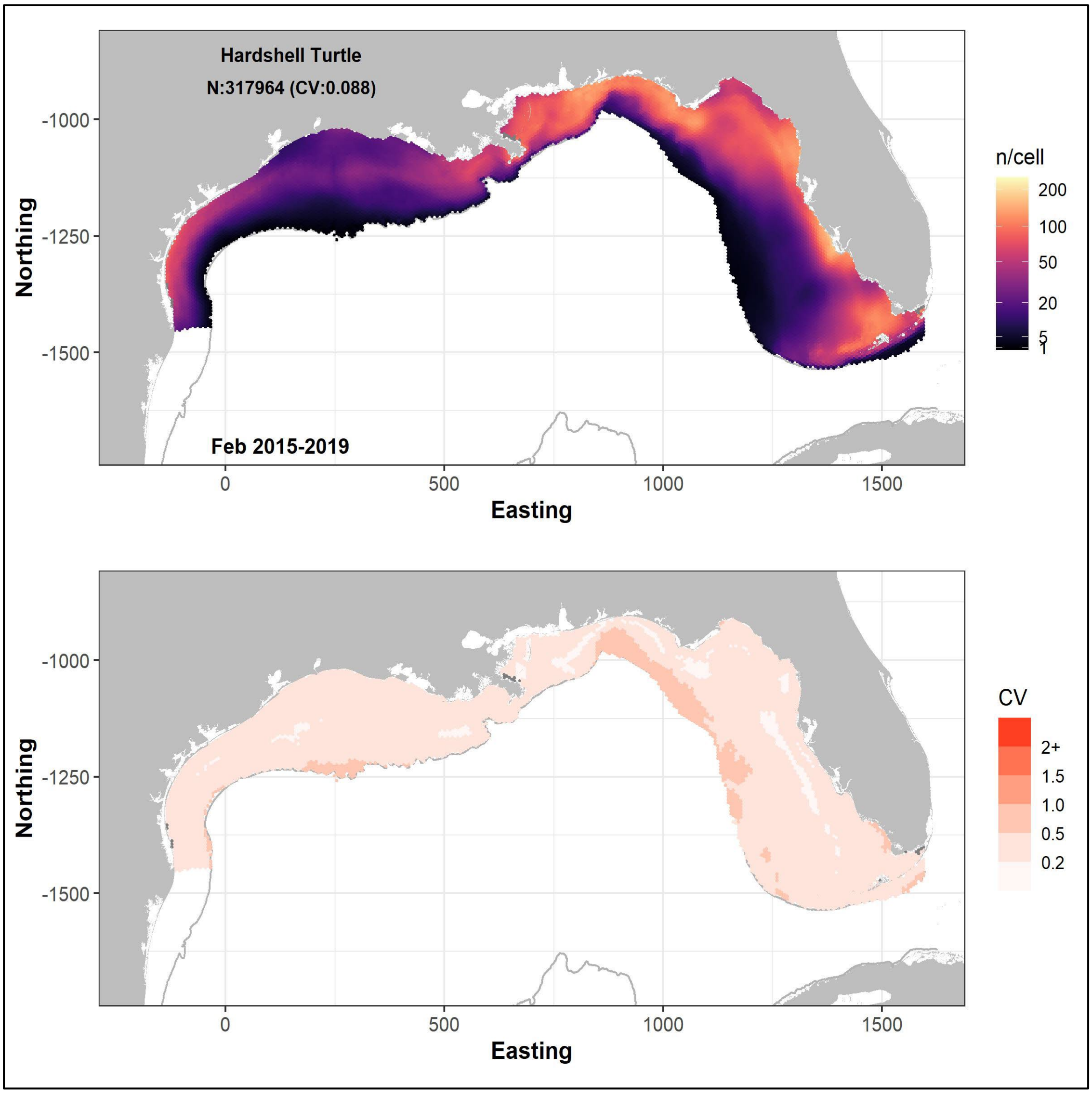

Figure D.5-39. Density model prediction for shelf unidentified hardshell turtles in the NGOM for the months of February 2015–2019.

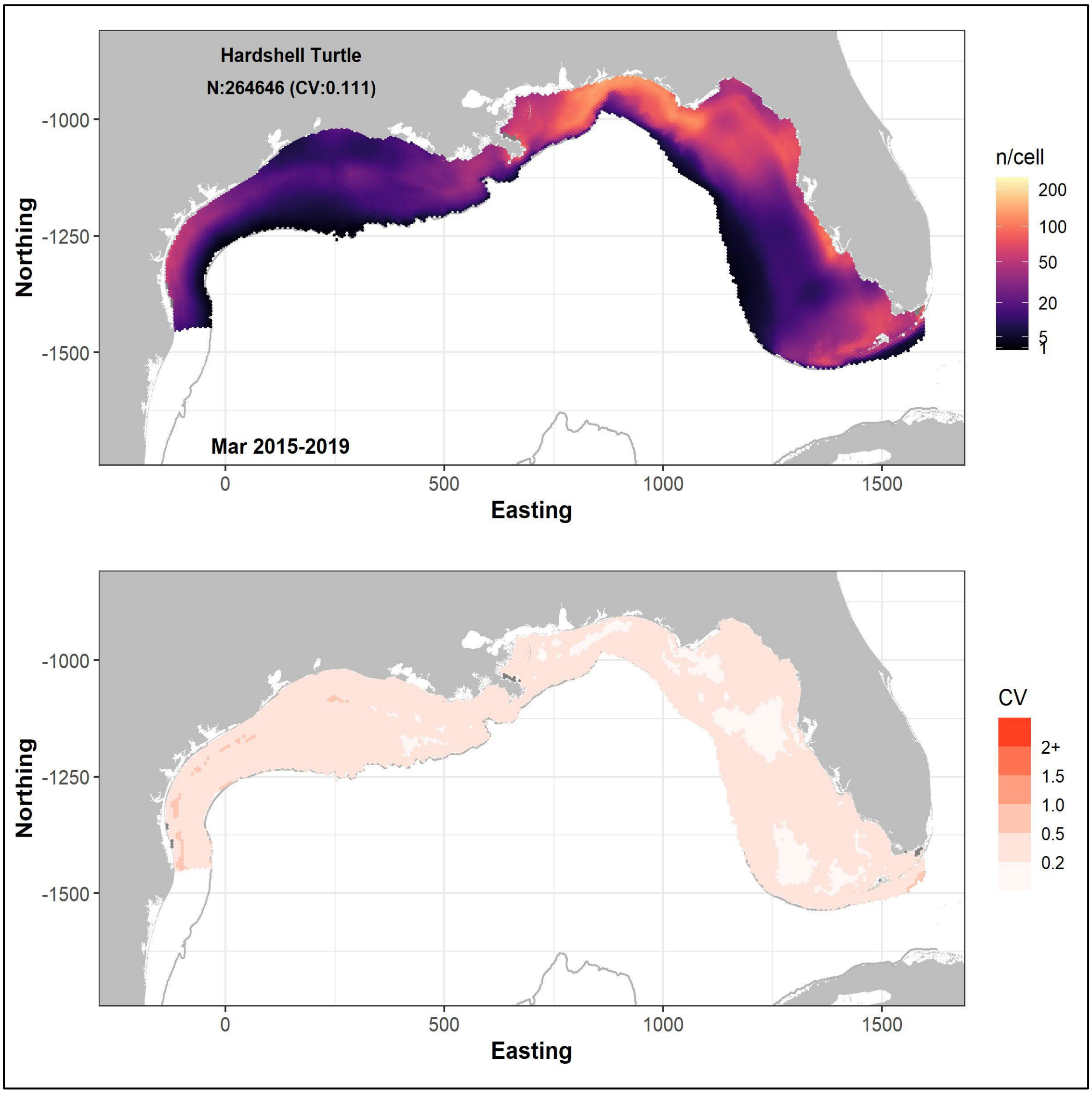

Figure D.5-40. Density model prediction for shelf unidentified hardshell turtles in the NGOM for the months of March 2015–2019.

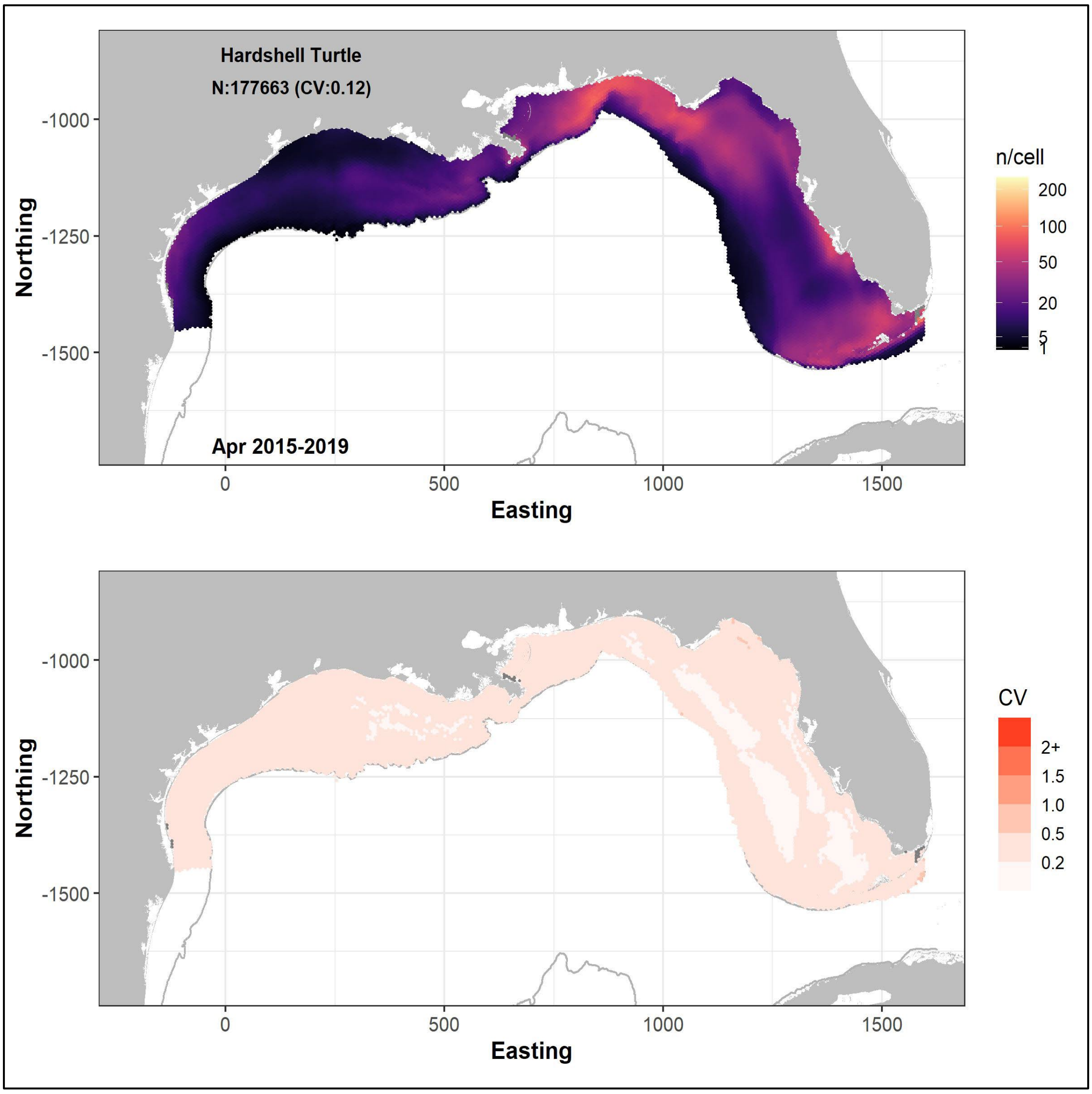

Figure D.5-41. Density model prediction for shelf unidentified hardshell turtles in the NGOM for the months of April 2015–2019.

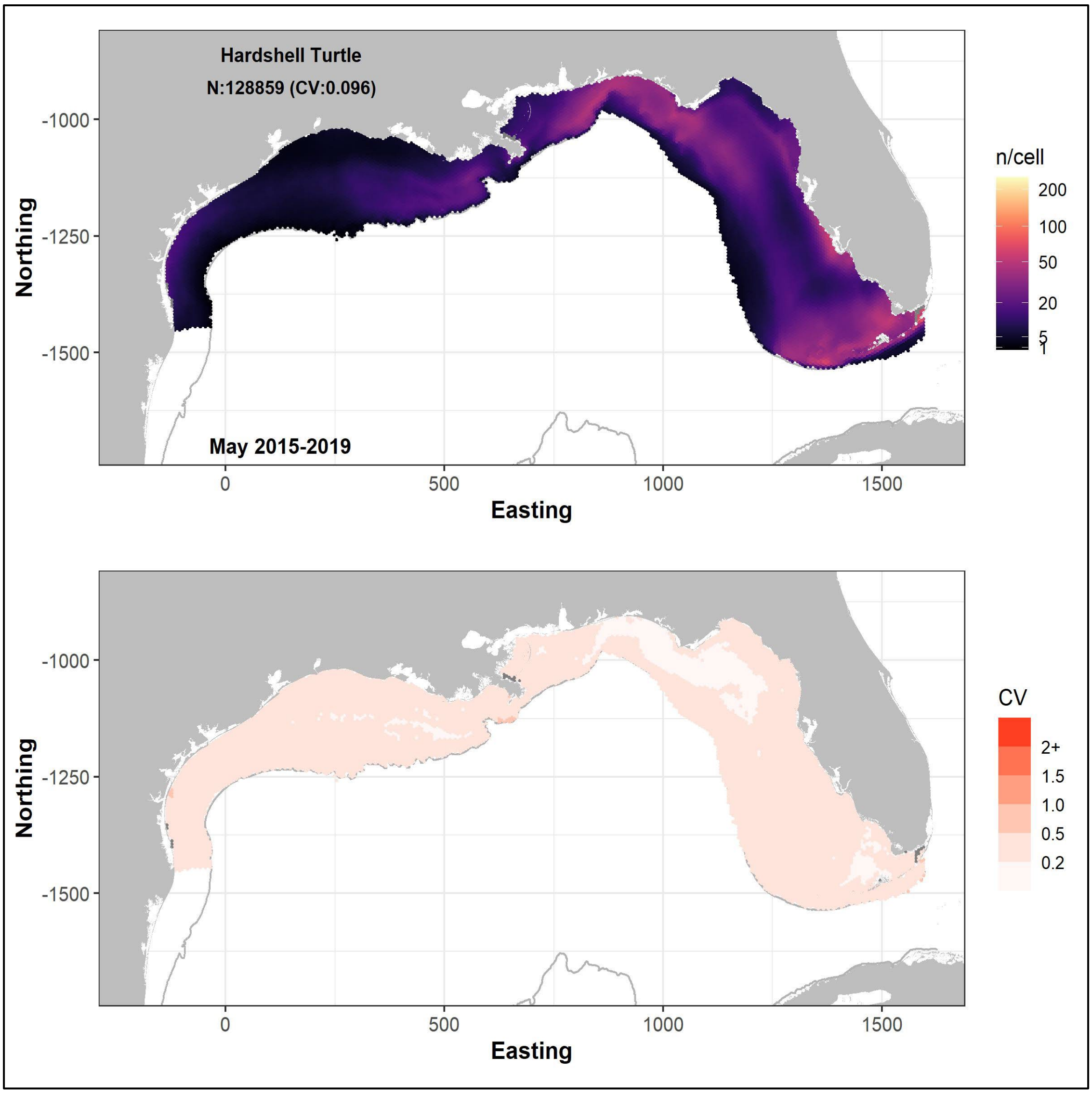

Figure D.5-42. Density model prediction for shelf unidentified hardshell turtles in the NGOM for the months of May 2015–2019.

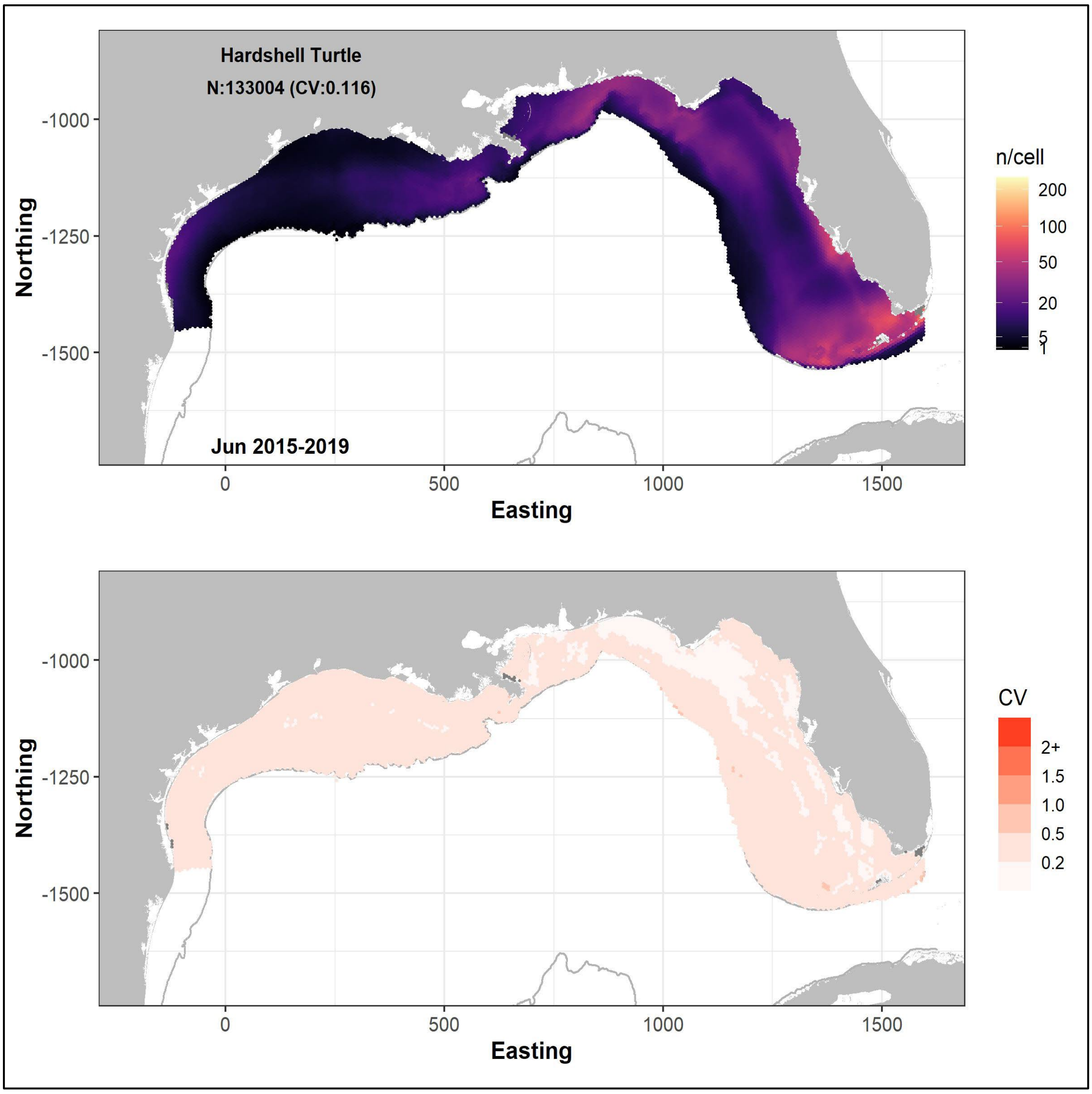

Figure D.5-43. Density model prediction for shelf unidentified hardshell turtles in the NGOM for the months of June 2015–2019.

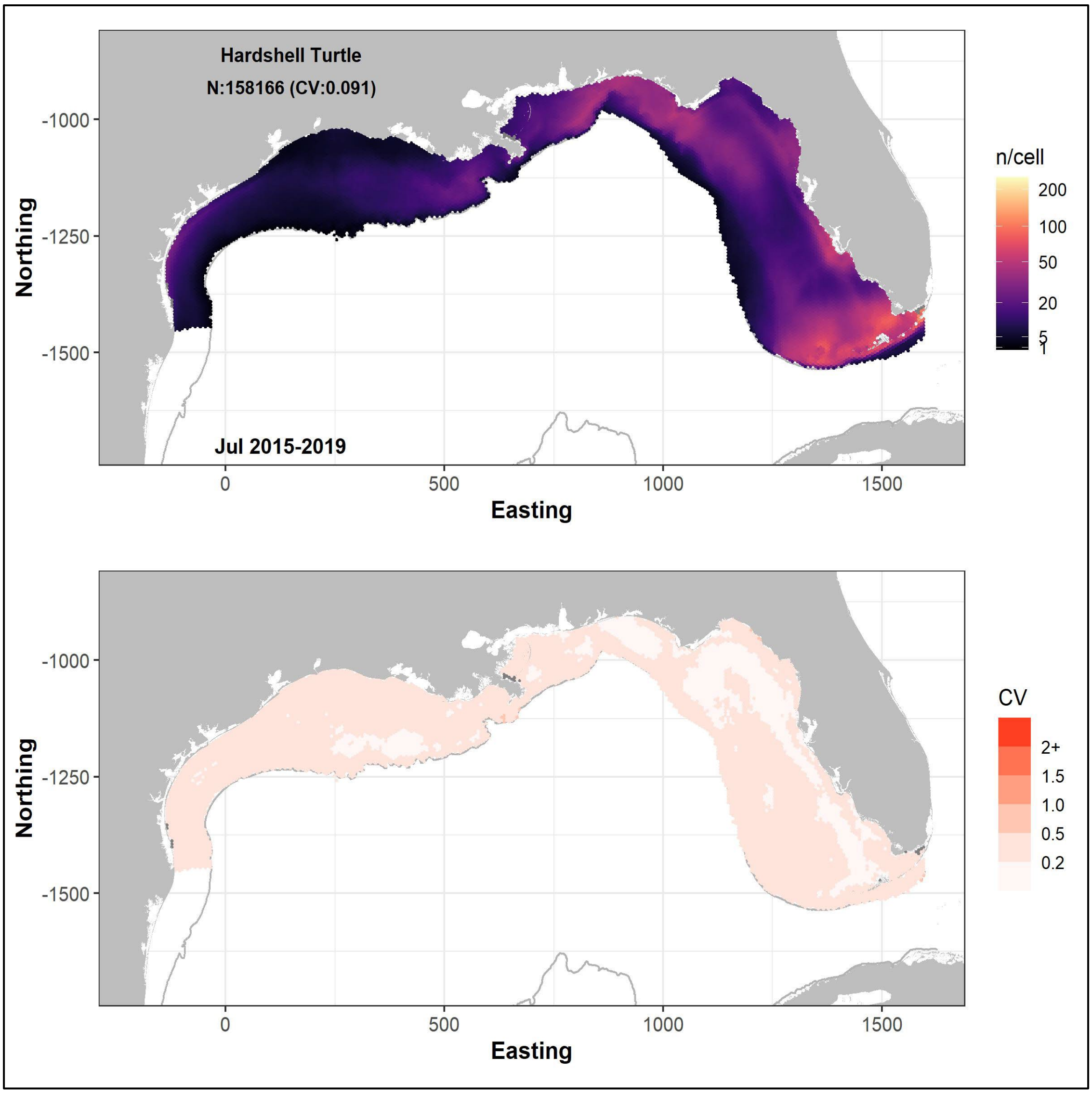

Figure D.5-44. Density model prediction for shelf unidentified hardshell turtles in the NGOM for the months of July 2015–2019.

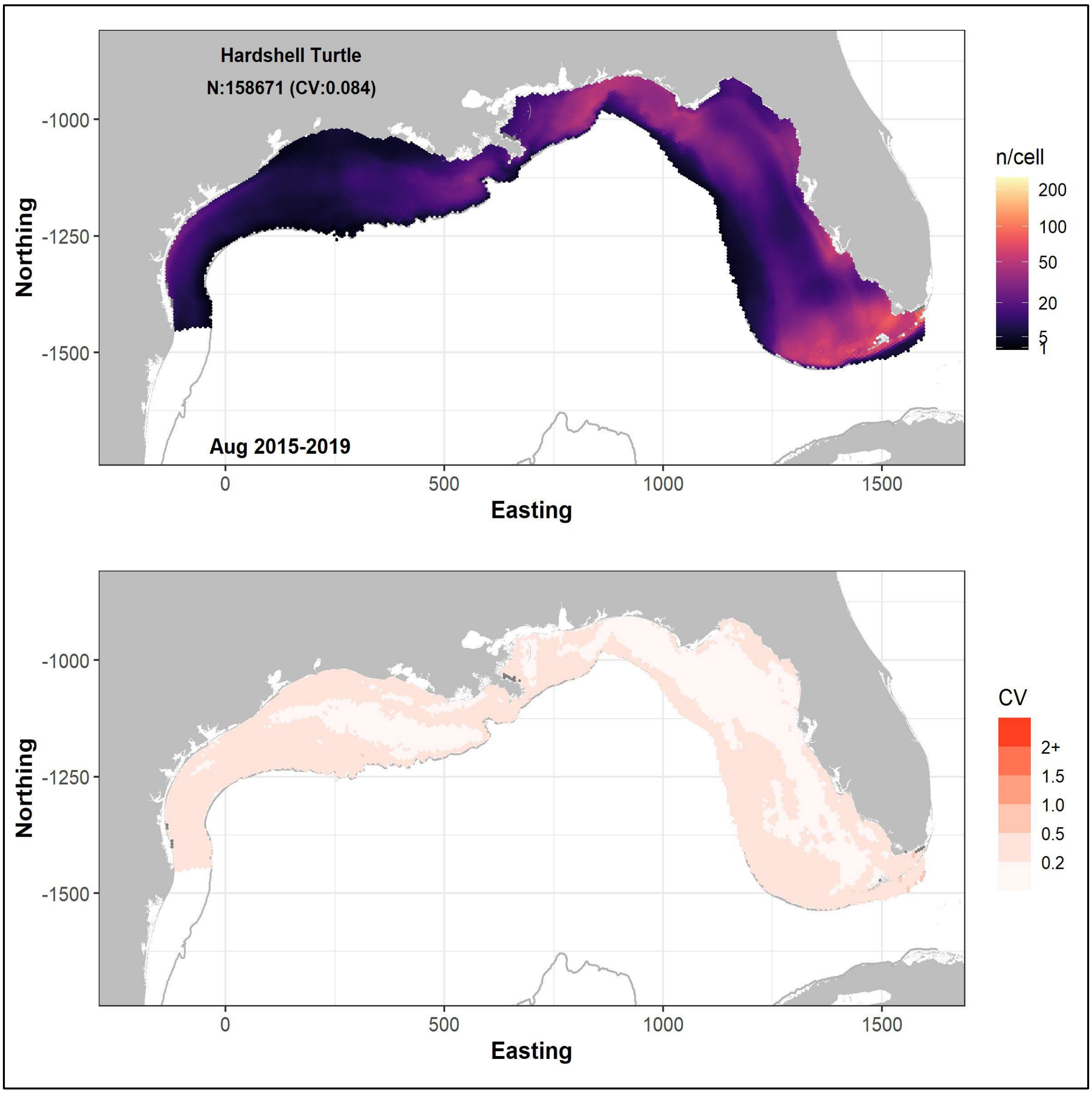

Figure D.5-45. Density model prediction for shelf unidentified hardshell turtles in the NGOM for the months of August 2015–2019.

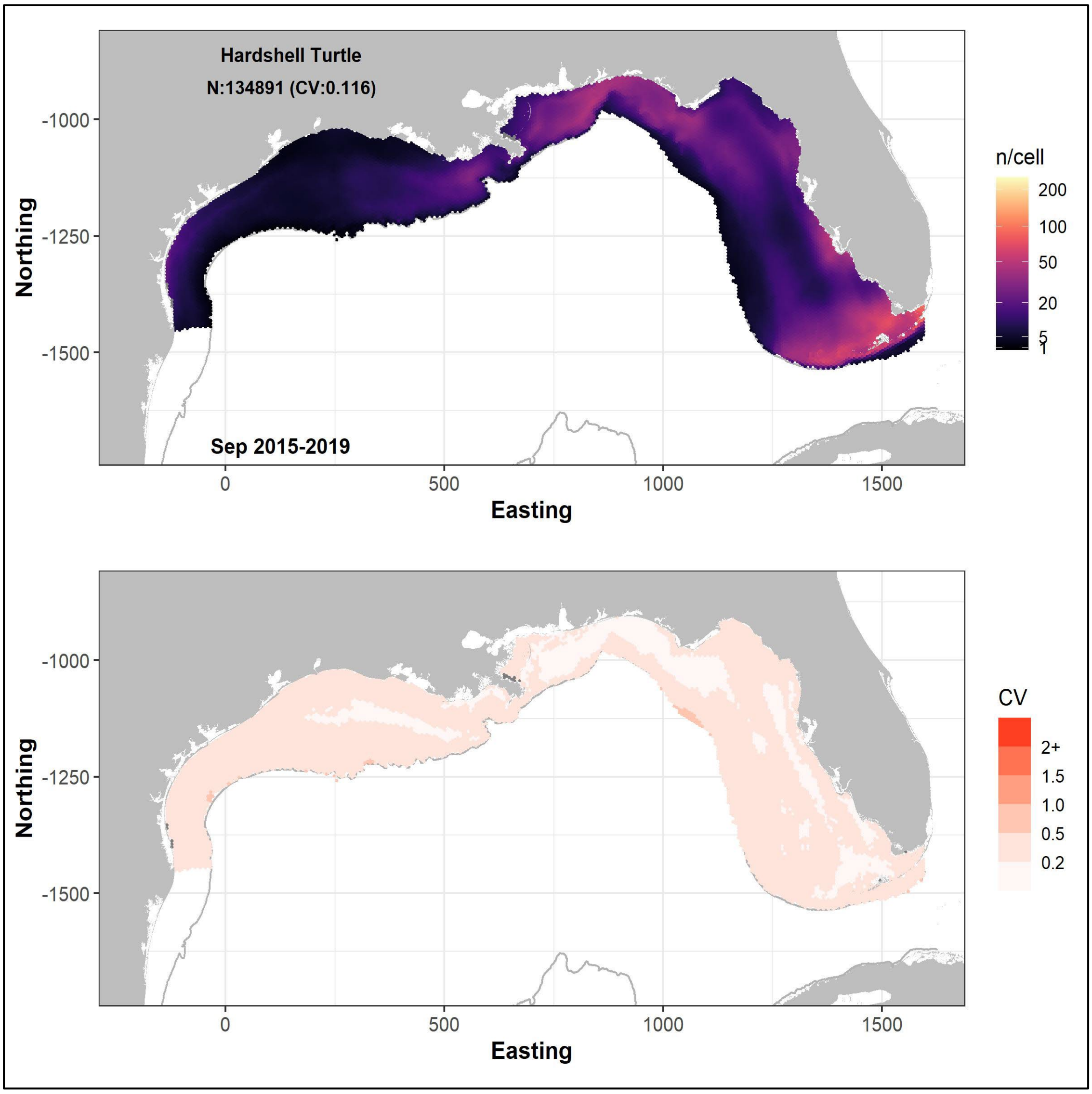

Figure D.5-46. Density model prediction for shelf unidentified hardshell turtles in the NGOM for the months of September 2015–2019.

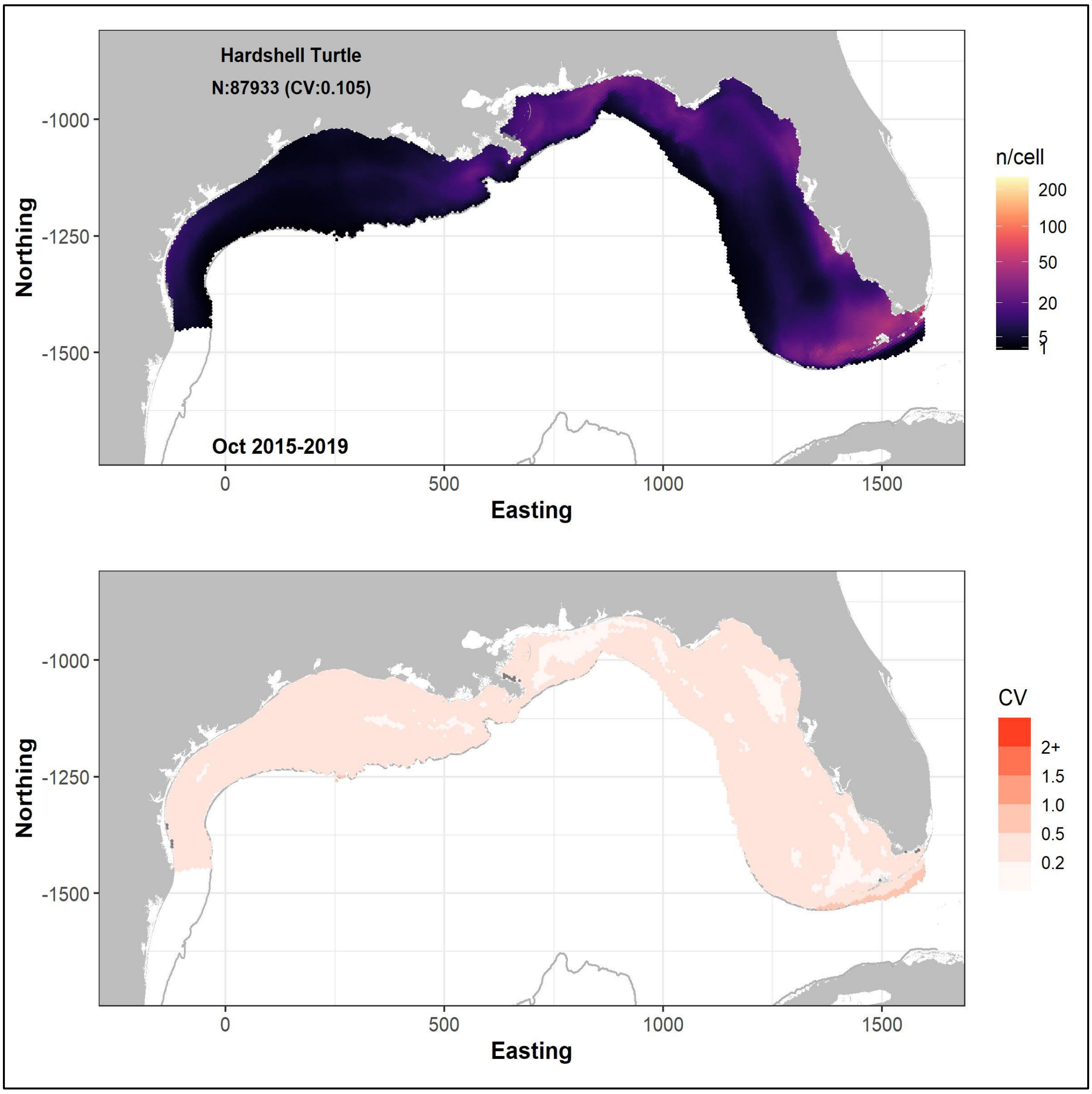

Figure D.5-47. Density model prediction for shelf unidentified hardshell turtles in the NGOM for the months of October 2015–2019.

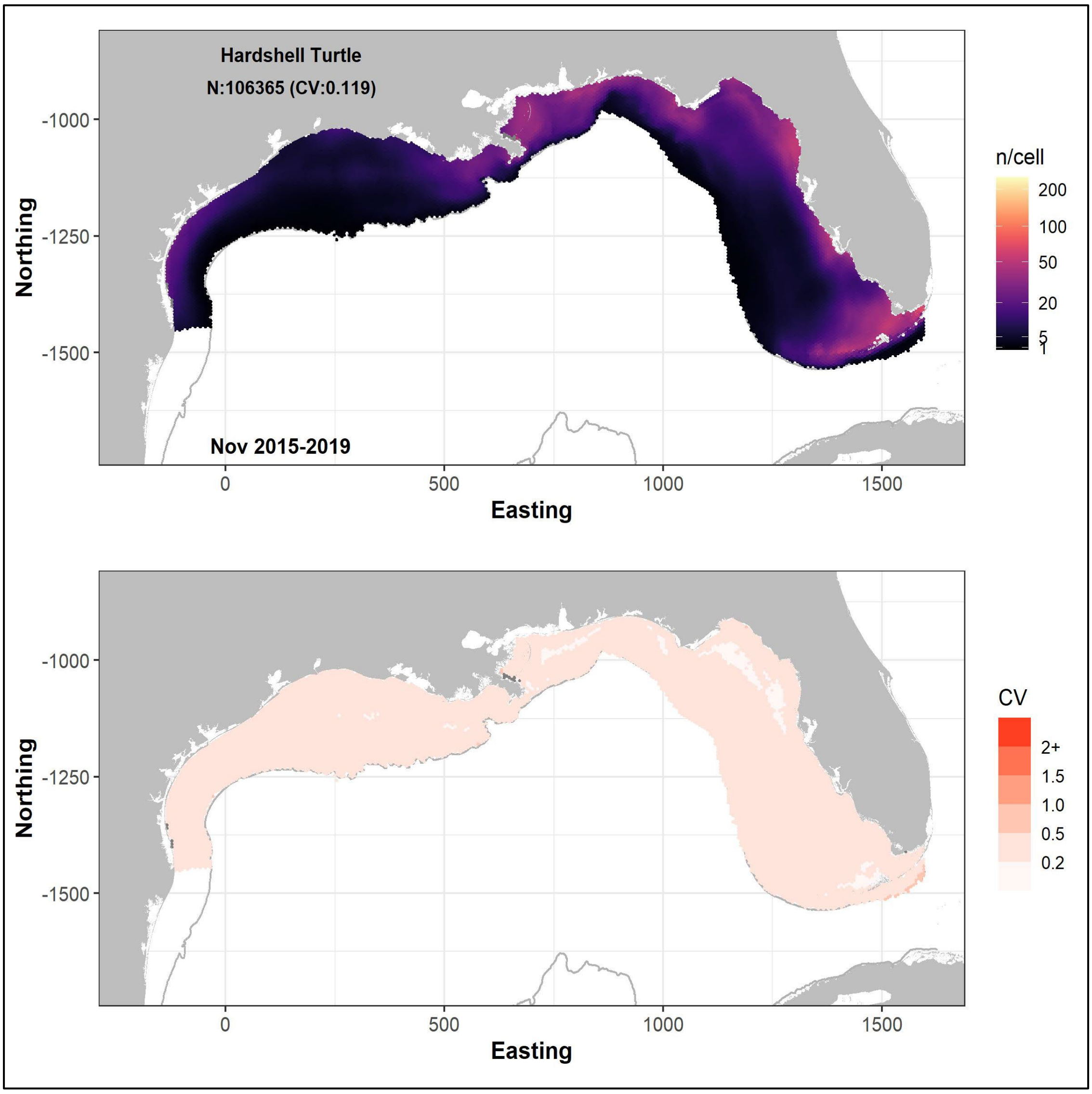

Figure D.5-48. Density model prediction for shelf unidentified hardshell turtles in the NGOM for the months of November 2015–2019.

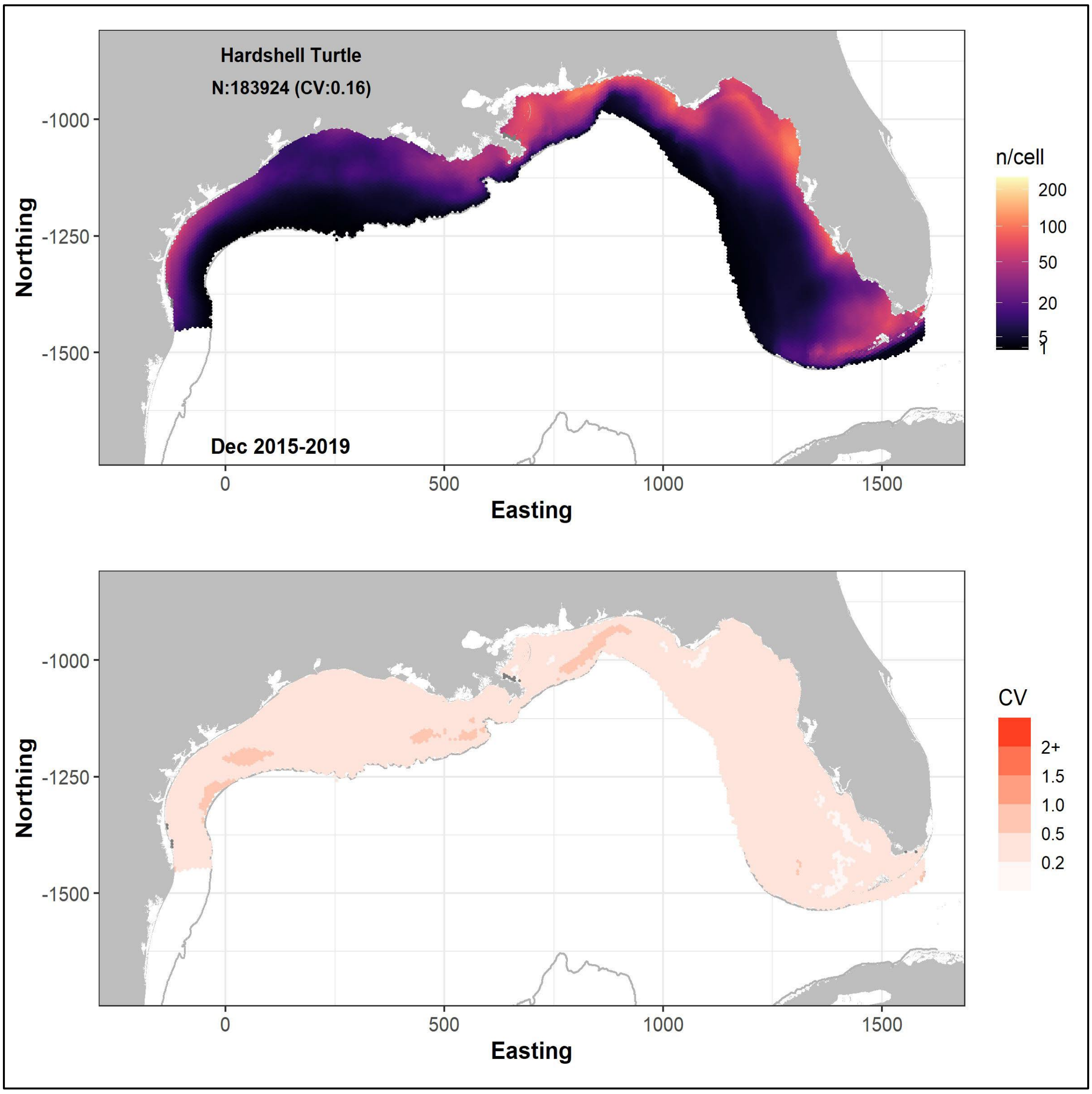

Figure D.5-49. Density model prediction for shelf unidentified hardshell turtles in the NGOM for the months of December 2015–2019.

D.5.5.4 Gulf-Wide Average Monthly Density: 2015–2019

Prediction maps were generated using monthly environmental parameters for the period of 2015–2019 extrapolating the model for unidentified hardshell turtles throughout the GOM. As noted above, these extrapolations should be treated with caution given the potential for changing species-environment relationships in unsampled areas (Figures D.5-50–D.5-61).

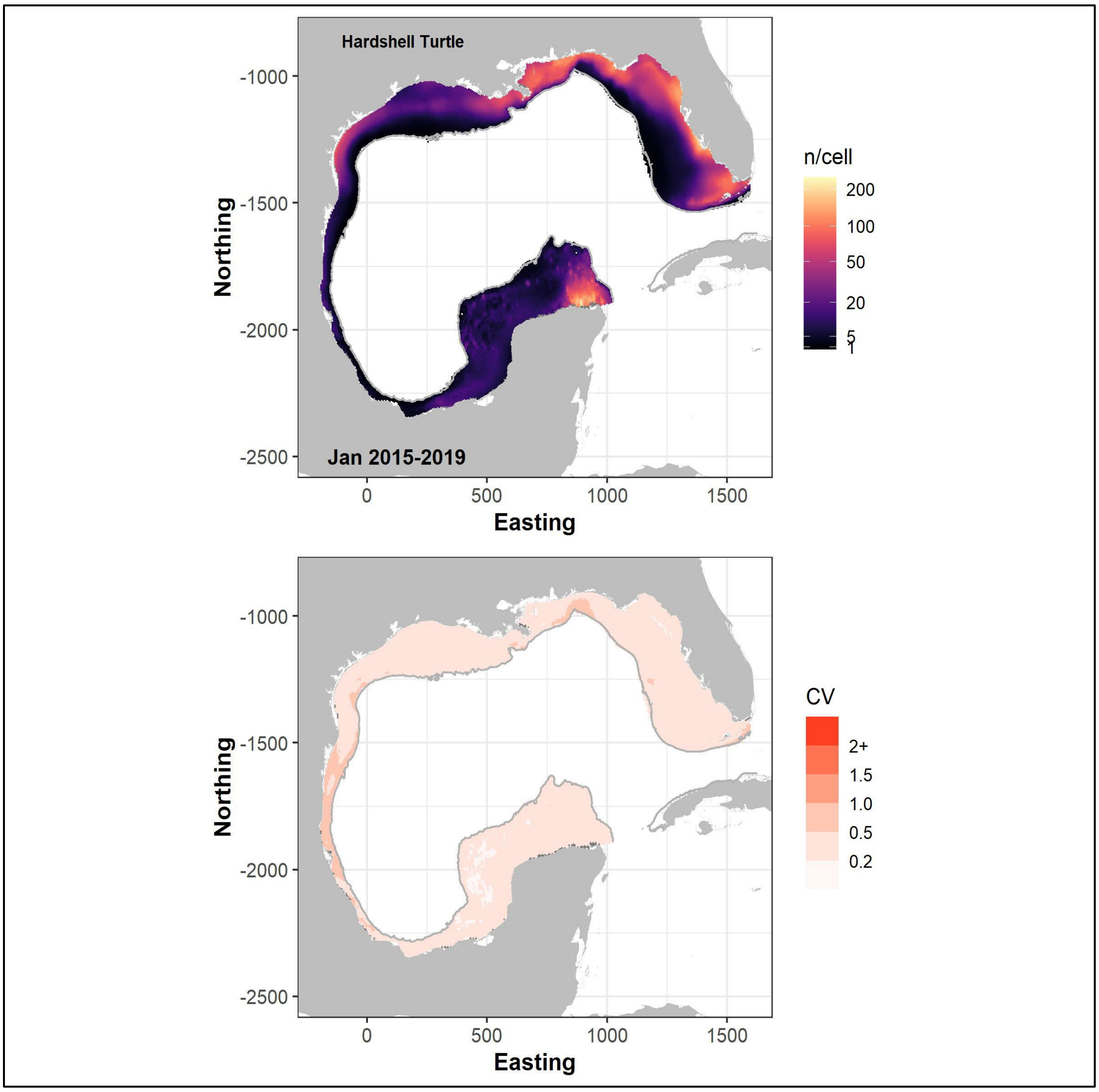

Figure D.5-50. Projected density model for shelf unidentified hardshell turtles in the entire GOM for the months of January 2015–2019.

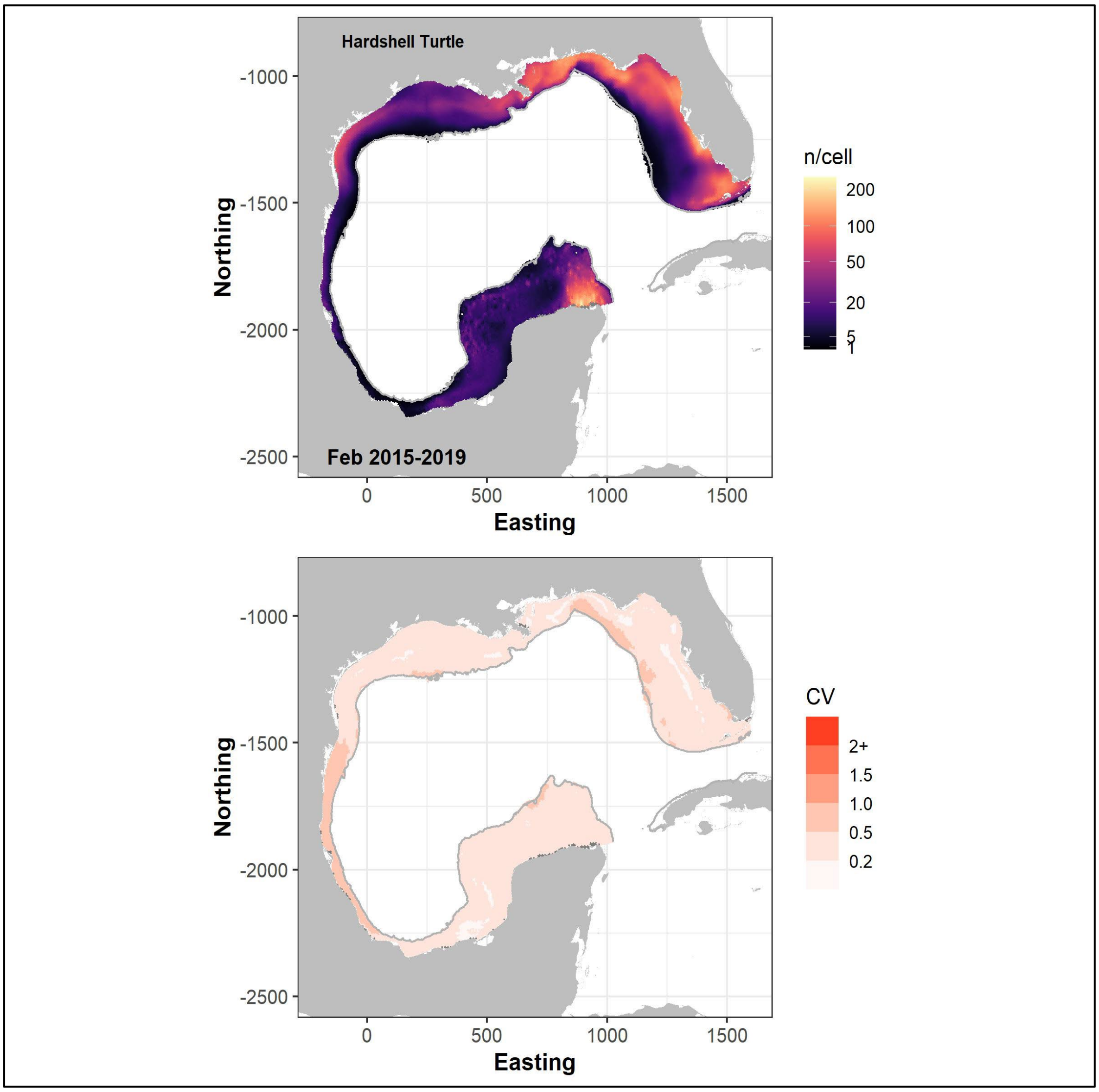

Figure D.5-51. Projected density model for shelf unidentified hardshell turtles in the entire GOM for the months of February 2015–2019.

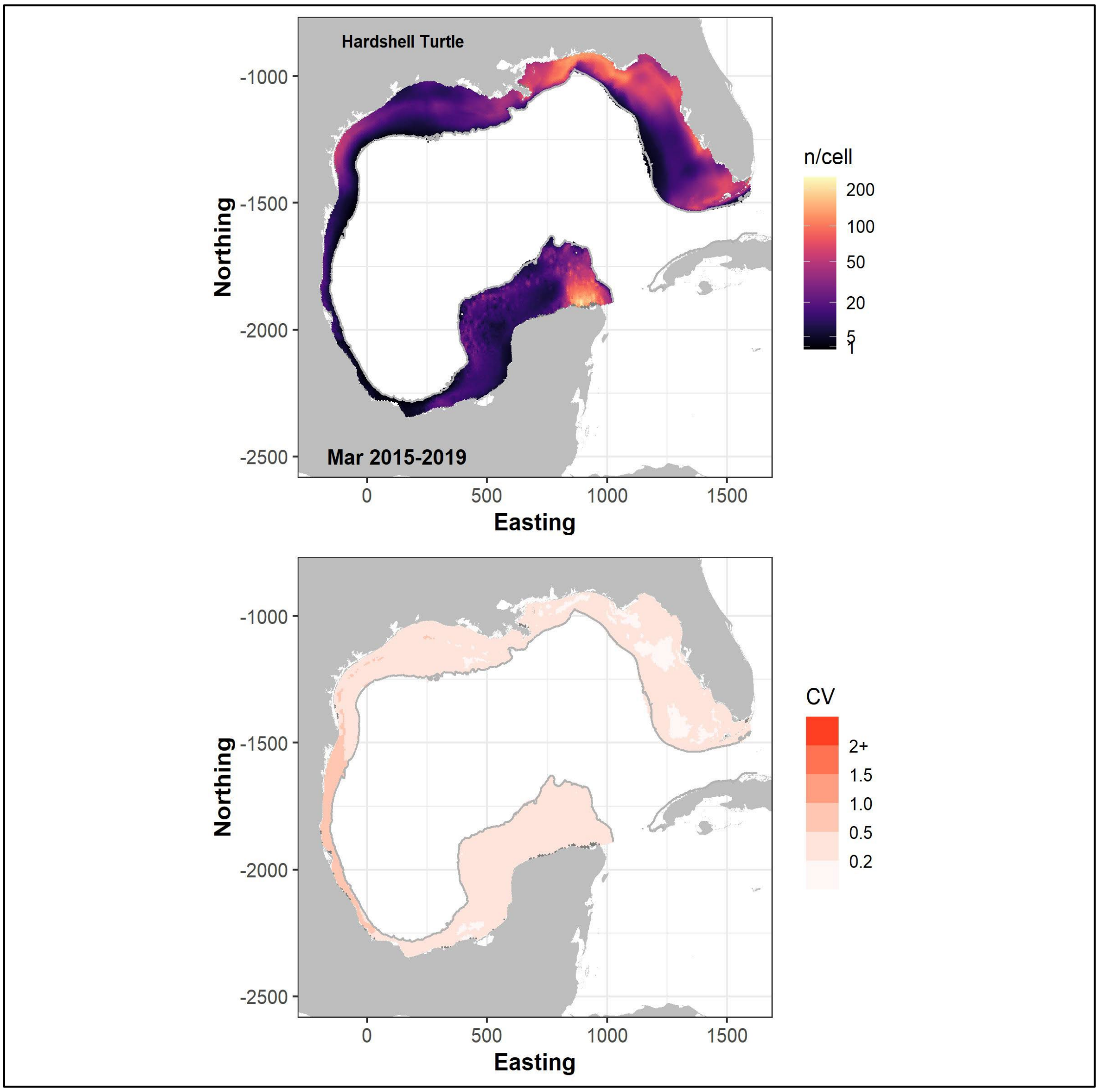

Figure D.5-52. Projected density model for shelf unidentified hardshell turtles in the entire GOM for the months of March 2015–2019.

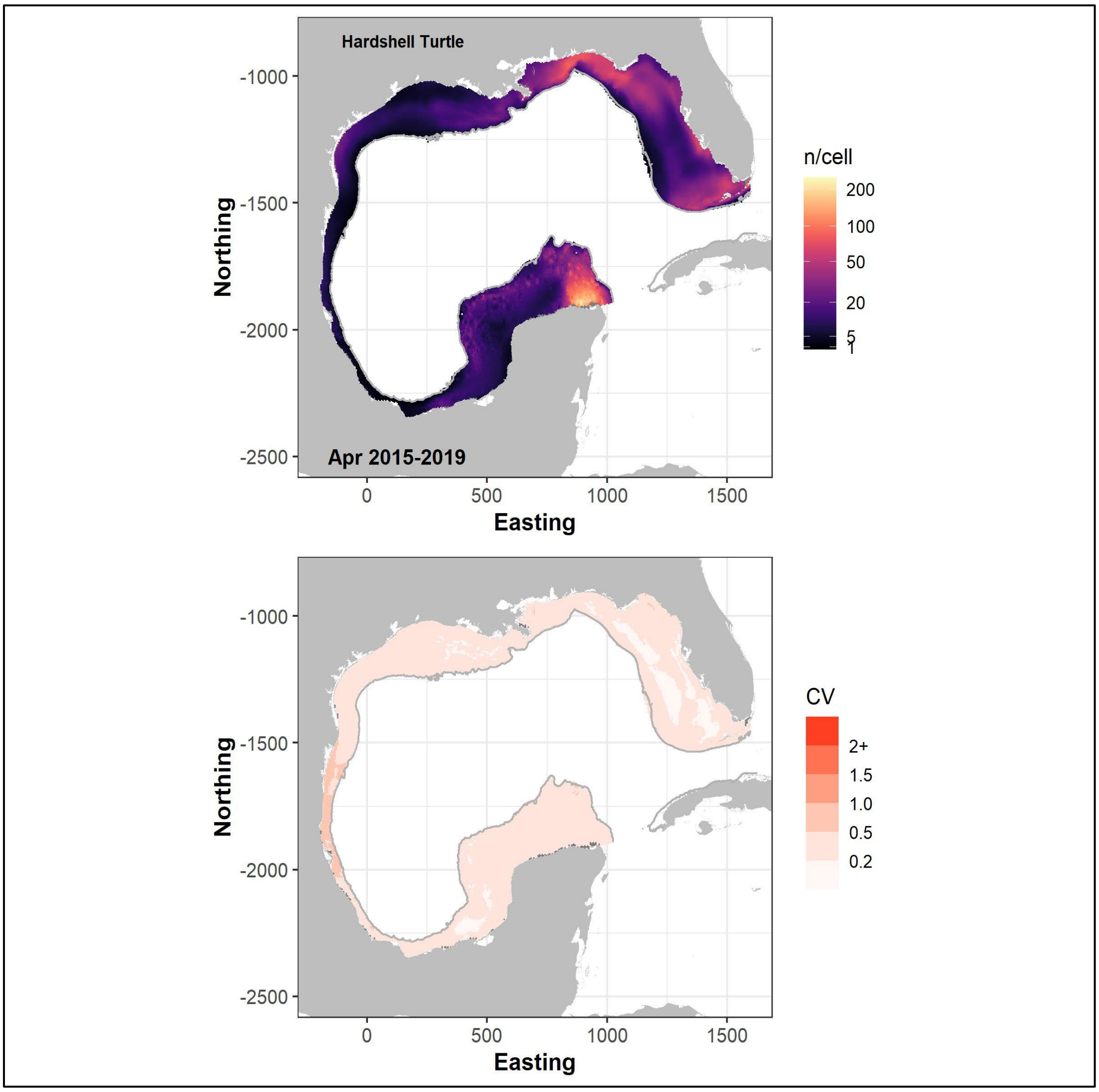

Figure D.5-53. Projected density model for shelf unidentified hardshell turtles in the entire GOM for the months of April 2015–2019.

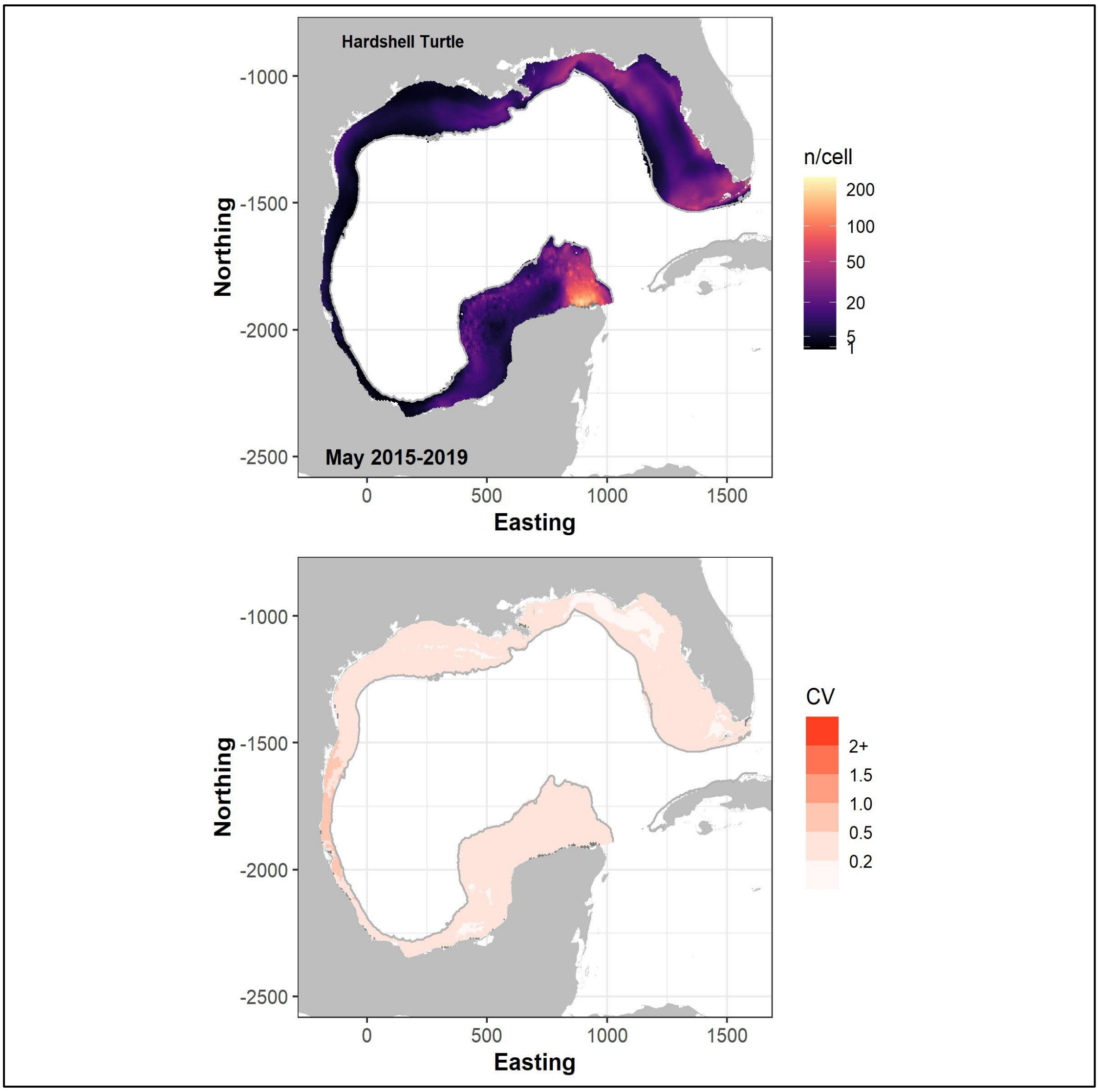

Figure D.5-54. Projected density model for shelf unidentified hardshell turtles in the entire GOM for the months of May 2015–2019.

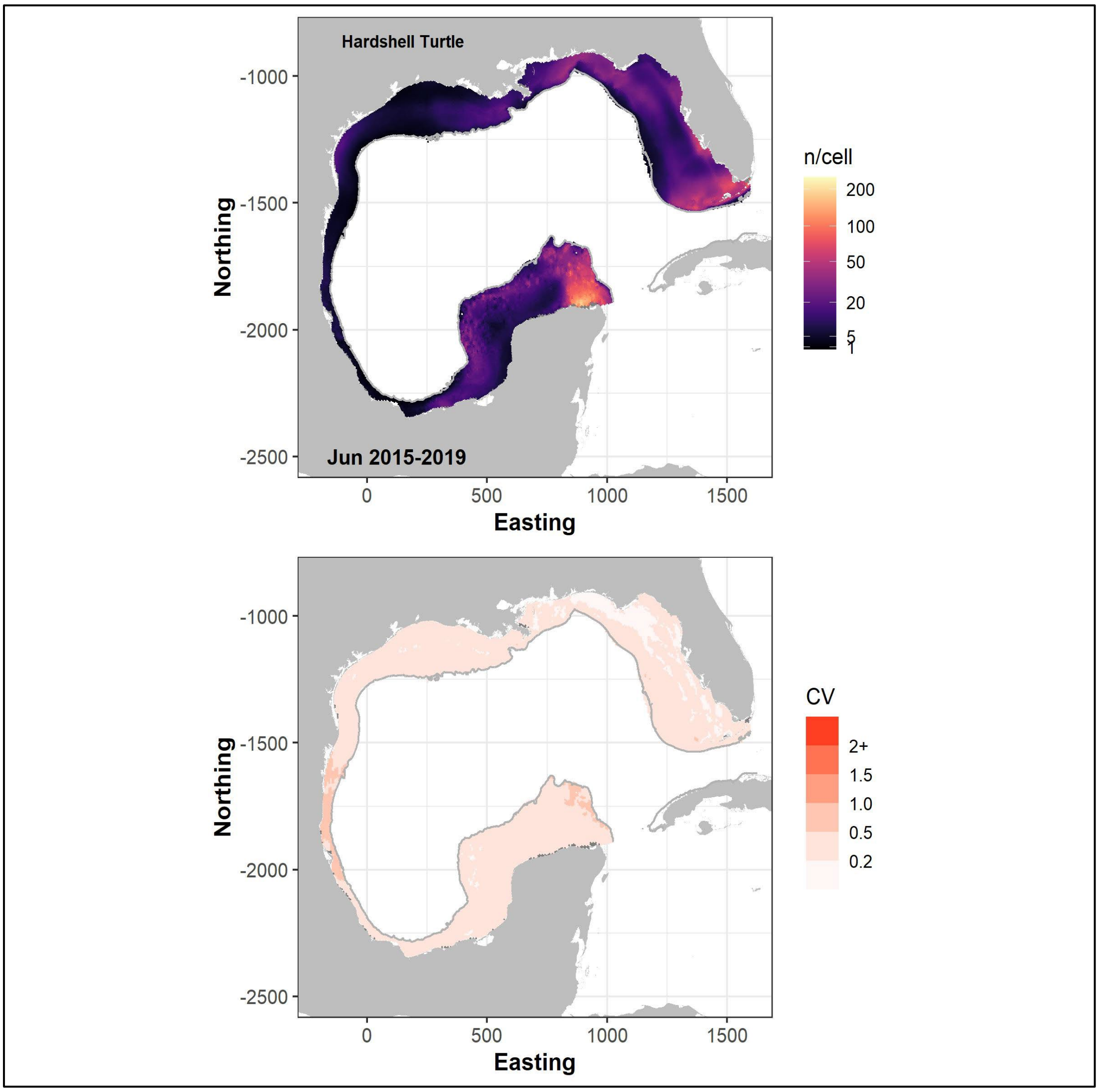

Figure D.5-55. Projected density model for shelf unidentified hardshell turtles in the entire GOM for the months of June 2015–2019.

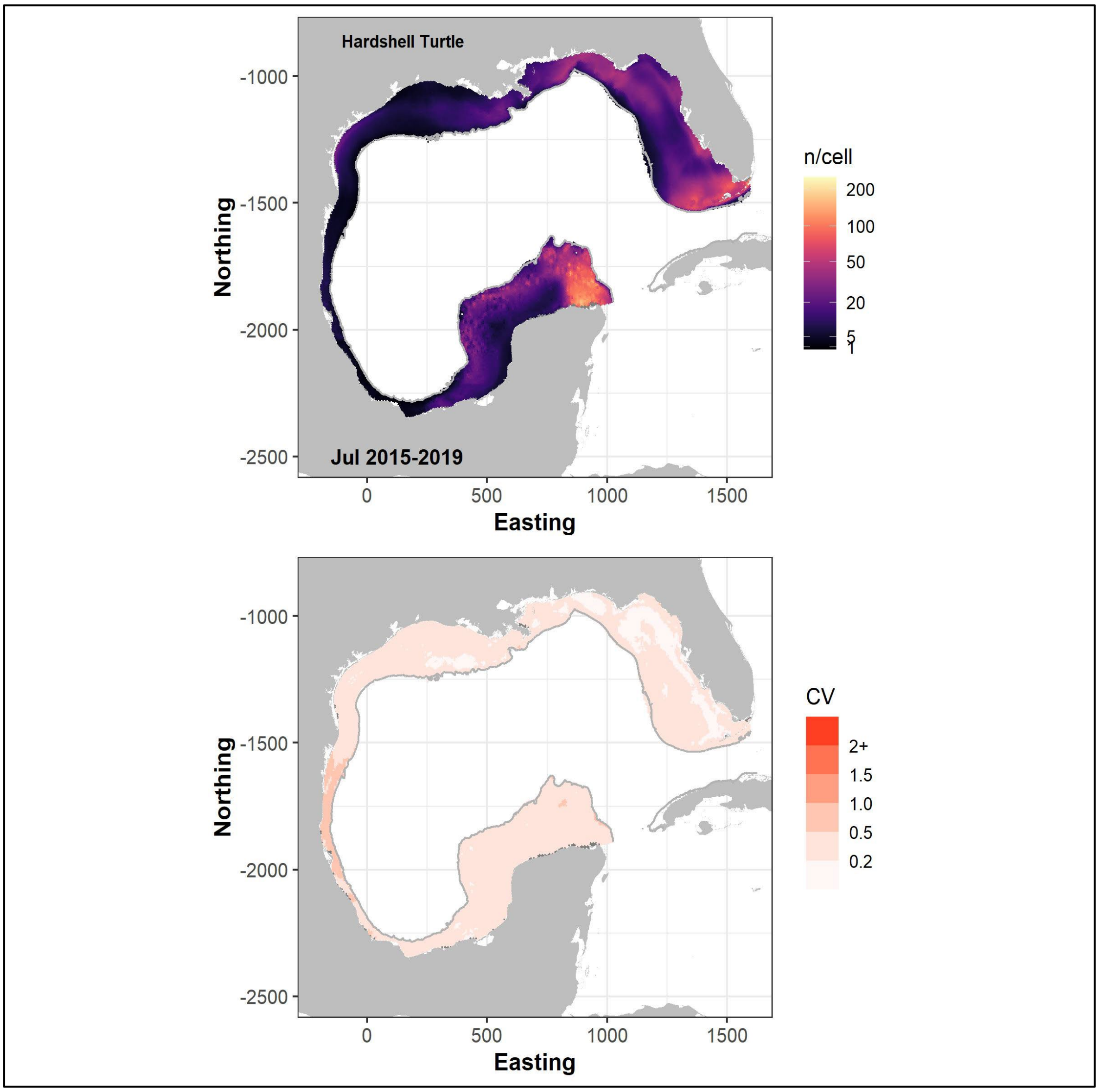

Figure D.5-56. Projected density model for shelf unidentified hardshell turtles in the entire GOM for the months of July 2015–2019.

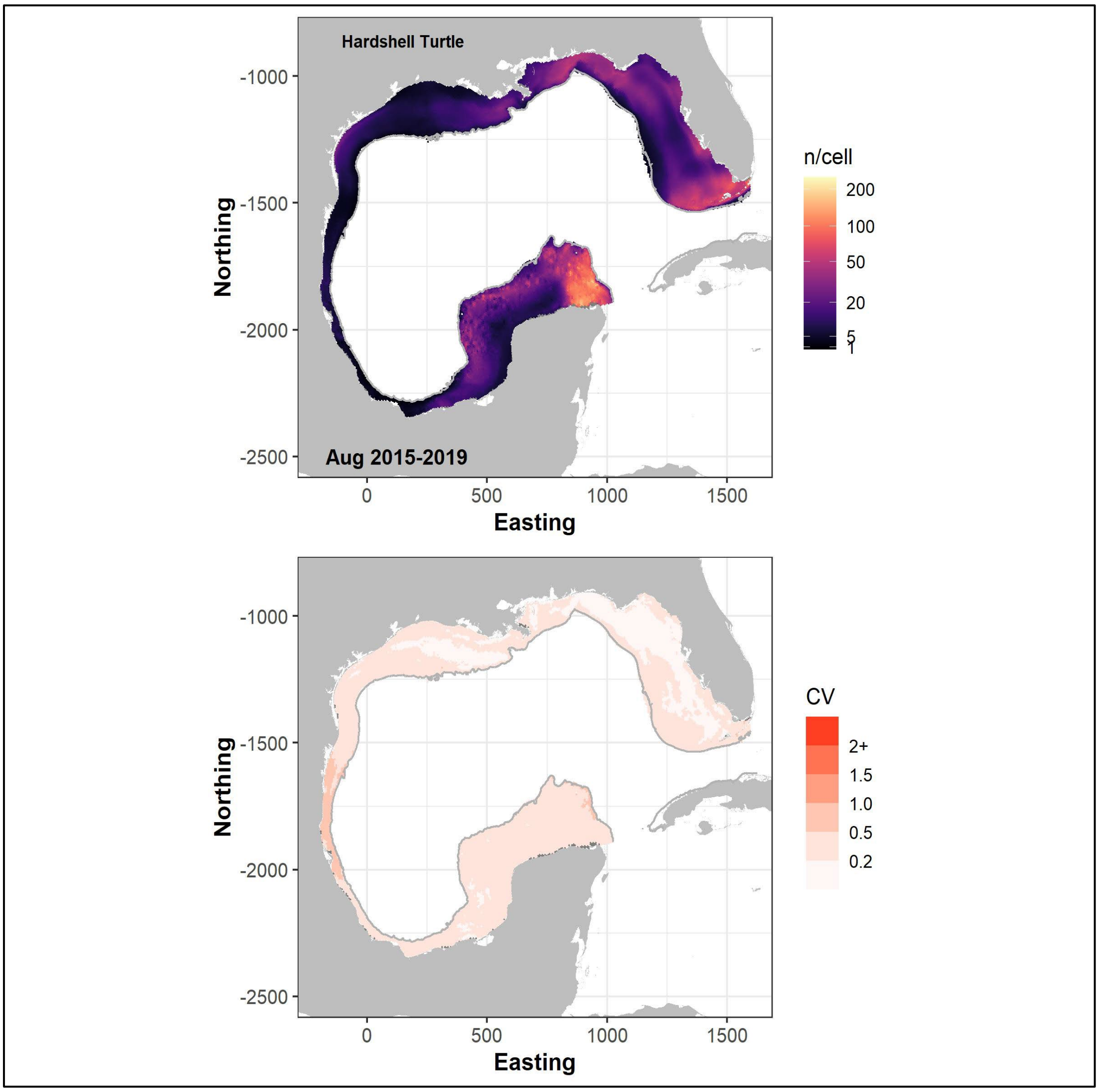

Figure D.5-57. Projected density model for shelf unidentified hardshell turtles in the entire GOM for the months of August 2015–2019.

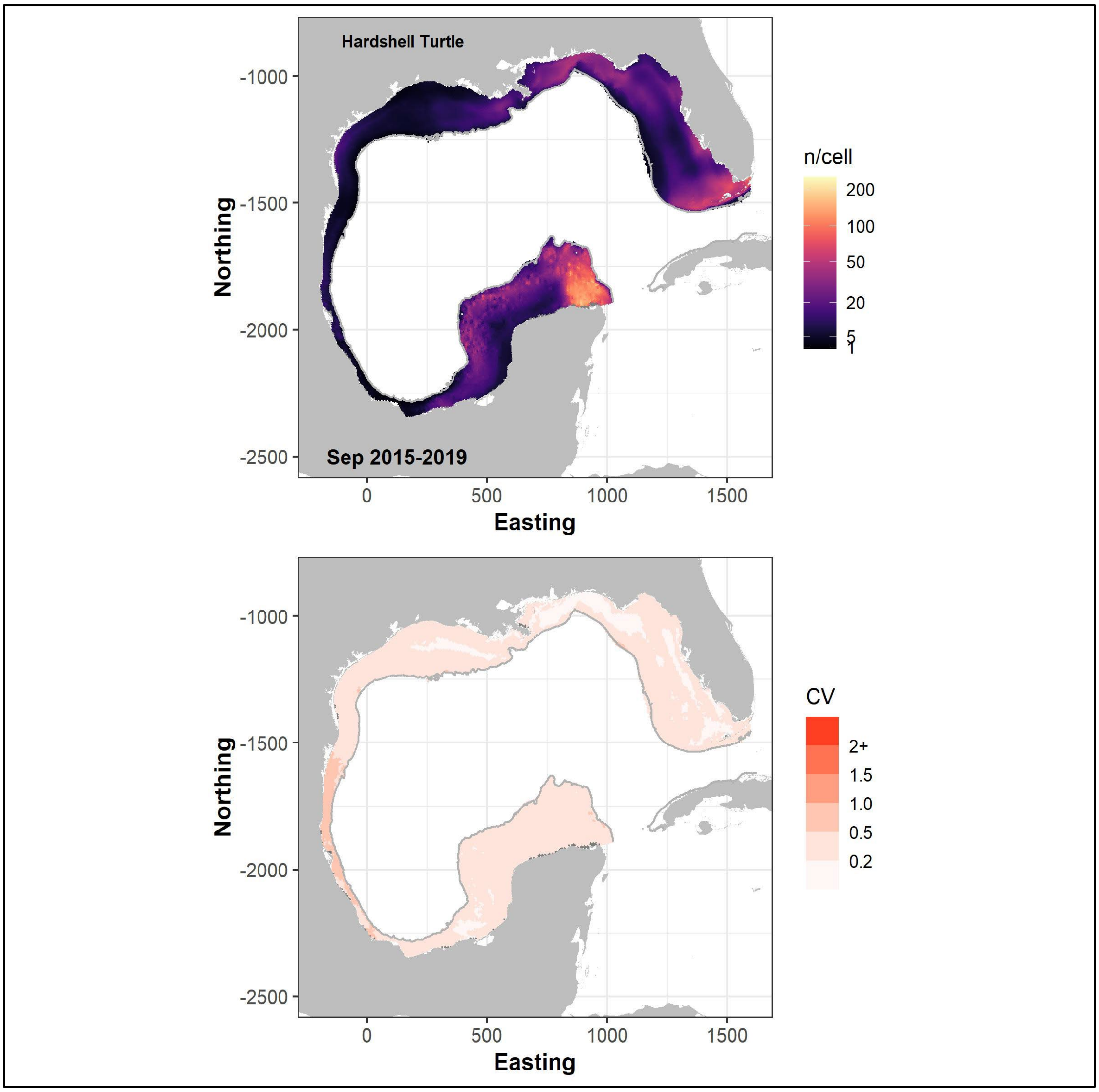

Figure D.5-58. Projected density model for shelf unidentified hardshell turtles in the entire GOM for the months of September 2015–2019.

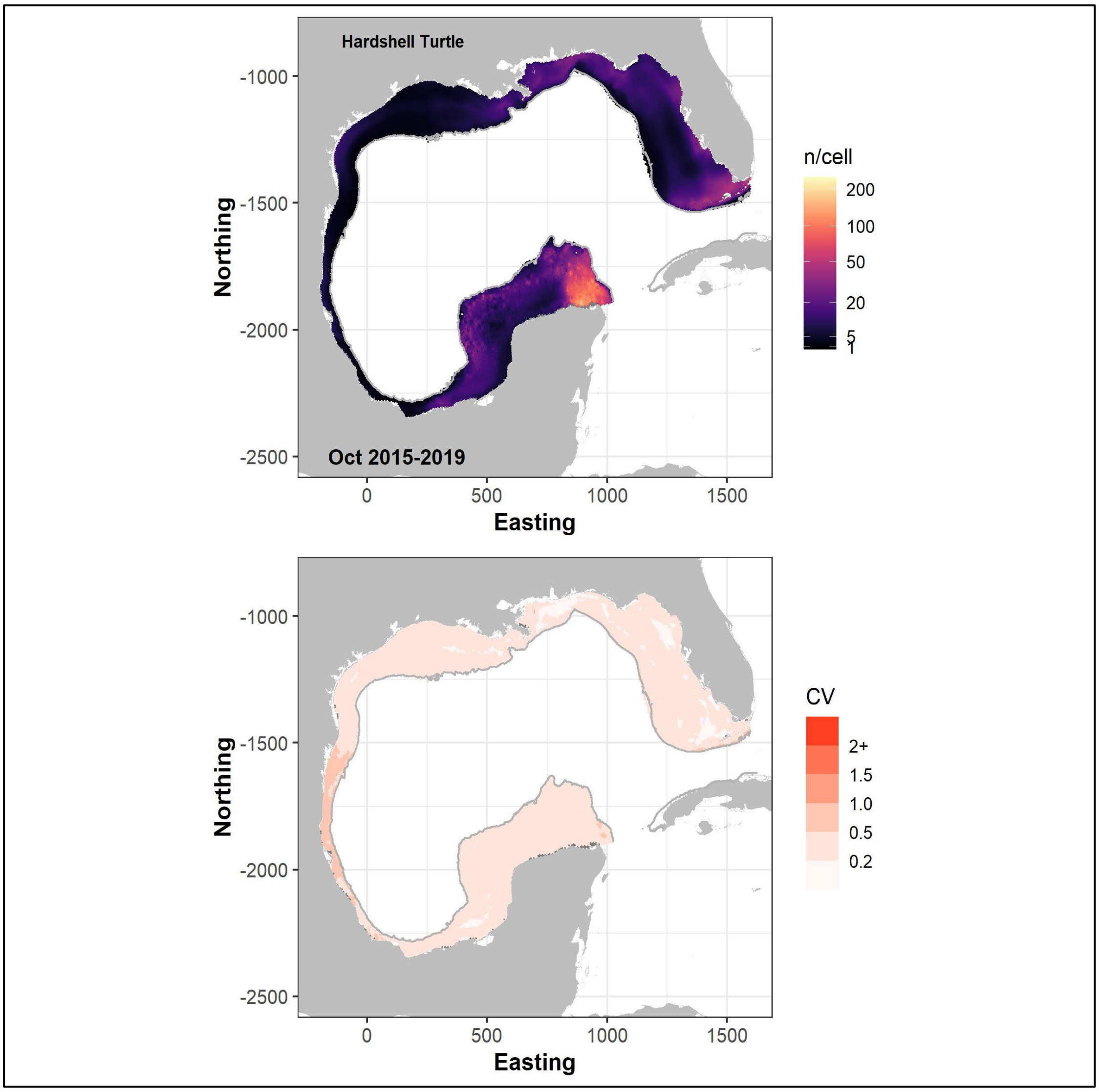

Figure D.5-59. Projected density model for shelf unidentified hardshell turtles in the entire GOM for the months of October 2015–2019.

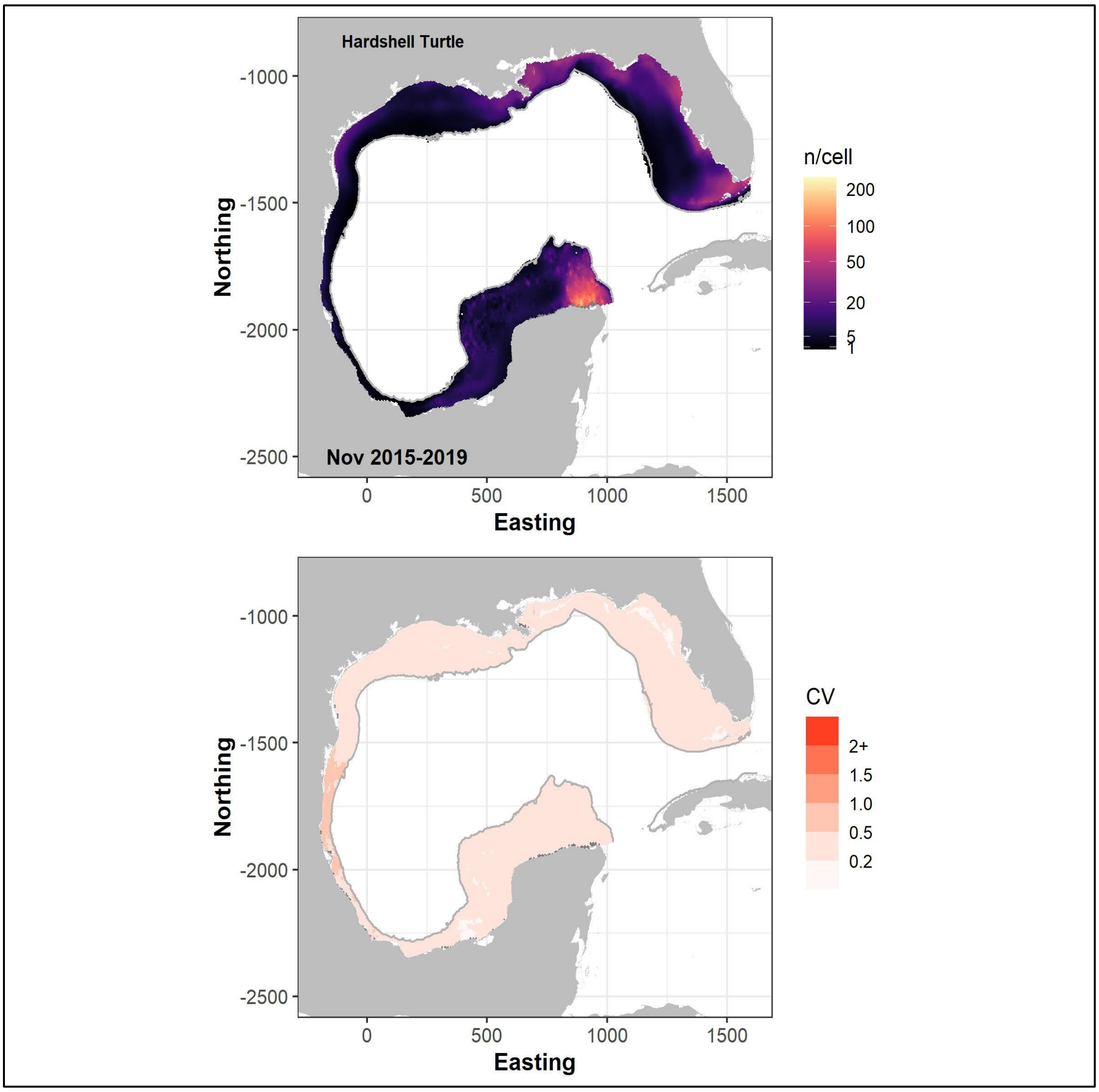

Figure D.5-60. Projected density model for shelf unidentified hardshell turtles in the entire GOM for the months of November 2015–2019.

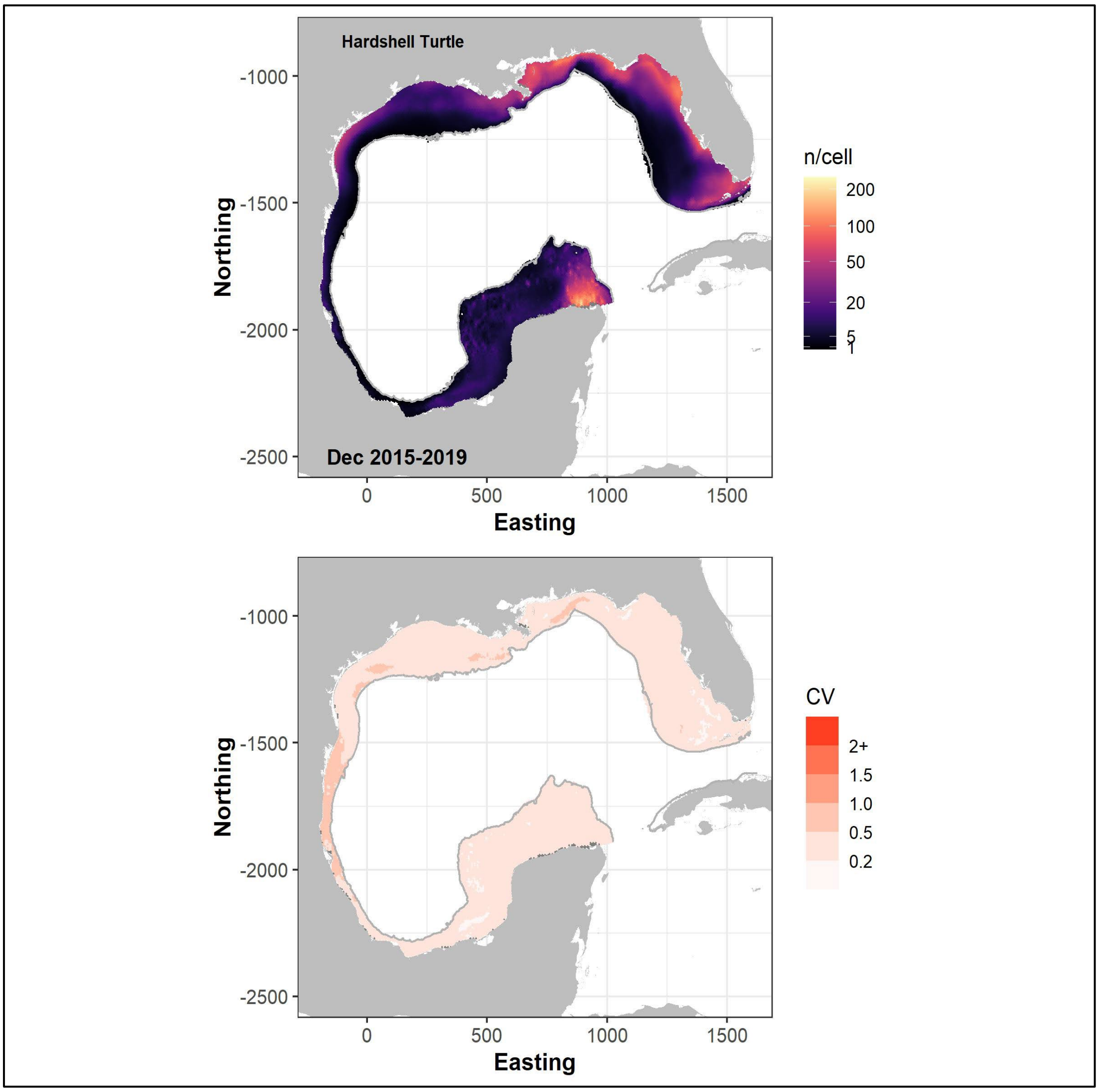

Figure D.5-61. Projected density model for shelf unidentified hardshell turtles in the entire GOM for the months of December 2015–2019.

Appendix D References

Garrison LP, Ortega-Ortiz J, Rappucci G. 2022. Abundance of sea turtles in the northern Gulf of Mexico from aerial line transect surveys. MMTD Contribution: #MMTD-2022-03. Miami (FL): Southeast Fisheries Science Center. 44 p.

Roberts KE, Garrison LP, Ortega-Ortiz J, Hu C, Zhang Y, Sasso CR, Lamont M, Hart KM. 2022. The influence of satellite-derived environmental and oceanographic parameters on marine turtle time at surface in the Gulf of Mexico. Remote Sens. 14(18):4534. doi:10.3390/rs14184534.