Spatiotemporal model-based index development for Bering Sea and Aleutian Islands crab stocks

Update for Crab Plan Team modeling workshop

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Introduction

The goal of this investigation was to develop spatiotemporal model-based indices of abundance for three Bering Sea and Aleutian Islands (BSAI) crab stocks: Tanner crab (*Chionoecetes bairdi*), Norton Sound red king crab (*Paralithodes camtschaticus*), and St. Matthew Island blue king crab (*Paralithodes platypus*). Research suggests that spatiotemporal model-based indices can be more robust to survey changes than are design-based indices, though the models must be well-specified (Yalcin et al. 2023). Spatiotemporal model-based indices are used in North Pacific Fishery Management Council (NPFMC) groundfish stock assessments for species including Eastern Bering Sea (EBS) walleye pollock (*Gadus chalcogrammus*) and EBS Pacific cod (*Gadus macrocephalus*), both of which use the vector-autoregressive spatial temporal (VAST) approach (Thorson 2019) to produce indices used in the assessments (Ianelli et al. 2024; Barbeaux et al. 2024). Previous BSAI crab stock assessments have presented models using spatiotemporal model-based indices (e.g., Ianelli et al. 2017), although these models were not accepted for harvest specifications (SSC 2017).

We generated biomass and abundance estimates using the R package *sdmTMB* (Anderson et al. 2022), which uses geostatistical time series data to estimate spatial and spatiotemporal generalized linear mixed effects models. This approach allows for index standardization when the set of stations surveyed is not consistent across years: one can generate a spatial grid that covers the area of interest, predict from the model onto that grid, and sum the predicted biomass to obtain an area-weighted biomass index that is independent of sampling locations (Anderson et al. 2022).

All three stock assessments for the crab stocks presented here use data from the National Marine Fisheries Service (NMFS) EBS bottom trawl survey (Stockhausen 2024; Hamazaki 2024; Stern and Palof 2024). The St. Matthew Island blue king crab stock assessment also uses data from the Alaska Department of Fish and Game (ADF&G) St. Matthew Island blue king crab pot survey, while the Norton Sound red king crab stock assessment uses data from the NMFS Northern Bering Sea bottom trawl survey and the ADF&G Norton Sound red king crab trawl survey.

Spatiotemporal model-based index development is expected to confer distinct advantages for each of the three stocks. For the St. Matthew Island blue king crab stock, standardizing the survey indices could allow the assessment to use the existing survey data more rigorously. The NMFS EBS trawl survey is undergoing changes including dropping the high sampling density “corner stations” near St. Matthew Island from 2024 onward (DePhilippo et al. 2023; Stern & Palof 2024); index standardization will allow the assessment to continue using the full time series of data despite changes in the spatial footprint of the survey. For Norton

Sound red king crab, a model-based approach could provide a more consistent way to combine the three existing trawl survey data sets into a single index of abundance.

Methods

We fit models using the R package *sdmTMB*. After fitting a model, we used the sanity() command to check whether the model converged, the Hessian matrix was positive definite, and any extreme eigenvalues were detected, among other checks. For models that passed the sanity() checks, we used the R package *DHARMa* (Hartig 2022) for model diagnostics. After calculating the DHARMa residuals using the function DHARMa::dharma_residuals(), we tested for quantile deviations, under/overdispersion, outliers, and zero inflation using the functions DHARMa::testQuantiles(), DHARMa::testDispersion(), DHARMa::testOutliers(), and DHARMa::testZeroInflation(), respectively.

A number of decision points arise when fitting models using *sdmTMB*, including: - the resolution of the spatial mesh used in fitting the model. A higher number of knots, specified when creating the spatial mesh using the make_mesh() function, indicates a higher resolution mesh. Few guidelines exist to aid in selection of an appropriate mesh resolution for a given dataset. - the spatiotemporal random fields estimation method. The spatiotemporal random fields can be estimated as independent and identically distributed (IID), first-order autoregressive (AR1), a random walk, or fixed at zero. - the model family. Many options exist, including tweedie(), delta_gamma(), and delta_lognormal().

Further decision points arise when evaluating fitted models: - the relative importance of different model diagnostics in selecting a preferred model. - the importance of visual model fit to survey observations in selecting a preferred model.

For each stock, we present a range of models to show the effects of the decision points that arise when fitting models, and discuss the evaluation of fitted models.

Tanner crab

We utilized abundance and biomass data collected from the NMFS summer bottom trawl survey (1975-2024) to fit Tanner crab models in *sdmTMB*. Sex-size/maturity categories included all males combined, immature females, and mature females, and data were filtered to only include crab with a carapace width greater than or equal to 25mm. As the survey gear and methods were standardized in 1982 (Stauffer 2004), we fit separate models to data before 1982 and data in and after 1982 for each sex-size/maturity category. Models were fit to data across entire Eastern Bering Sea survey grid using a 50-knot, 90-knot, and 120-knot mesh (Figures 1 - 3). These models were then predicted on an EBS-wide survey grid (Figure **??**), a grid encompassing the EBS area west of 166° (for the Tanner West stock; Figure XX, Appendix), and a grid encompassing the EBS area east of 166° (for the Tanner East stock; Figure XX, Appendix). Each prediction grid was a resolution of 5 km^2.

Norton Sound red king crab

We combined data from the NMFS trawl survey (1976-1991), ADF&G trawl survey (1996-2024), and NMFS NBS trawl survey (2010-2023) into a single data set to which we fit models in *sdmTMB*. We filtered the data set to ensure that it included only observations with coordinates falling within the Norton Sound Section of Statistical Area Q. For model fitting, we used spatial meshes at three resolutions, specified in terms of the number of knots (vertices): 100 knots, 50 knots, and 30 knots (Figures 17 - 15). We used a prediction grid with resolution of 5 km^2 (Figure 14).

St. Matthew Island blue king crab

For model fitting, we used spatial meshes at three resolutions, specified in terms of the number of knots (vertices): 120 knots, 90 knots, and 50 knots (Figures 28 - 26). We used a prediction grid with resolution of 4 km^2 (Figure 29).

Results

Tanner crab

Model diagnostics

Predicted abundance

Predicted index fits to observations

Norton Sound red king crab

Model diagnostics

The DHARMa residuals diagnostic plots show evidence of quantile deviations for all three NSRKC models (Figures 18 - 20). The models with 100 knots and 50 knots showed evidence of underdispersion, with observed data less dispersed than expected under the fitted models, while the model with 30 knots did not. None of the models showed evidence of outliers or zero inflation.

Predicted abundance

Heat maps of predicted NSRKC abundance for the three models are show in figures 21 - 23.

St. Matthew Island blue king crab

Model diagnostics

Examination of DHARMa residuals showed similar patterns for the three SMBKC models (Figures 30 - 32). All three models showed evidence of underdispersion, with observed data less dispersed than expected under the fitted models. None of the models showed evidence of outliers. All three models showed evidence of quantile deviations. The model with 120 knots showed evidence of zero inflation, with the observed data containing more zeros than would be expected under the fitted model, but the models with 50 and 90 knots did not show evidence of zero inflation.

Predicted abundance

Heat maps of predicted SMBKC abundance for the three models are show in figures 33 - 35.

Predicted index fits to observations

The model-predicted indices varied in their fits to the survey biomass observations, with the model fit using a mesh with an intermediate number of knots seeming to fit the survey observations more closely than the models fit to meshes with either higher or lower numbers of knots (Figure 36).

Conclusions

Acknowledgements

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Tables

Figures

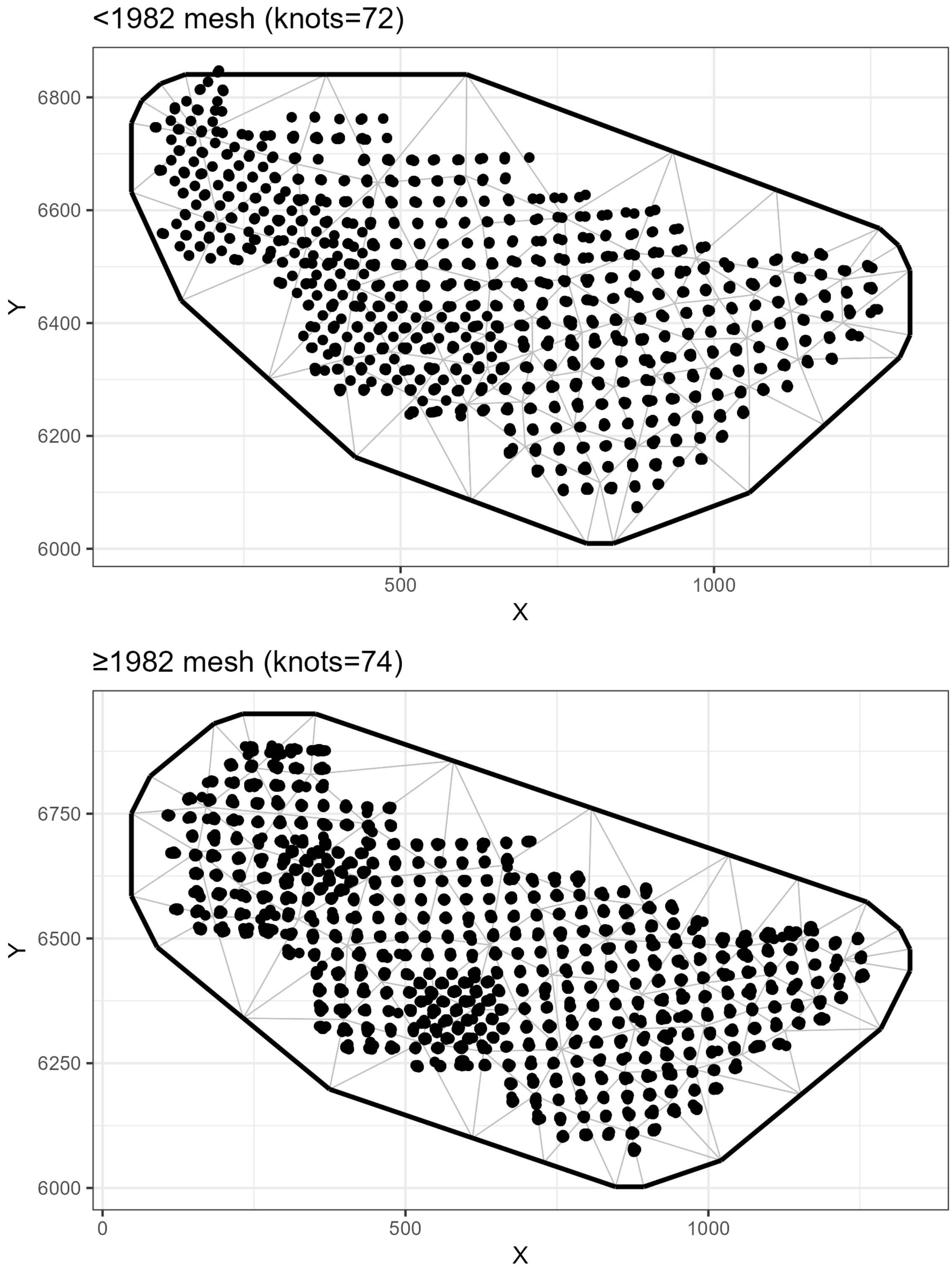
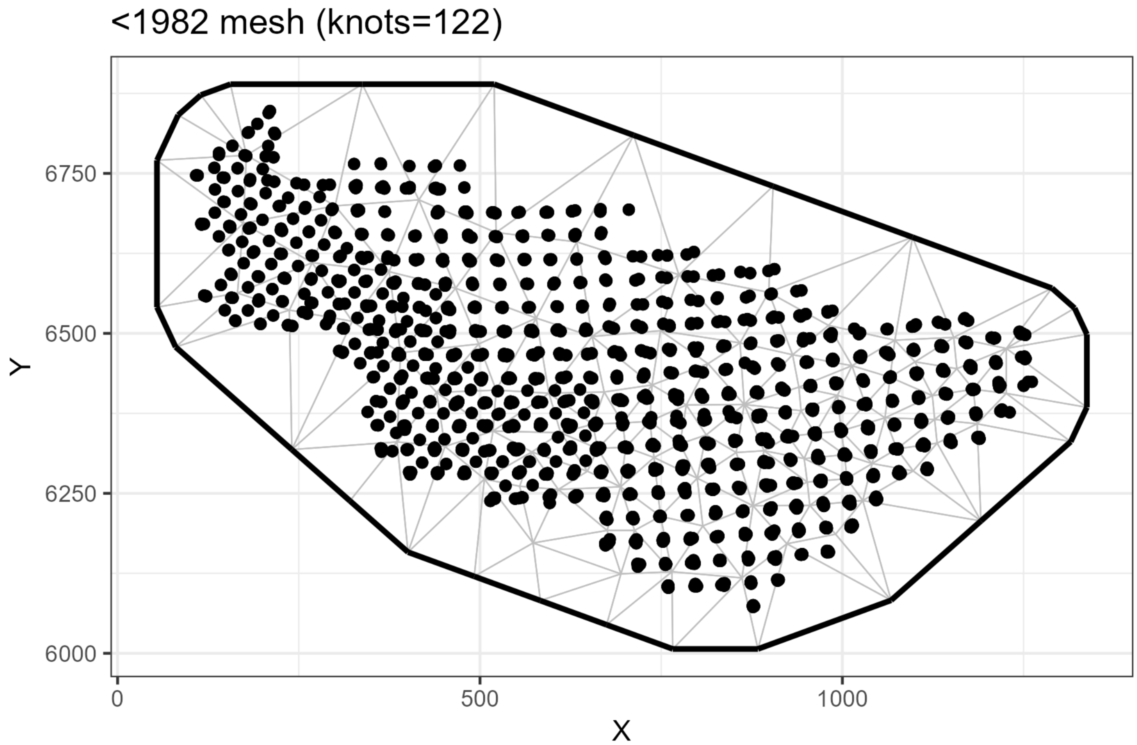


Figure 1: Spatial mesh with 50 knots used for fitting Tanner crab spatial models. Points represent observations and vertices represent knot locations.



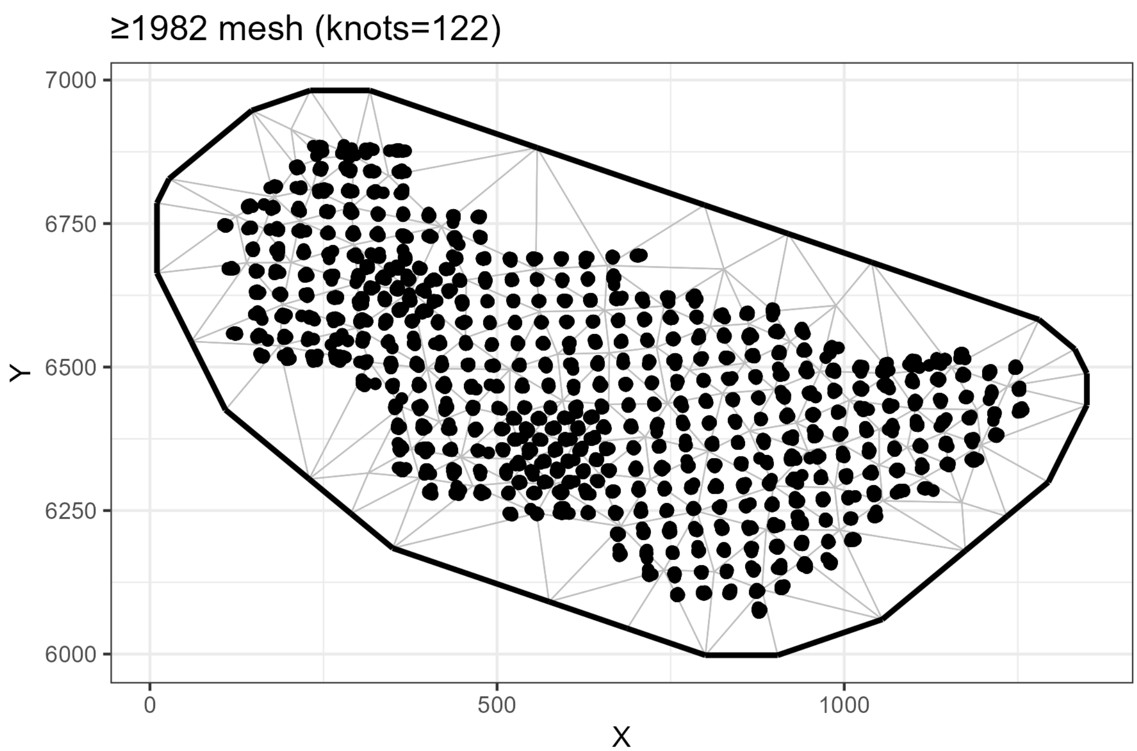


Figure 2: Spatial mesh with 90 knots used for fitting Tanner crab spatial models. Points represent observations and vertices represent knot locations.

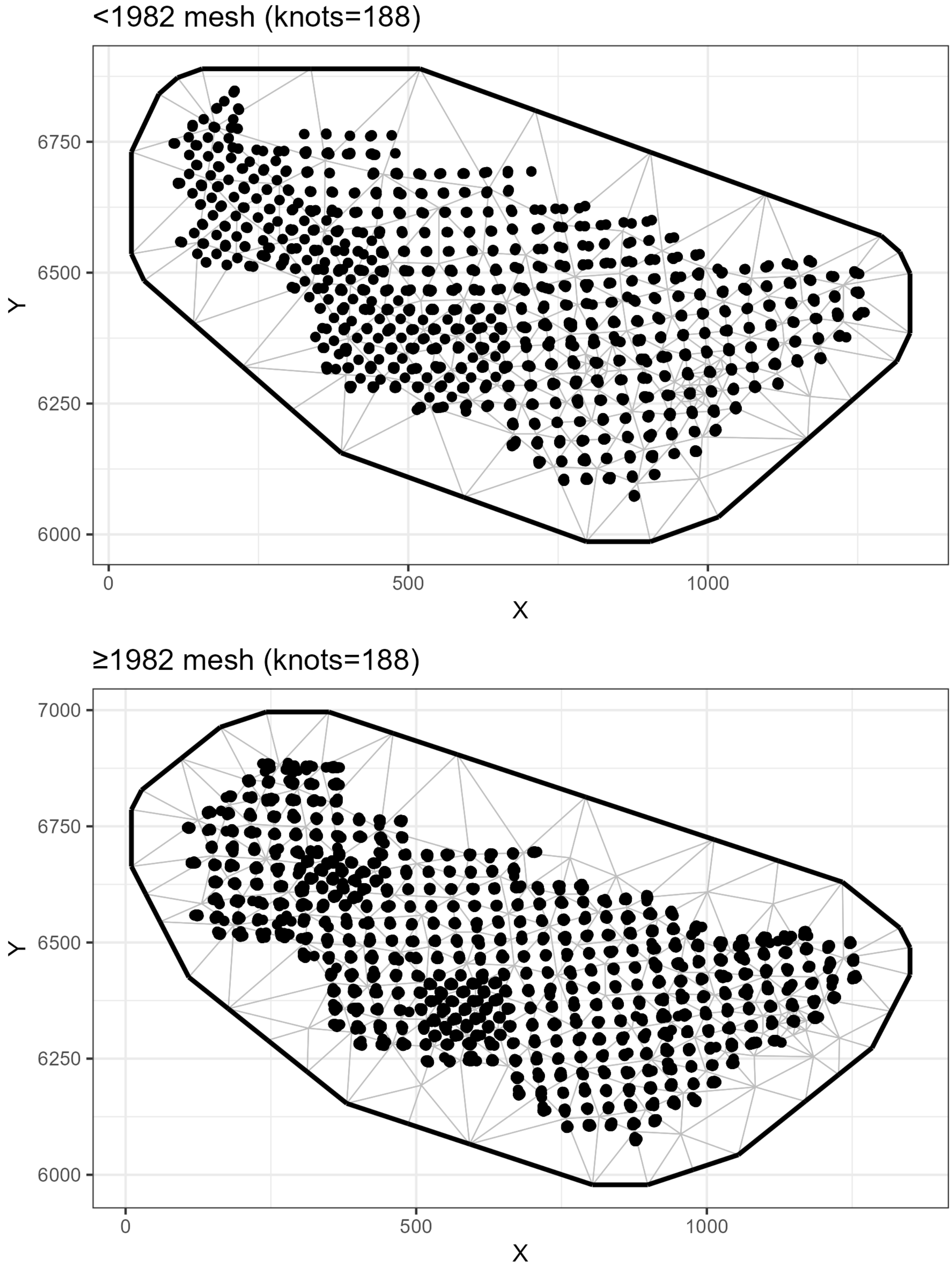


Figure 3: Spatial mesh with 120 knots used for fitting Tanner crab spatial models. Points represent observations and vertices represent knot locations.

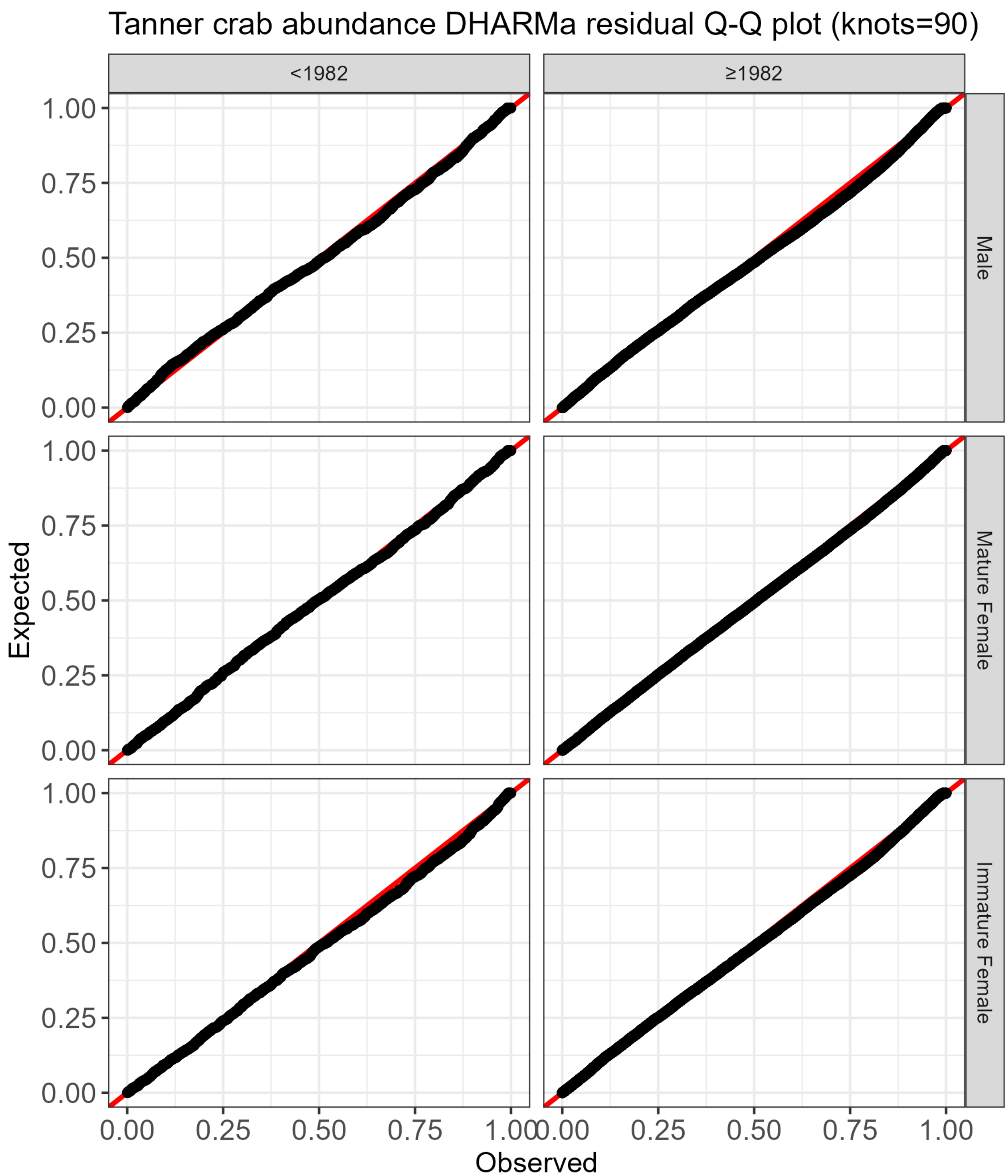


Figure 4: Q-Q plot of DHARMa residuals for EBS-wide abundance models fit with NMFS summer bottom trawl survey data before 1988 (left) and 1988 onward (right) using 90 knots in the model mesh.

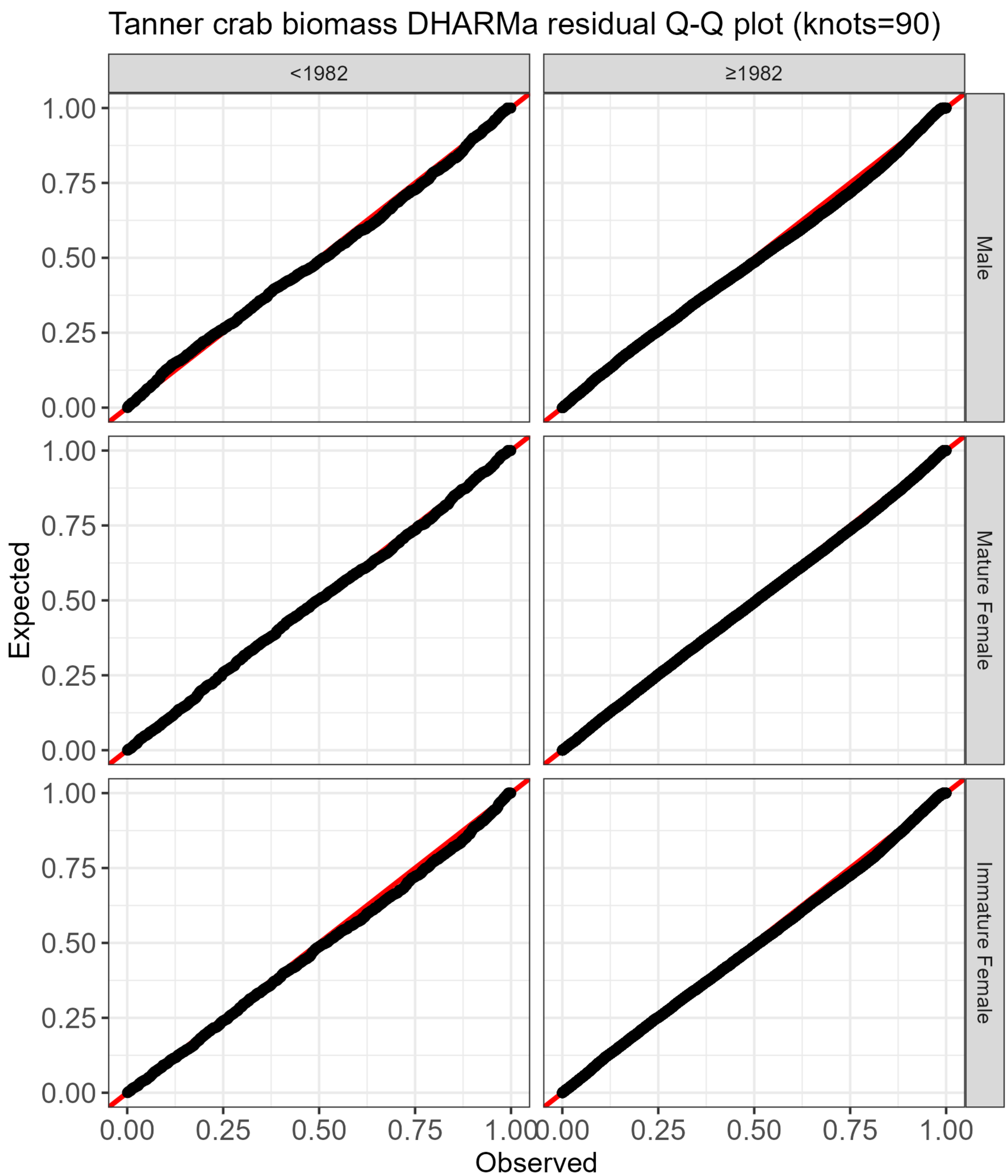


Figure 5: Q-Q plot of DHARMa residuals for EBS-wide biomass models fit with NMFS summer bottom trawl survey data before 1988 (left) and 1988 onward (right) using 90 knots in the model mesh.

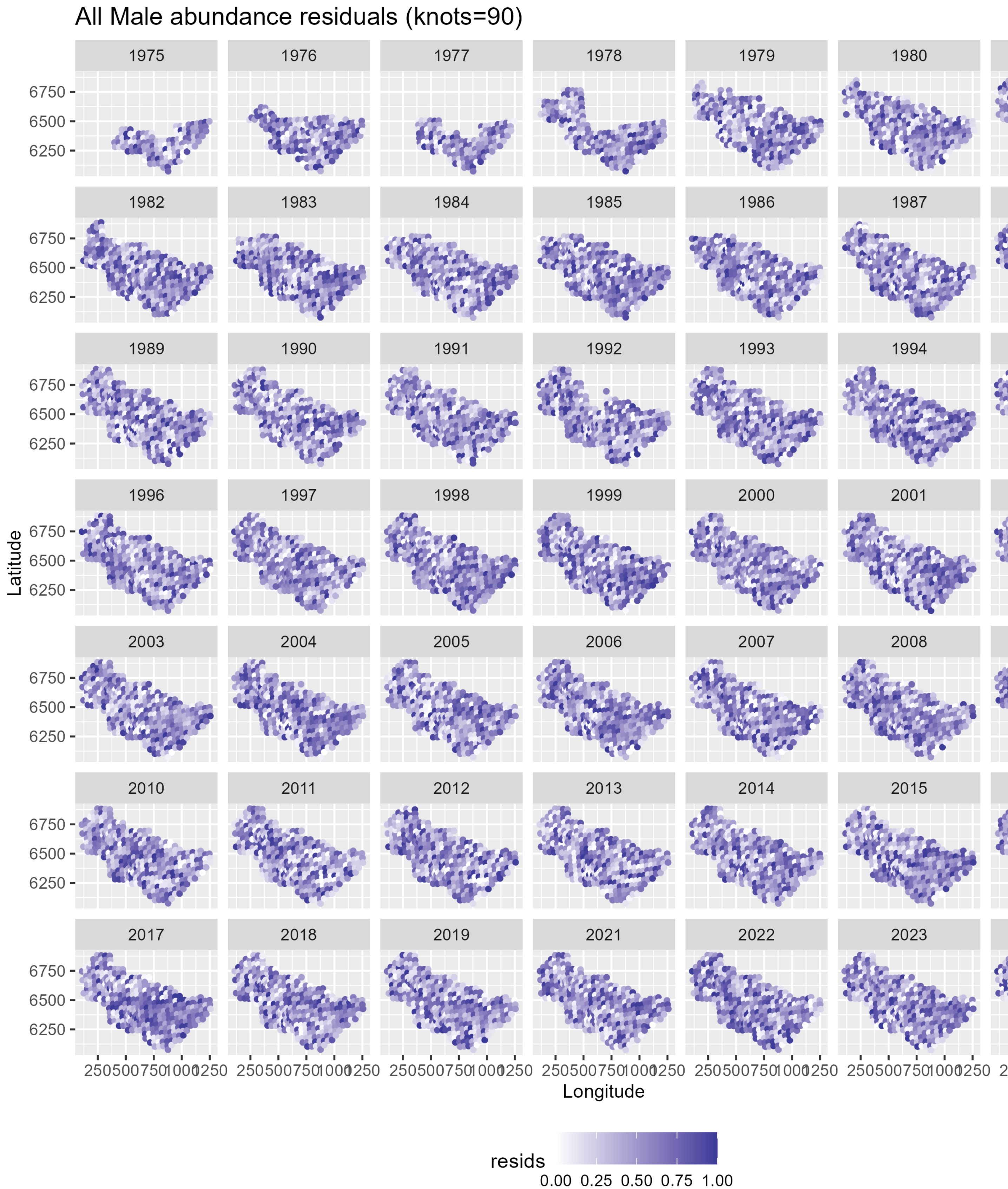


Figure 6: Spatial plot of DHARMa residuals for EBS-wide male abundance models fit using NMFS summer bottom trawl survey data before 1988 and 1988 onward with a 90-knot mesh. Predictions from both these periods/models are combined in this figure.

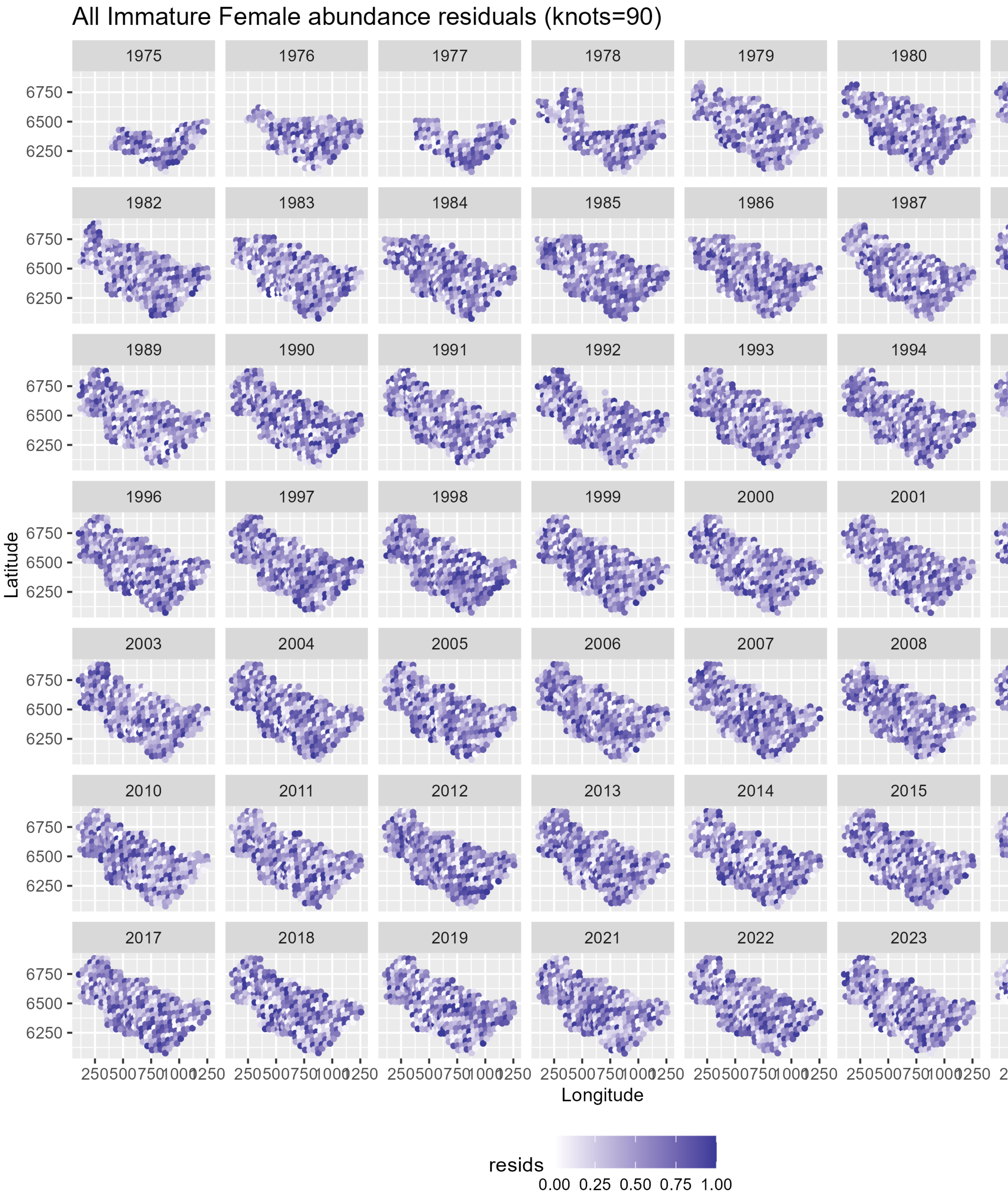


Figure 7: Spatial plot of DHARMa residuals for EBS-wide immature female abundance models fit using NMFS summer bottom trawl survey data before 1988 and 1988 onward with a 90-knot mesh. Predictions from both these periods/models are combined in this figure.

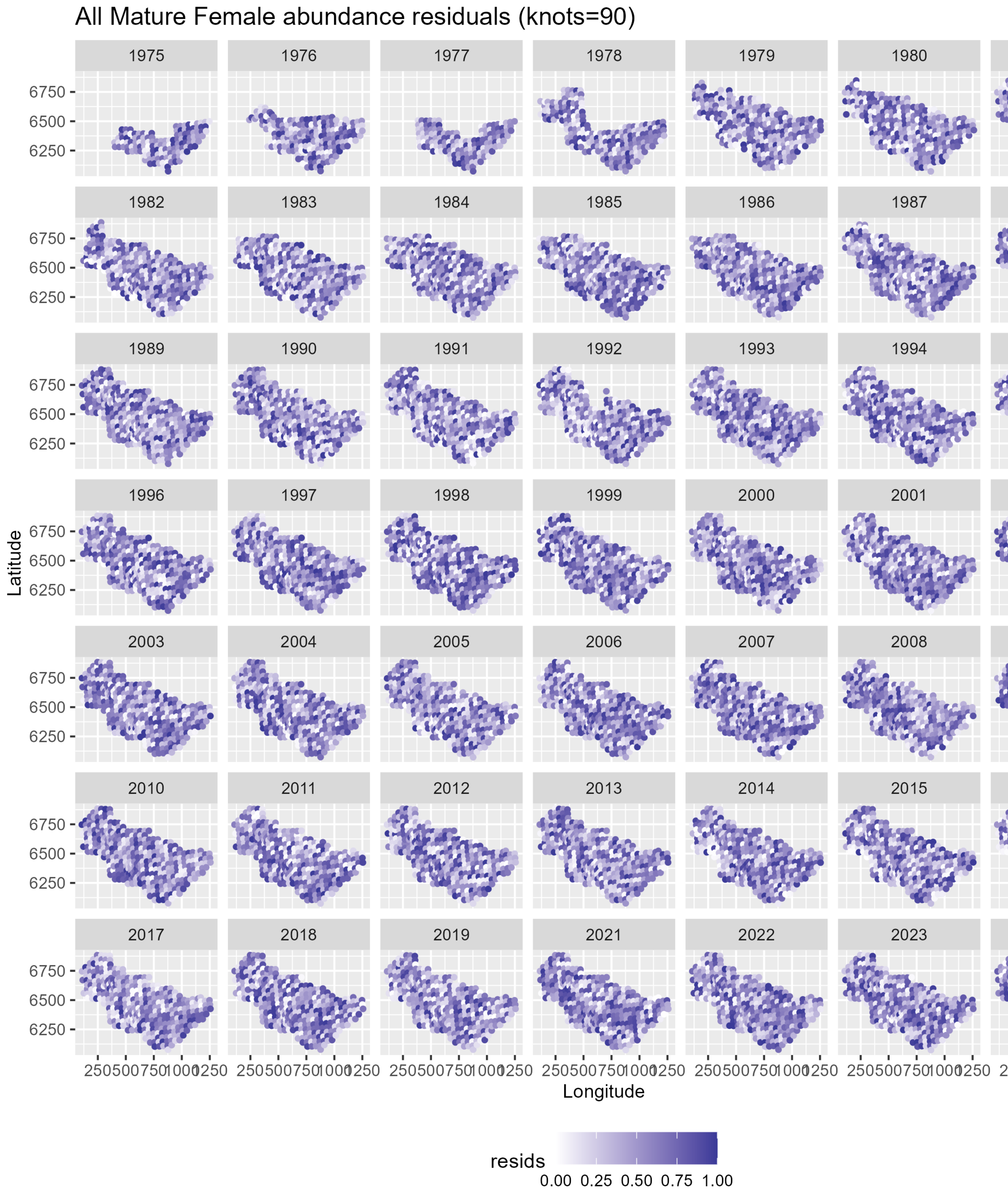


Figure 8: Spatial plot of DHARMa residuals for EBS-wide mature female abundance models fit using NMFS summer bottom trawl survey data before 1988 and 1988 onward with a 90-knot mesh. Predictions from both these periods/models are combined in this figure.

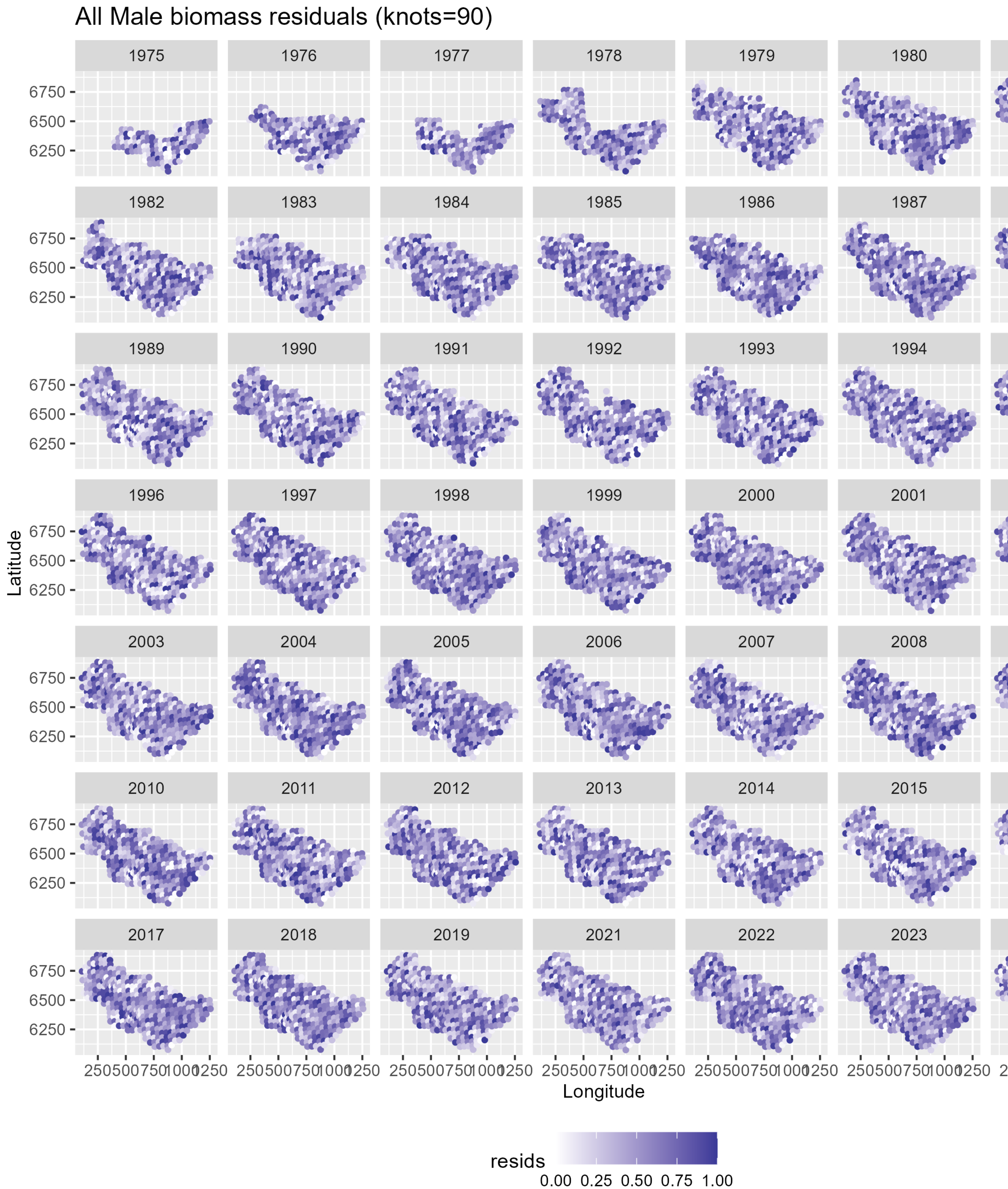


Figure 9: Spatial plot of DHARMa residuals for EBS-wide male biomass models fit using NMFS summer bottom trawl survey data before 1988 and 1988 onward with a 90-knot mesh. Predictions from both these periods/models are combined in this figure.

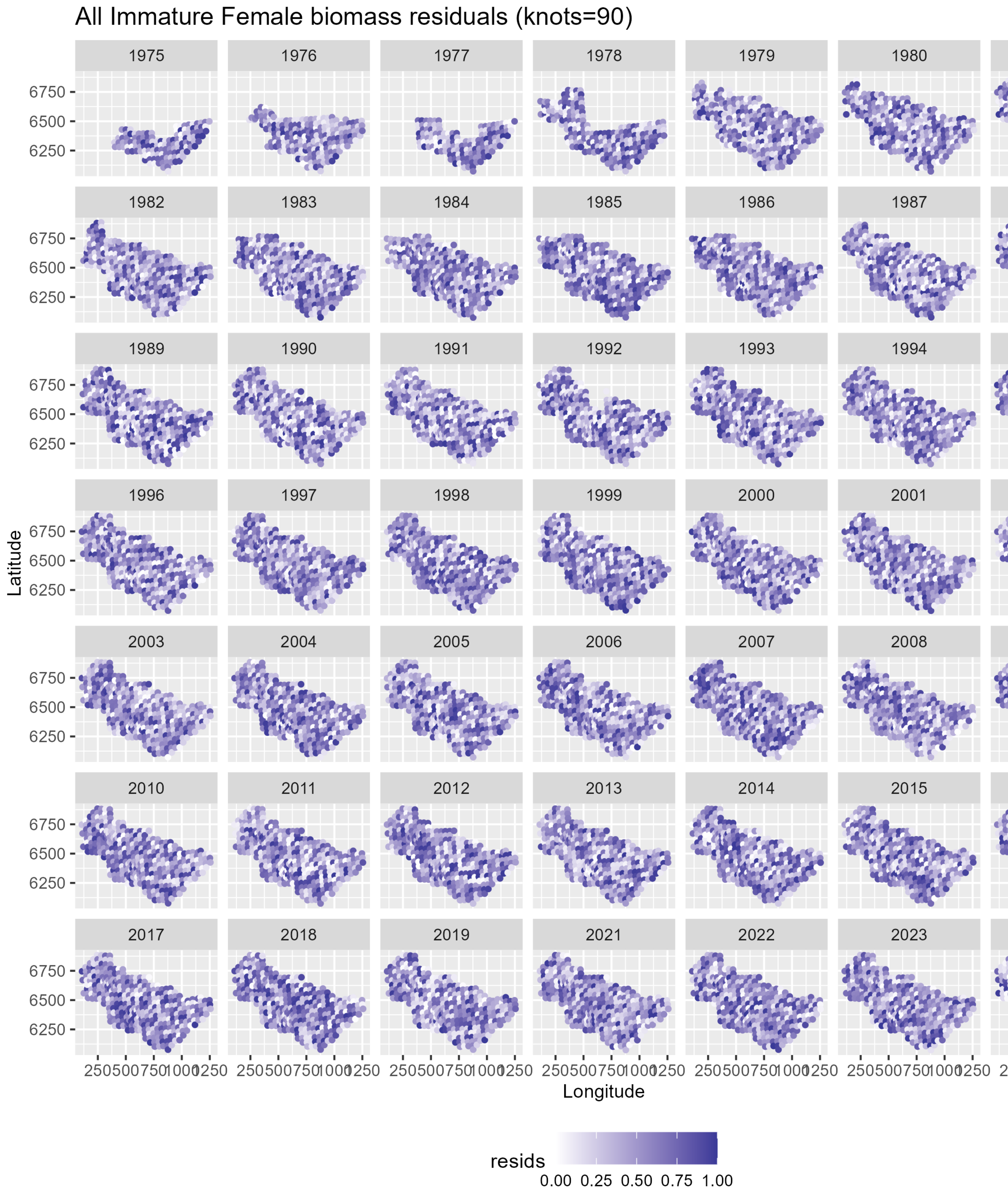


Figure 10: Spatial plot of DHARMa residuals for EBS-wide immature female biomass models fit using NMFS summer bottom trawl survey data before 1988 and 1988 onward with a 90-knot mesh. Predictions from both these periods/models are combined in this figure.

Figure 11: Spatial plot of DHARMa residuals for EBS-wide mature female biomass models fit using NMFS summer bottom trawl survey data before 1988 and 1988 onward with a 90-knot mesh. Predictions from both these periods/models are combined in this figure.

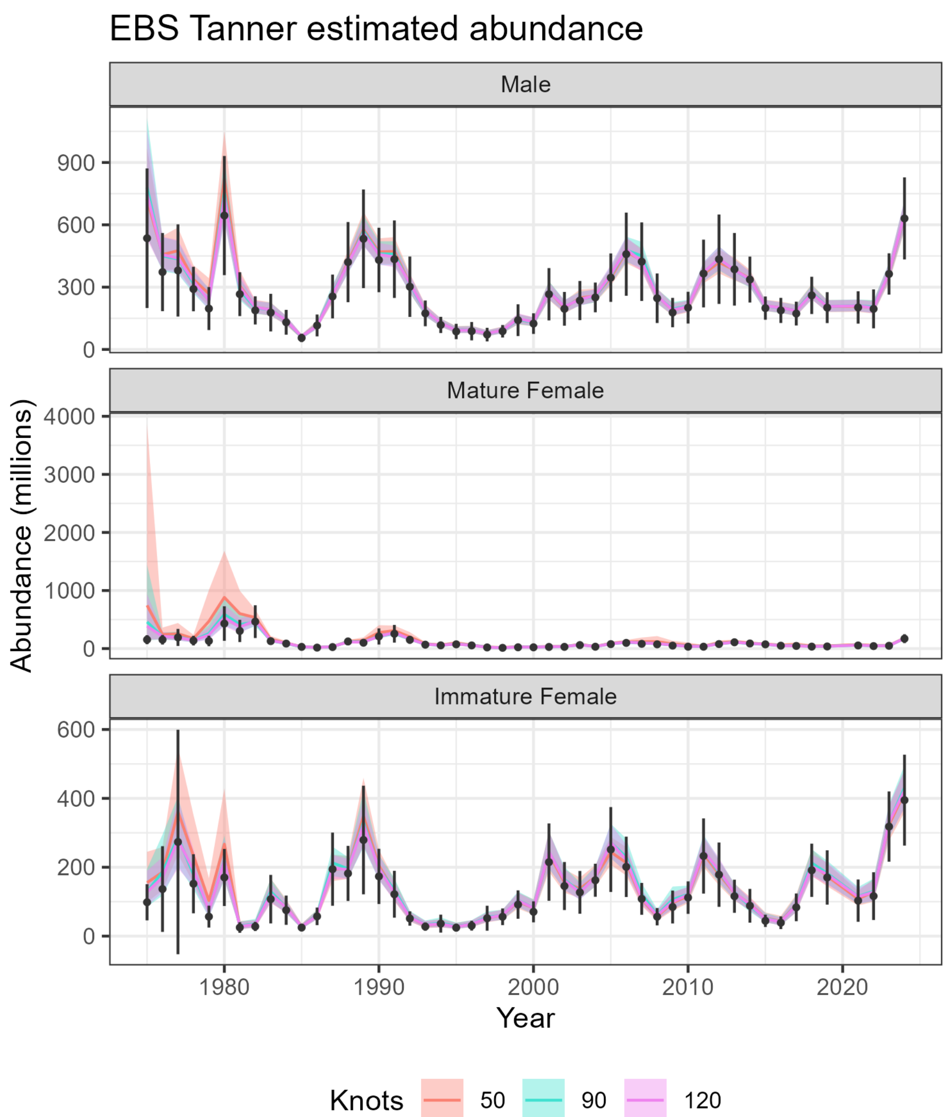


Figure 12: Estimated abundance (millions) for Tanner crab. Colored lines represent abundance (±95% CI) estimated by sdmTMB, with orange, blue, and pink denoting models fit with a 50-, 90-, and 120-knot mesh, respectively. Black points represent abundance (±95% CI) estimated by the NMFS summer bottom trawl survey.

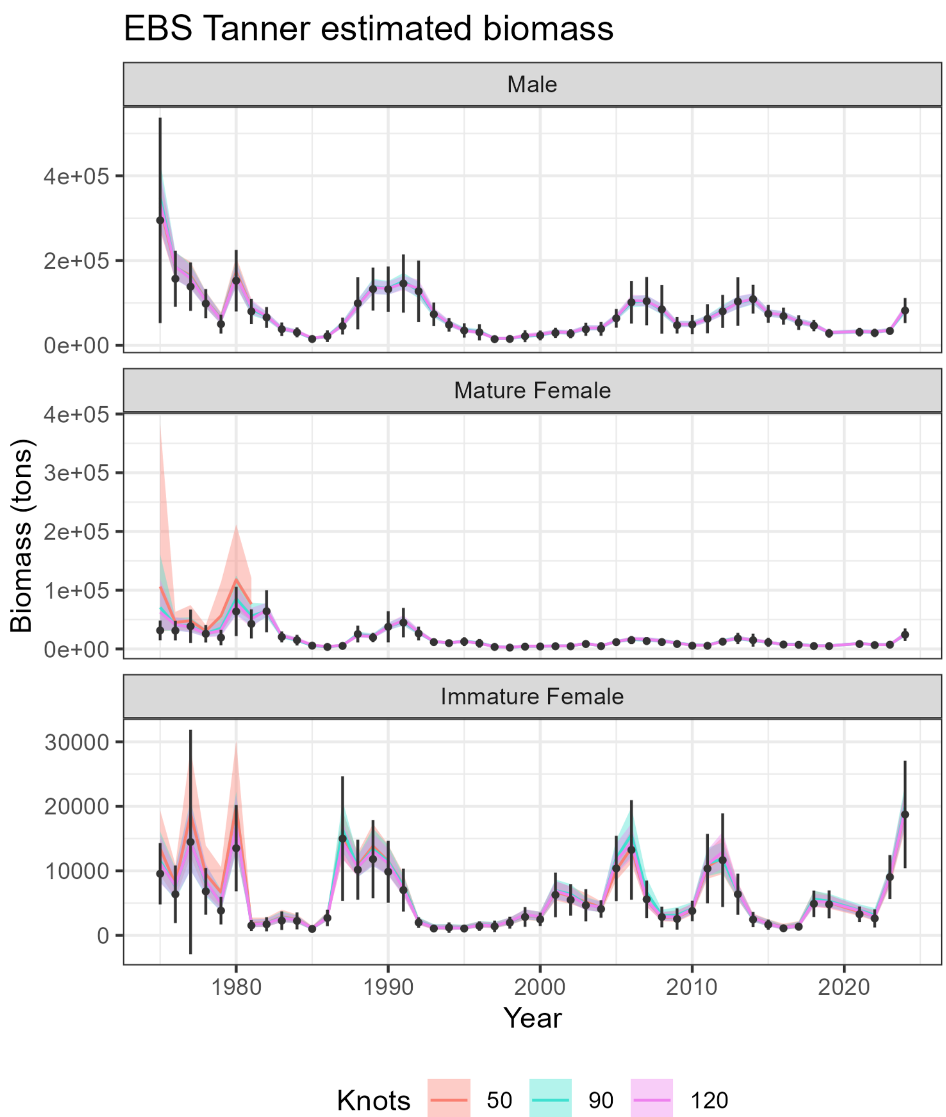


Figure 13: Estimated biomass (tons) for Eastern Bering Sea Tanner crab. Colored lines represent abundance (±95% CI) estimated by sdmTMB, with orange, blue, and pink denoting models fit with a 50-, 90-, and 120-knot mesh, respectively. Black points represent biomass (±95% CI) estimated by the NMFS summer bottom trawl survey.

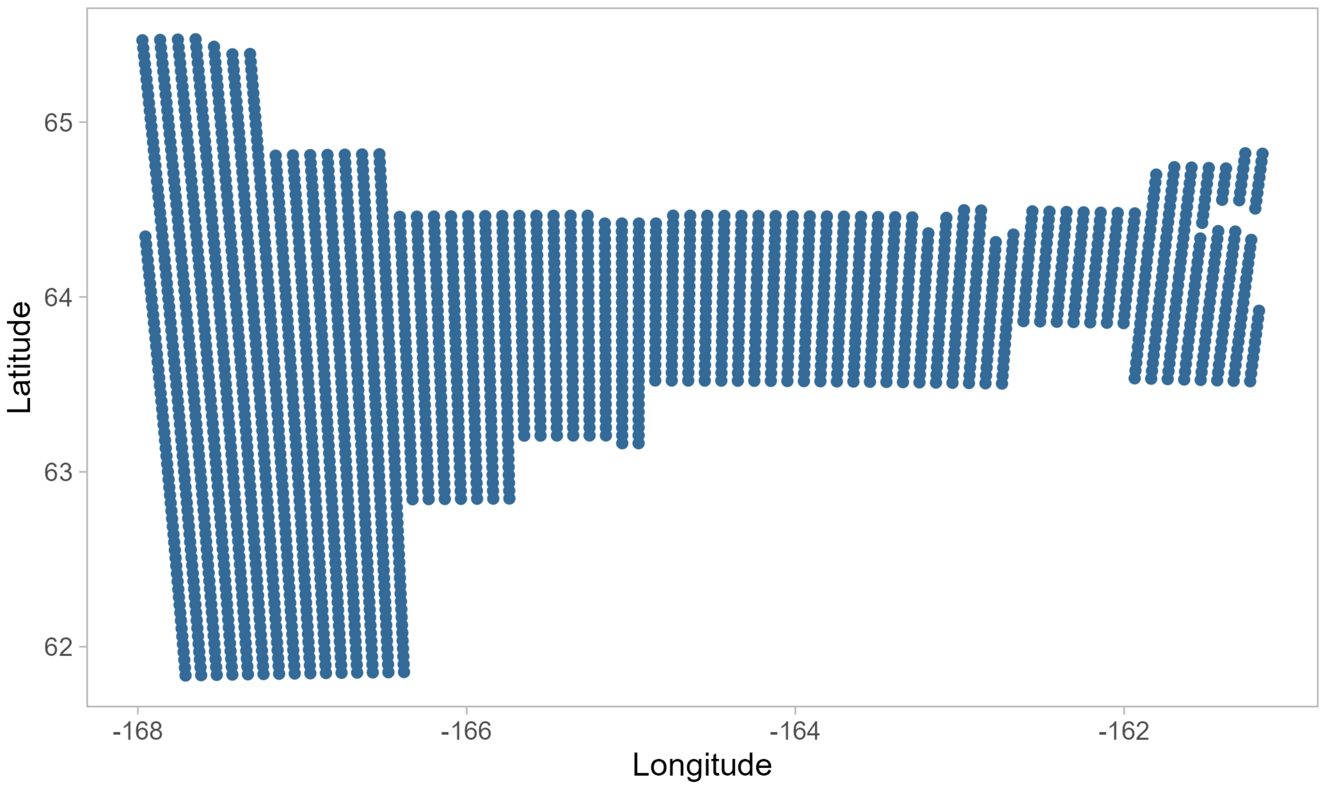


Figure 14: Prediction grid used for Norton Sound red king crab spatial abundance predictions. Spatial resolution is 5 km^2.

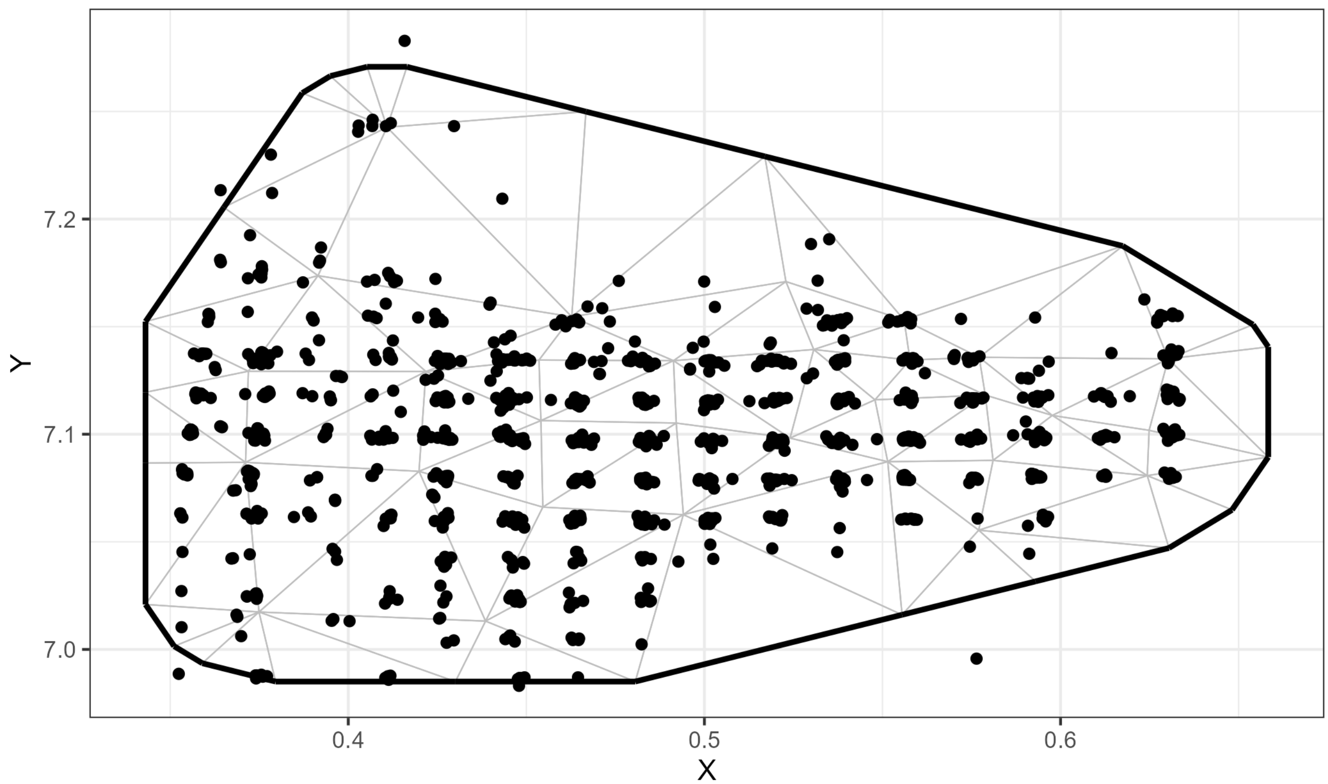


Figure 15: Spatial mesh with 30 knots used for fitting Norton Sound red king crab spatial models. Points represent observations and vertices represent knot locations.

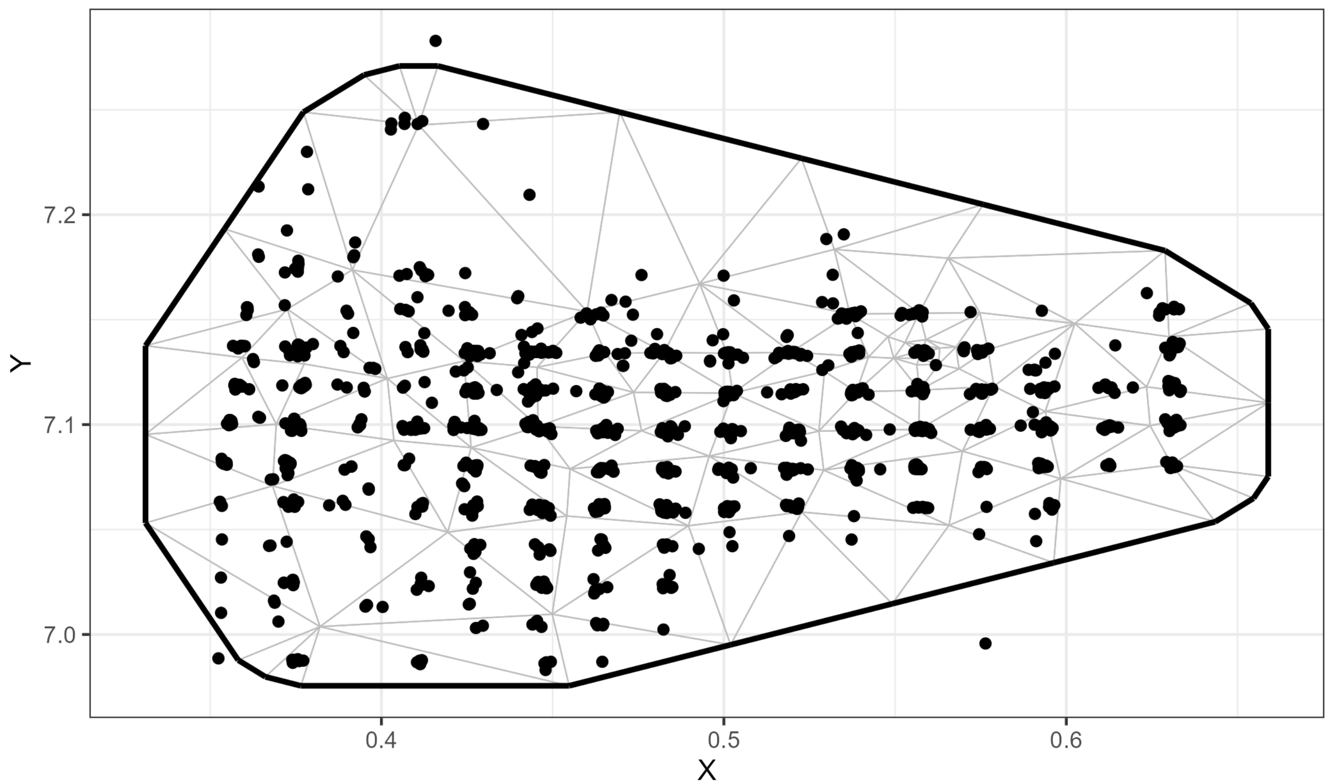


Figure 16: Spatial mesh with 50 knots used for fitting Norton Sound red king crab spatial models. Points represent observations and vertices represent knot locations.

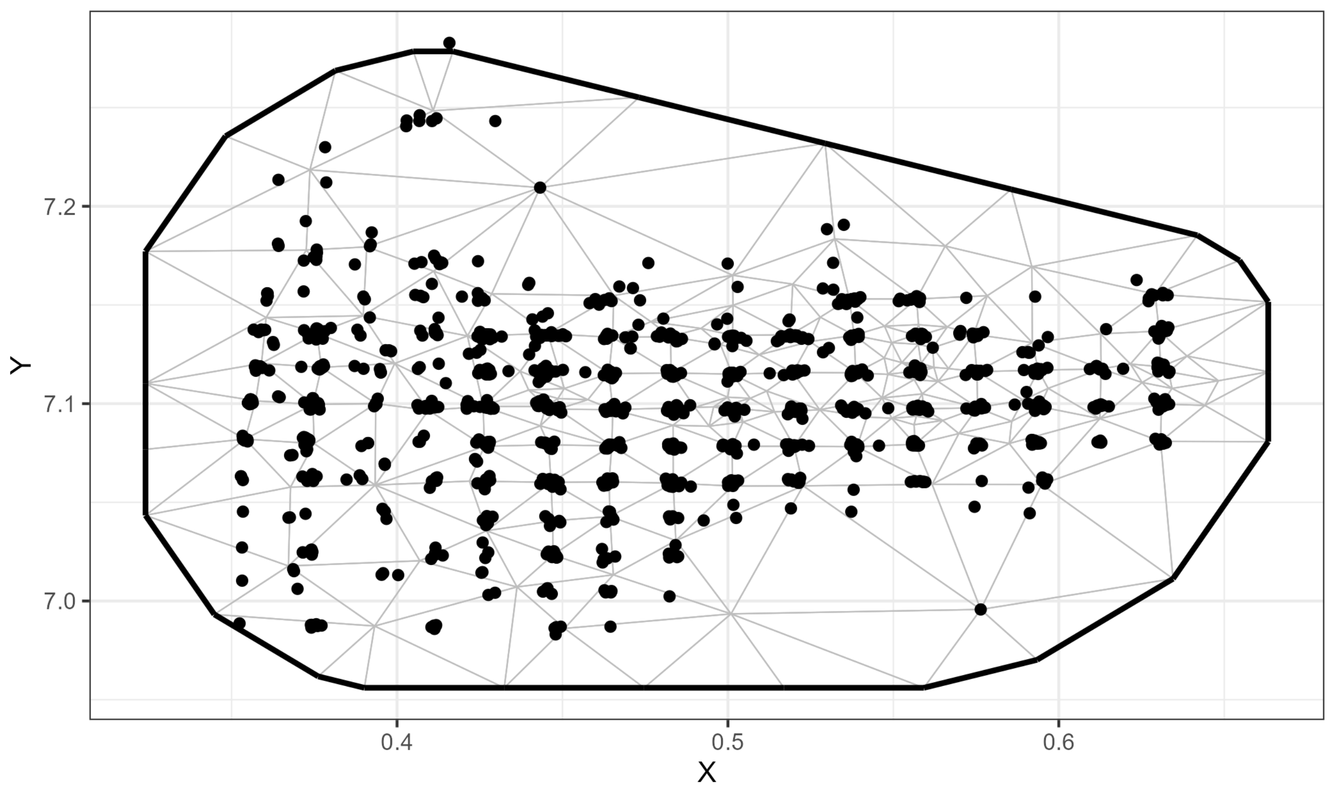


Figure 17: Spatial mesh with 100 knots used for fitting Norton Sound red king crab spatial models. Points represent observations and vertices represent knot locations.

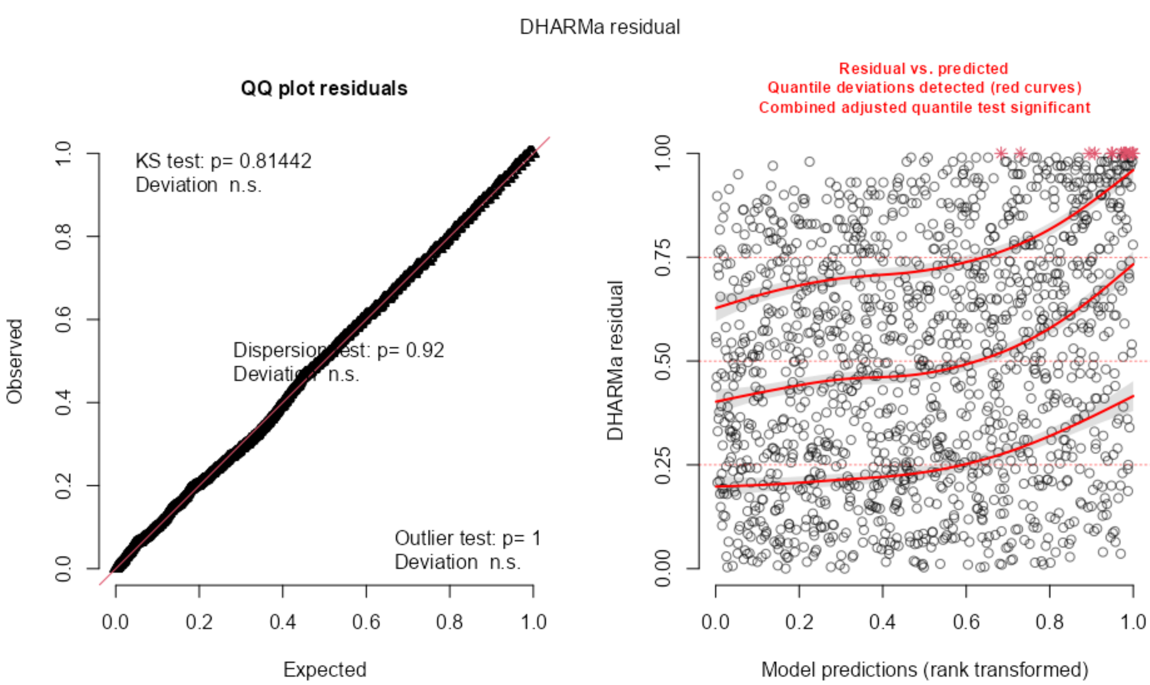


Figure 18: Model diagnostic plots using DHARMa residuals for the Norton Sound red king crab model with 30 knots.

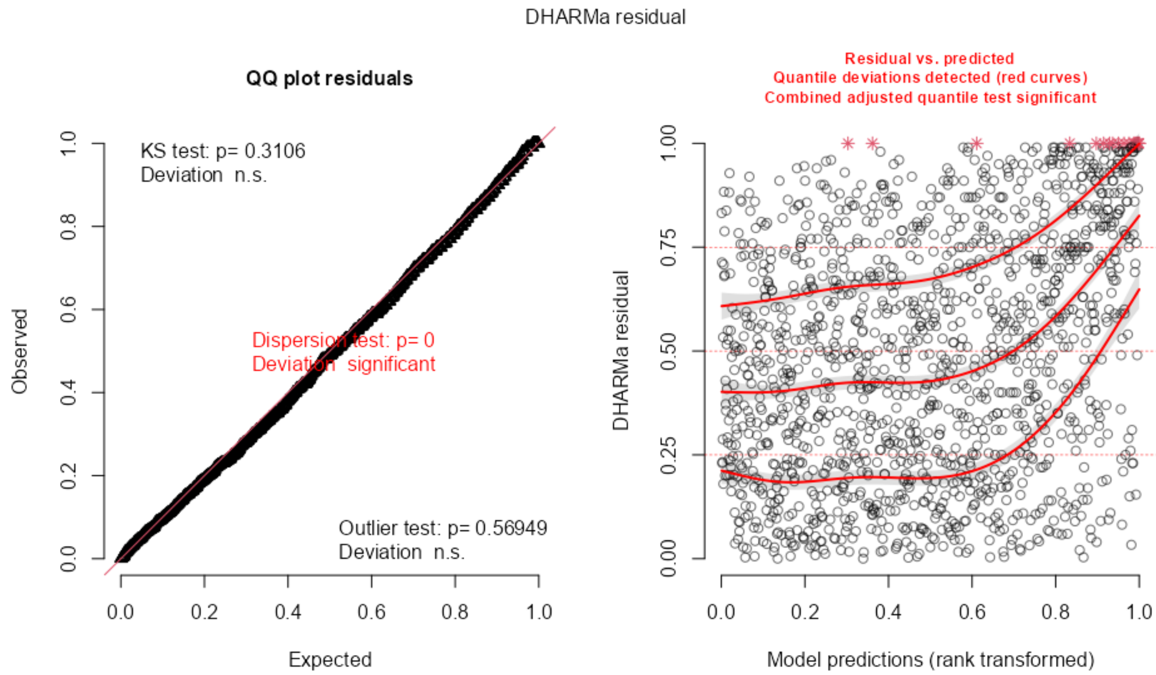


Figure 19: Model diagnostic plots using DHARMa residuals for the Norton Sound red king crab model with 50 knots.

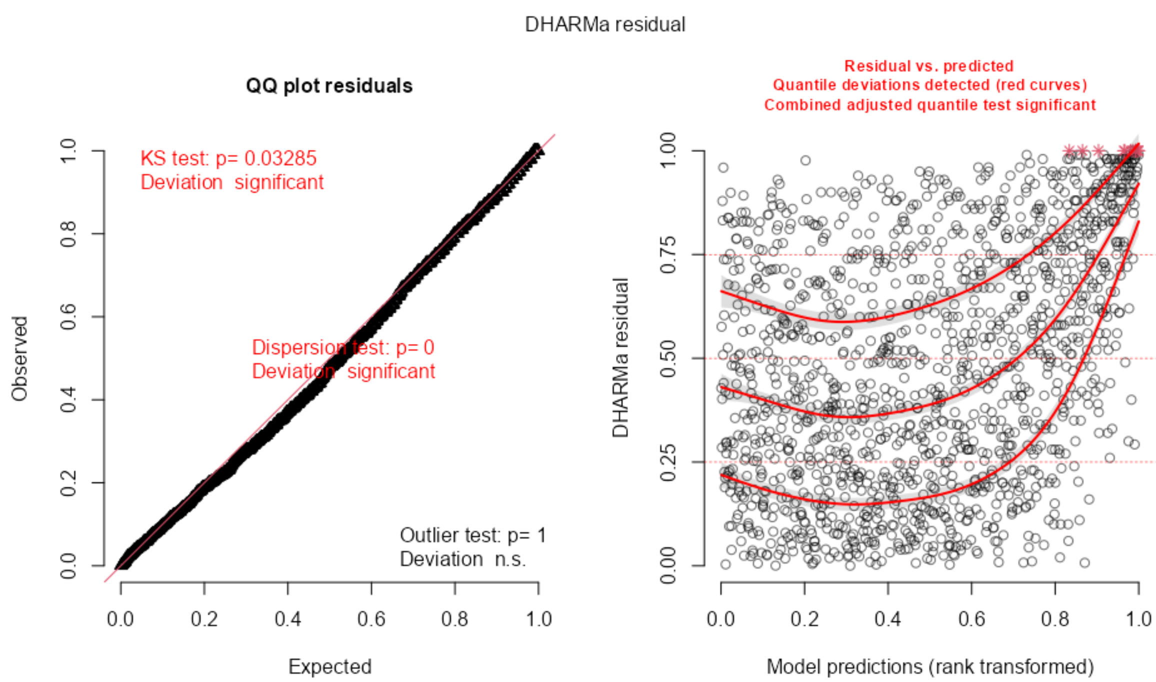


Figure 20: Model diagnostic plots using DHARMa residuals for Norton Sound red king crab model with 100 knots.

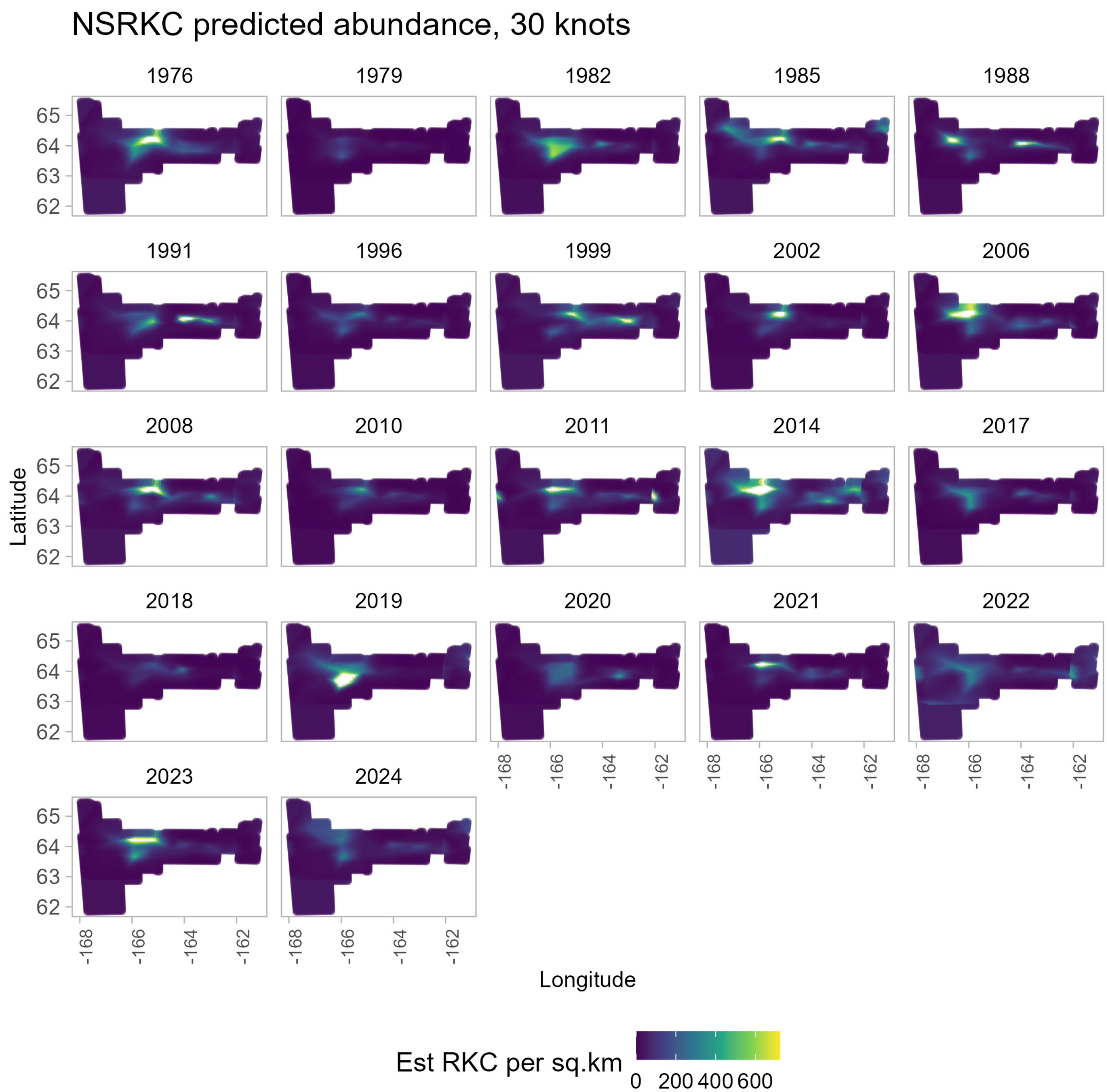


Figure 21: Heat map of Norton Sound red king crab predicted abundance generated using the model with 50 knots.

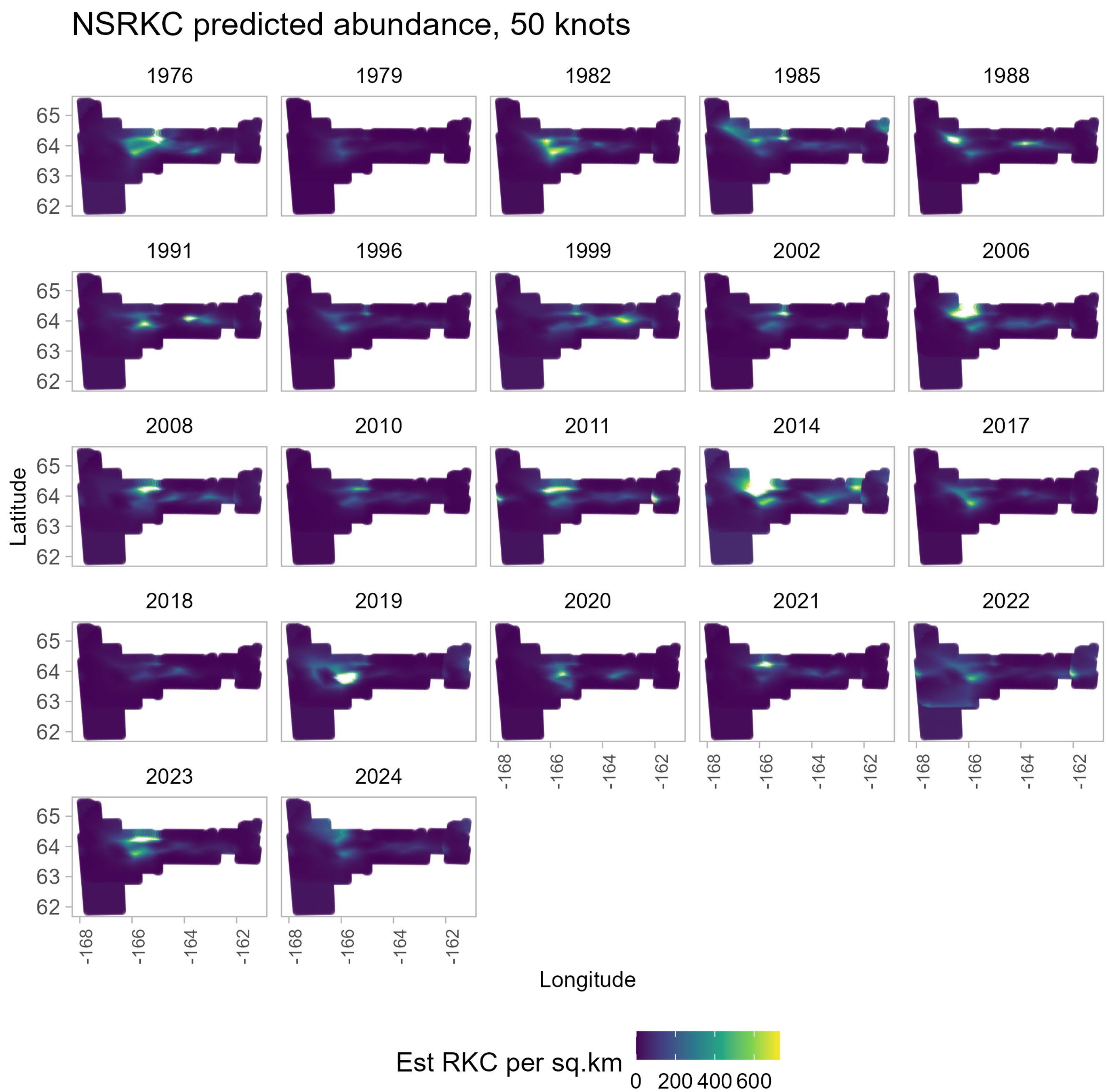


Figure 22: Heat map of Norton Sound red blue king crab predicted abundance generated using the model with 90 knots.

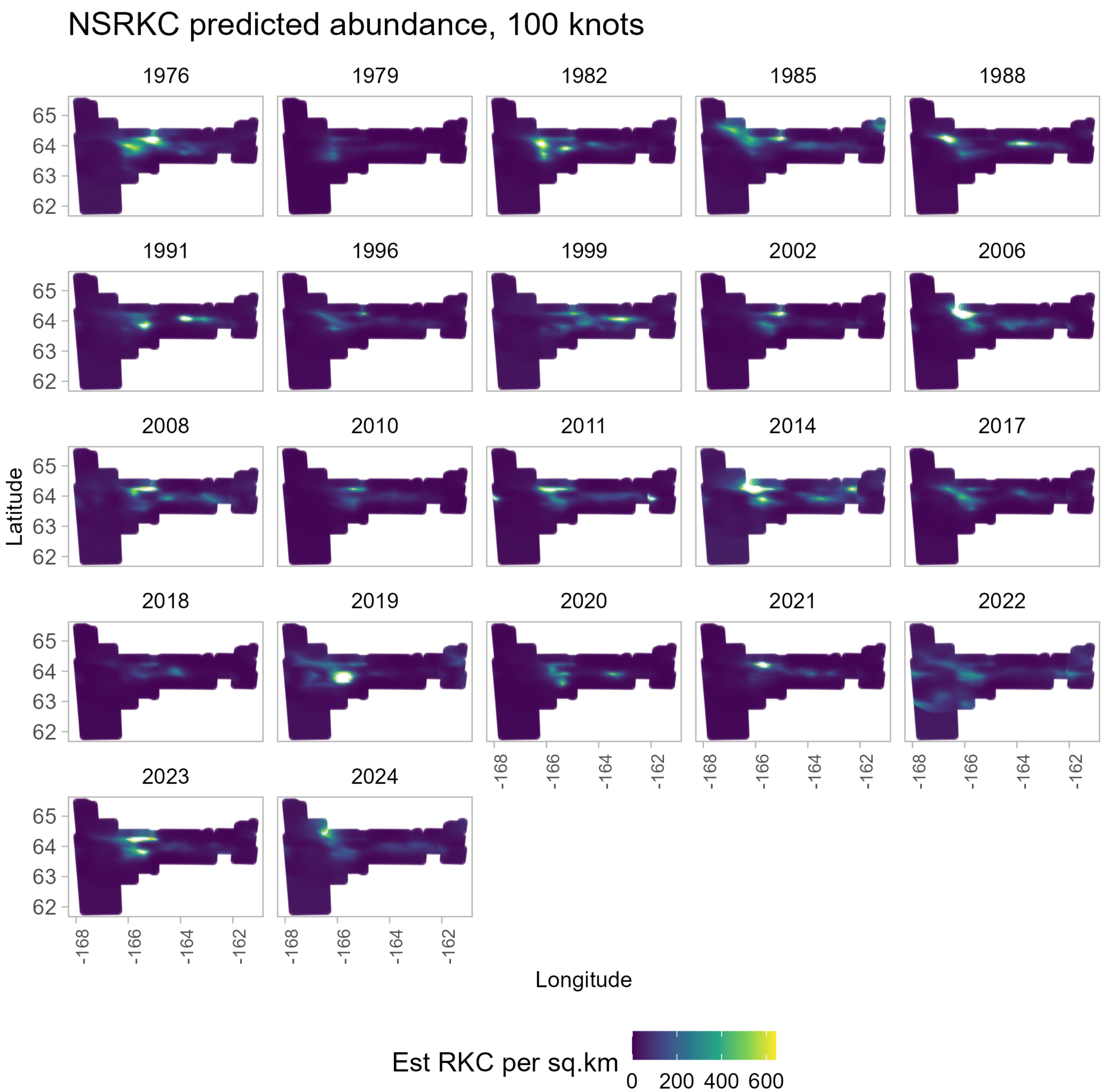


Figure 23: Heat map of Norton Sound red blue king crab predicted abundance generated using the model with 120 knots.

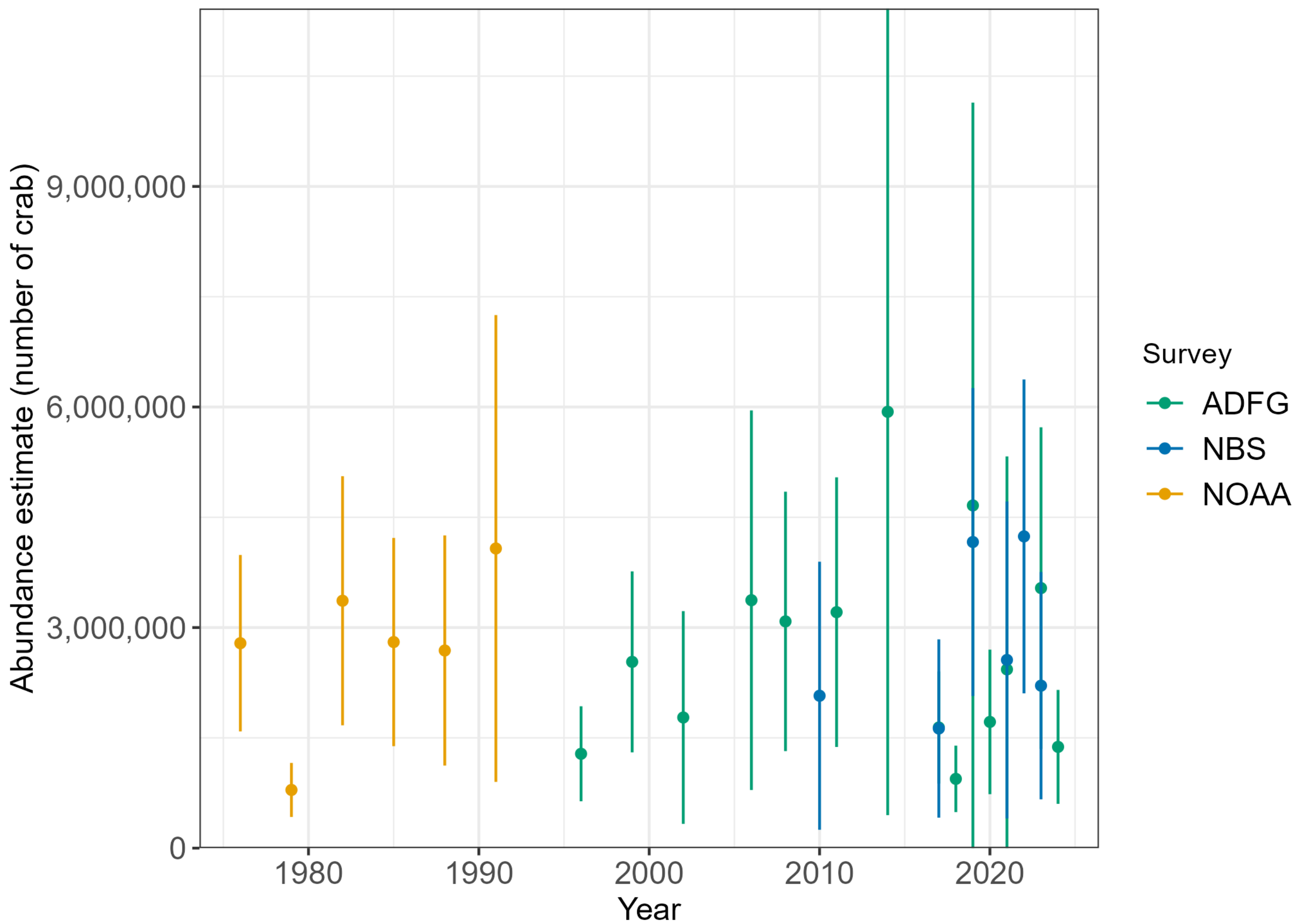


Figure 24: Estimated abundance in number of crab for Norton Sound red king crab. Colored points represent abundance (±95% CI) estimated by the trawl surveys.

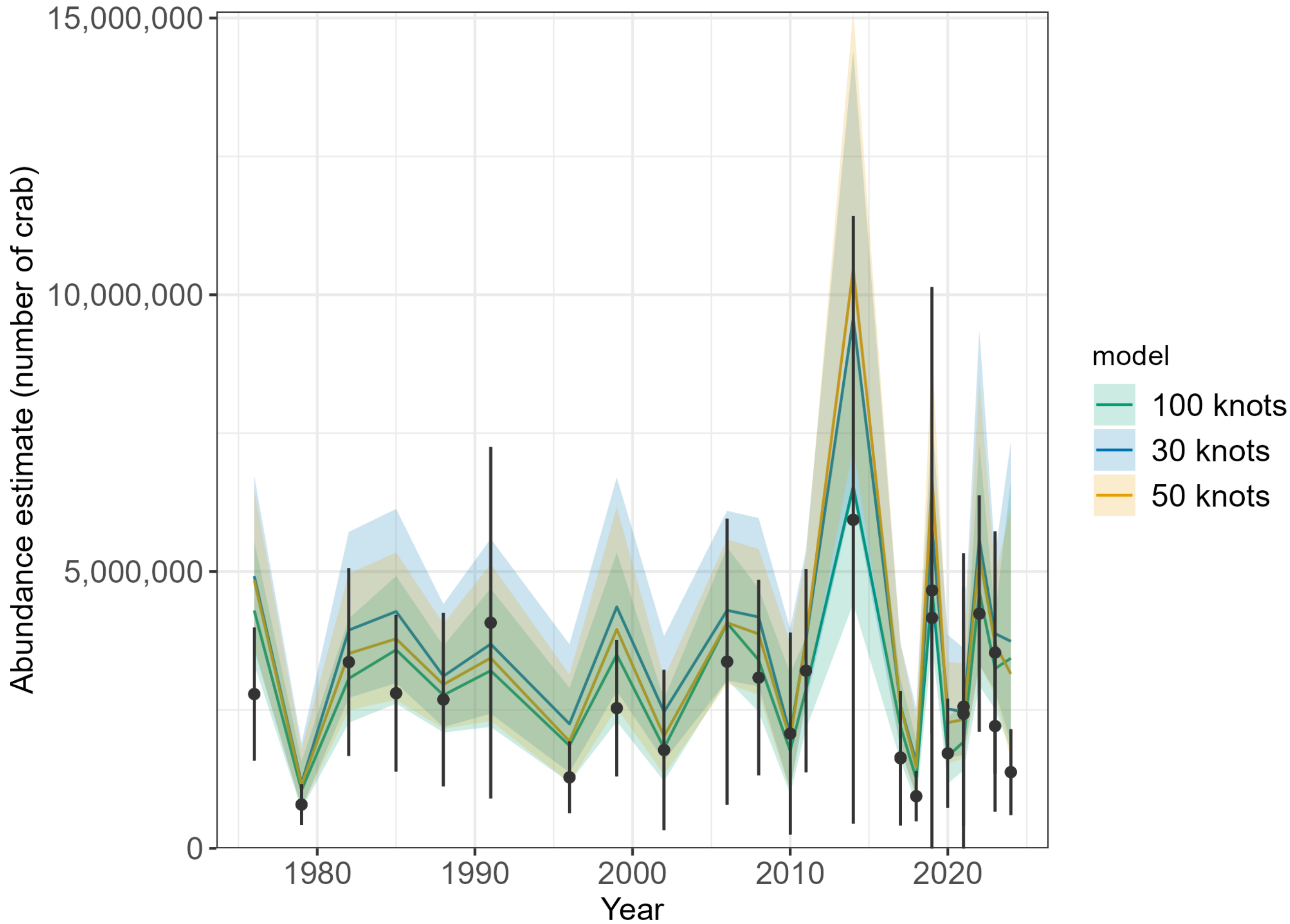


Figure 25: Estimated abundance in number of crab for Norton Sound red king crab. Colored lines represent abundance (±95% CI) estimated using sdmTMB. Black points represent abundance (±95% CI) estimated by the trawl surveys.

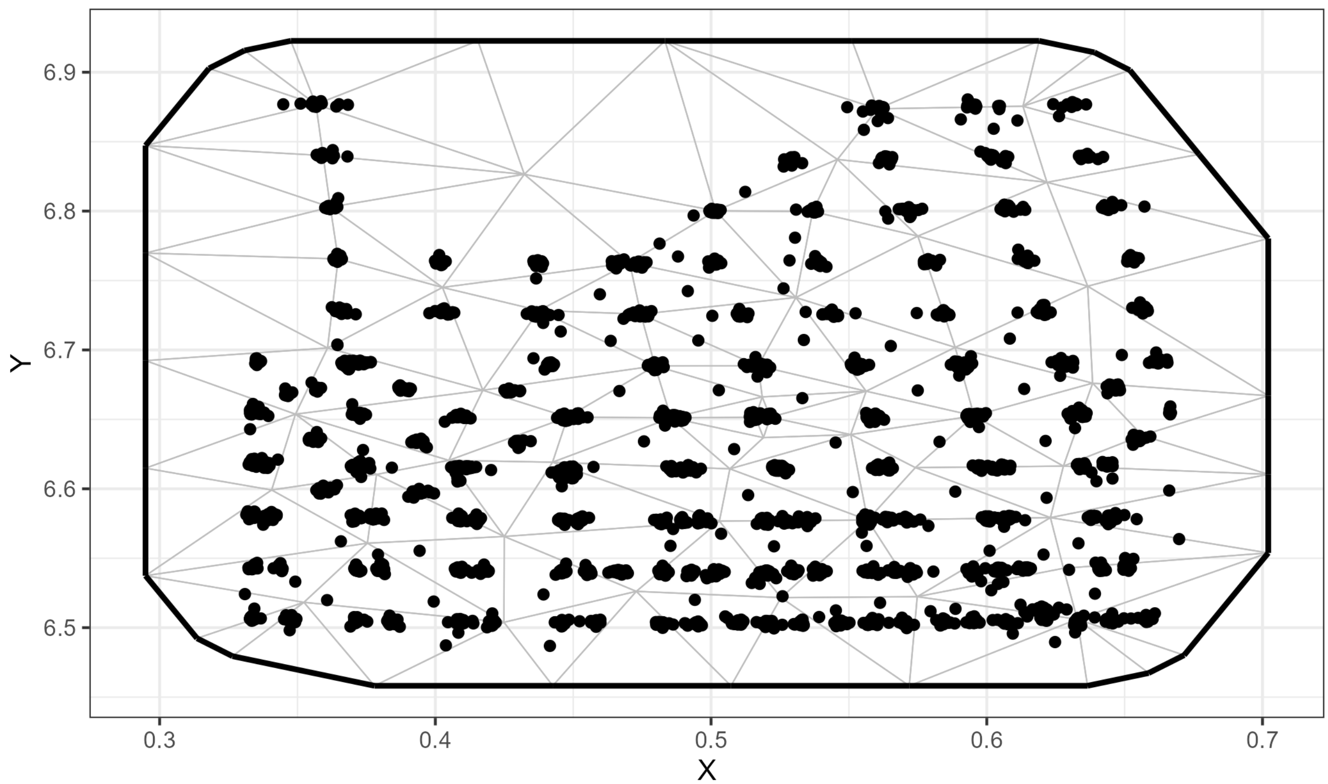


Figure 26: Spatial mesh with 50 knots used for fitting St. Matthew Island blue king crab spatial models. Points represent observations and vertices represent knot locations.

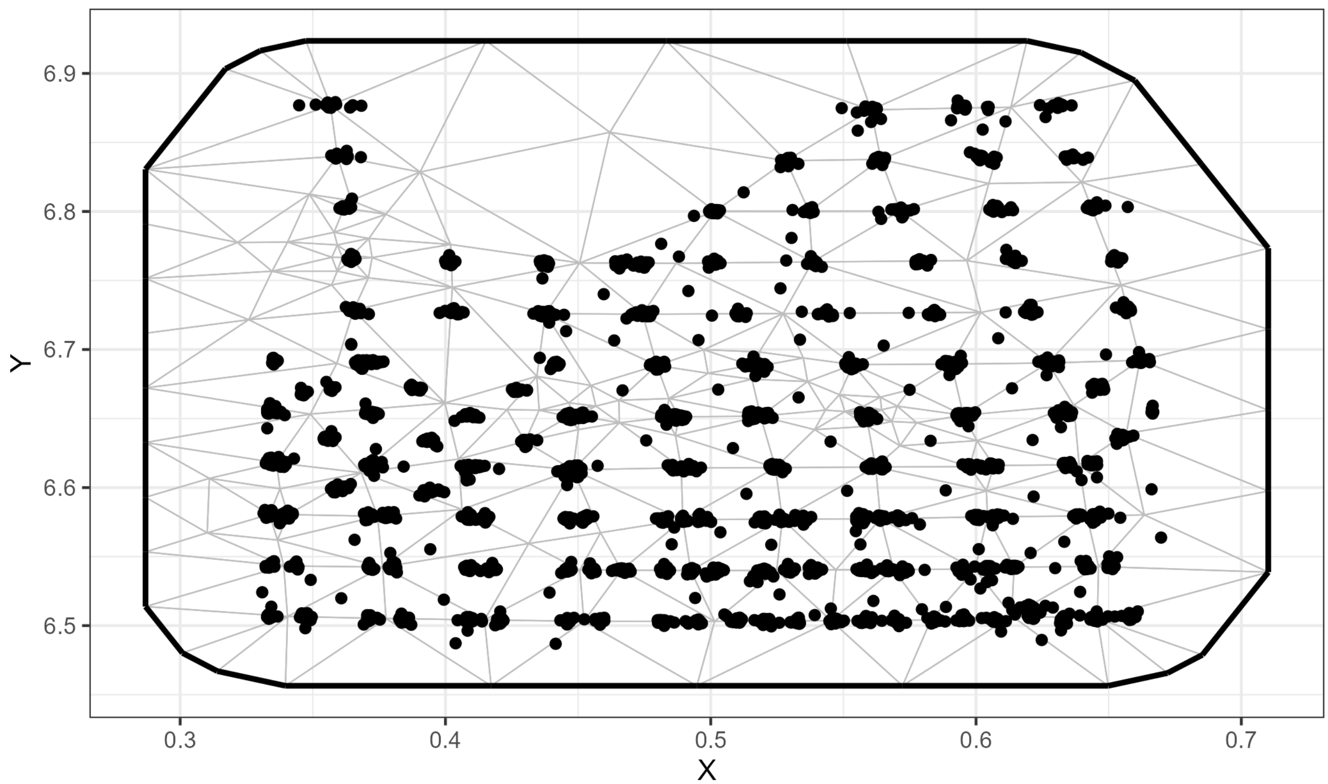


Figure 27: Spatial mesh with 90 knots used for fitting St. Matthew Island blue king crab spatial models. Points represent observations and vertices represent knot locations.

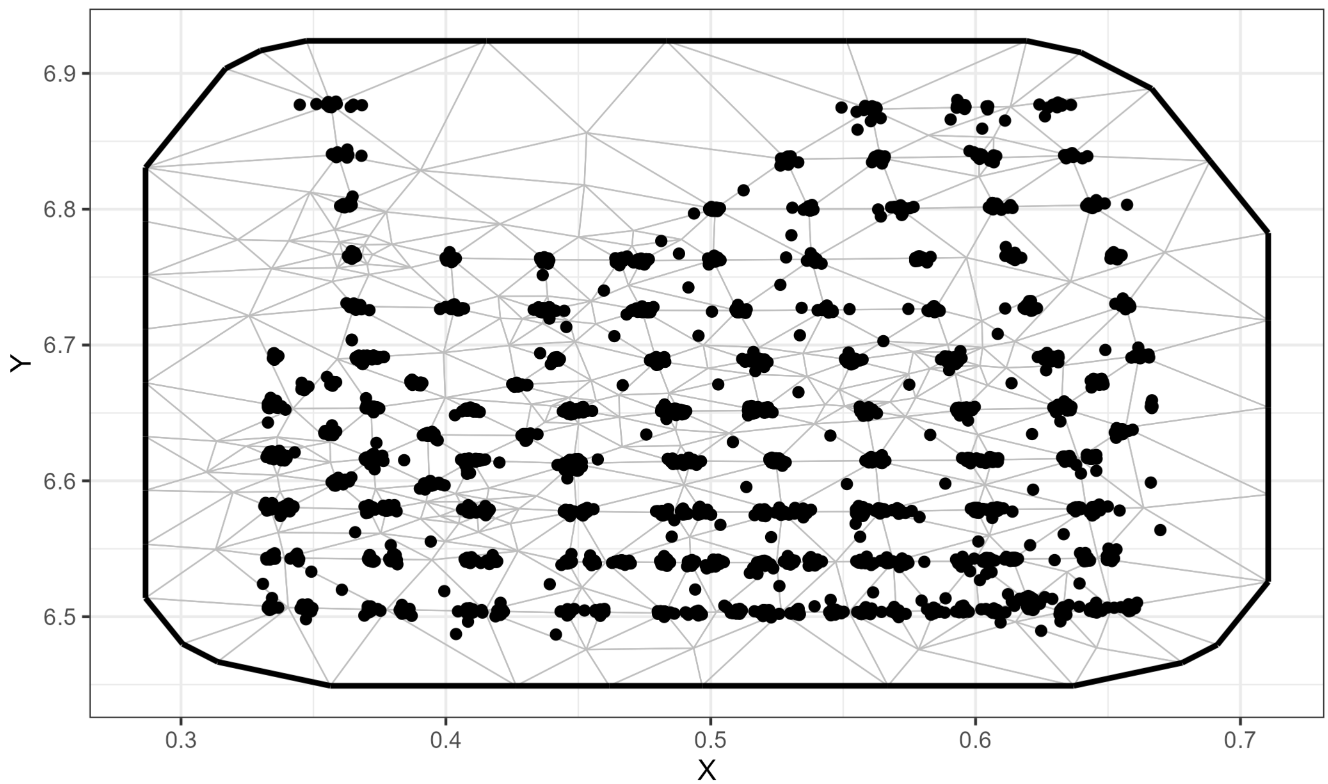


Figure 28: Spatial mesh with 120 knots used for fitting St. Matthew Island blue king crab spatial models. Points represent observations and vertices represent knot locations.

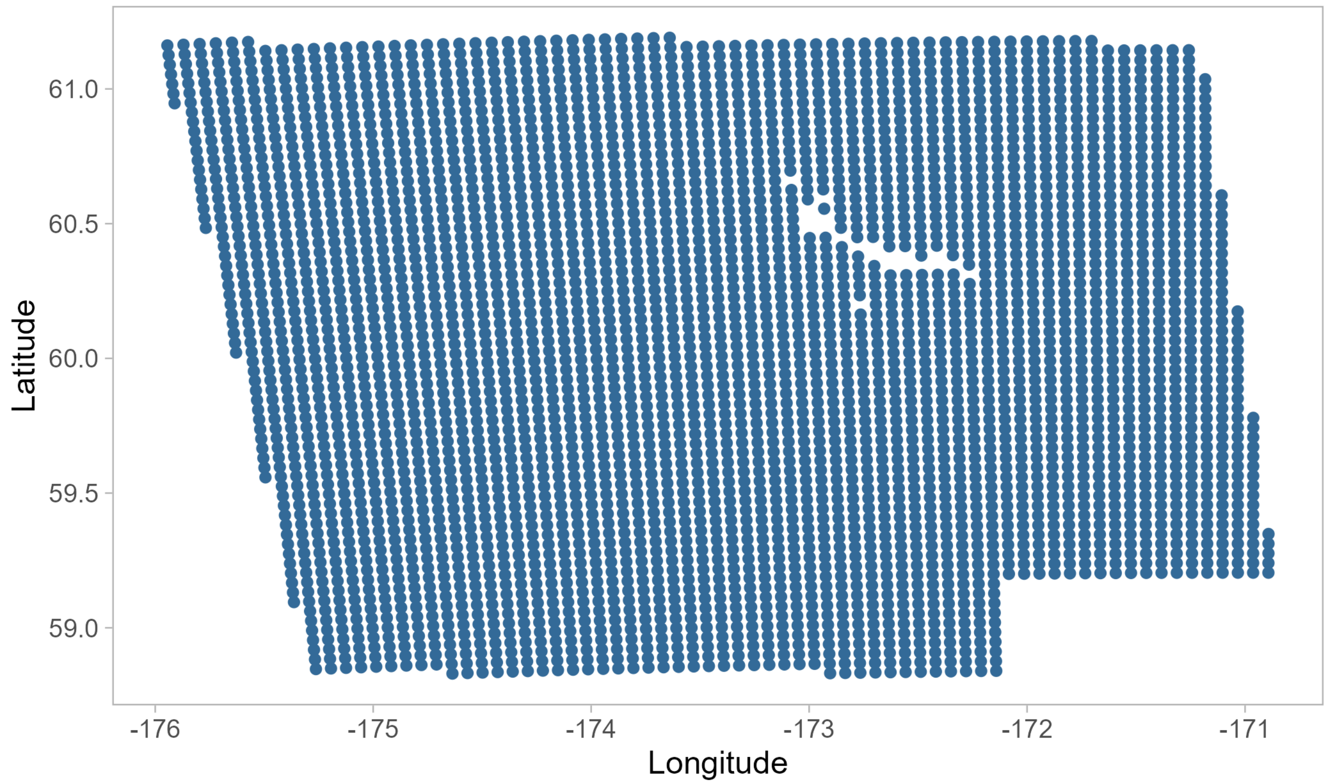


Figure 29: Prediction grid used for St. Matthew Island blue king crab spatial abundance predictions. Spatial resolution is 4 km^2.

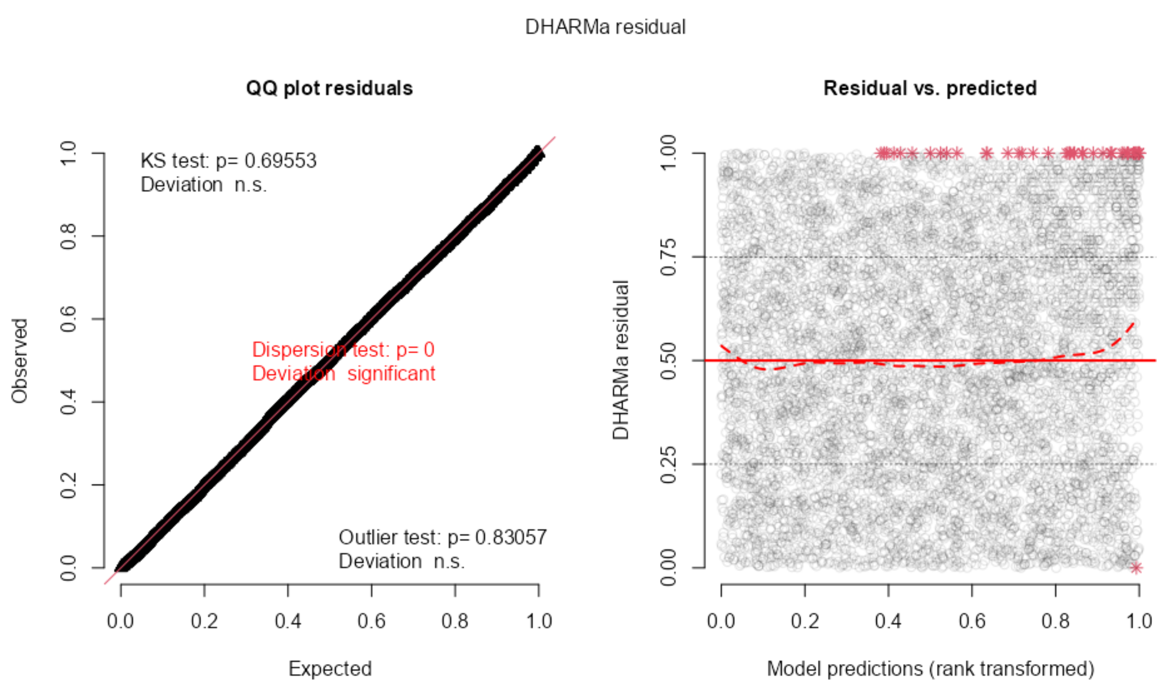


Figure 30: Model diagnostic plots using DHARMa residuals for the model with 50 knots.

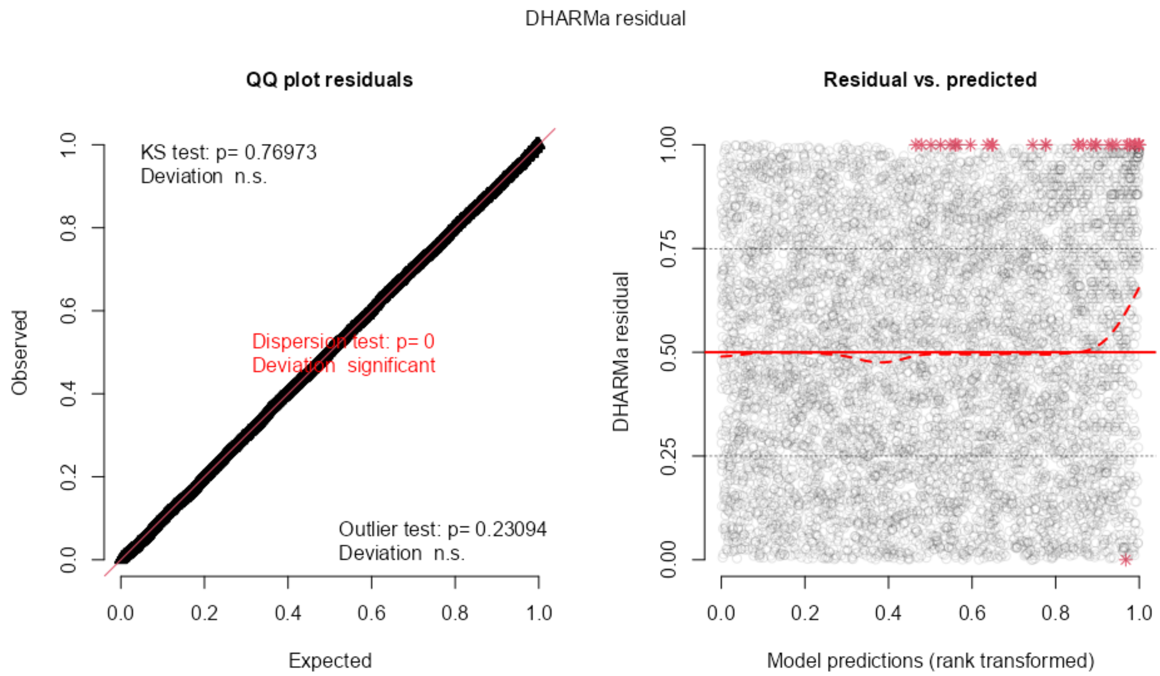


Figure 31: Model diagnostic plots using DHARMa residuals for the model with 90 knots.

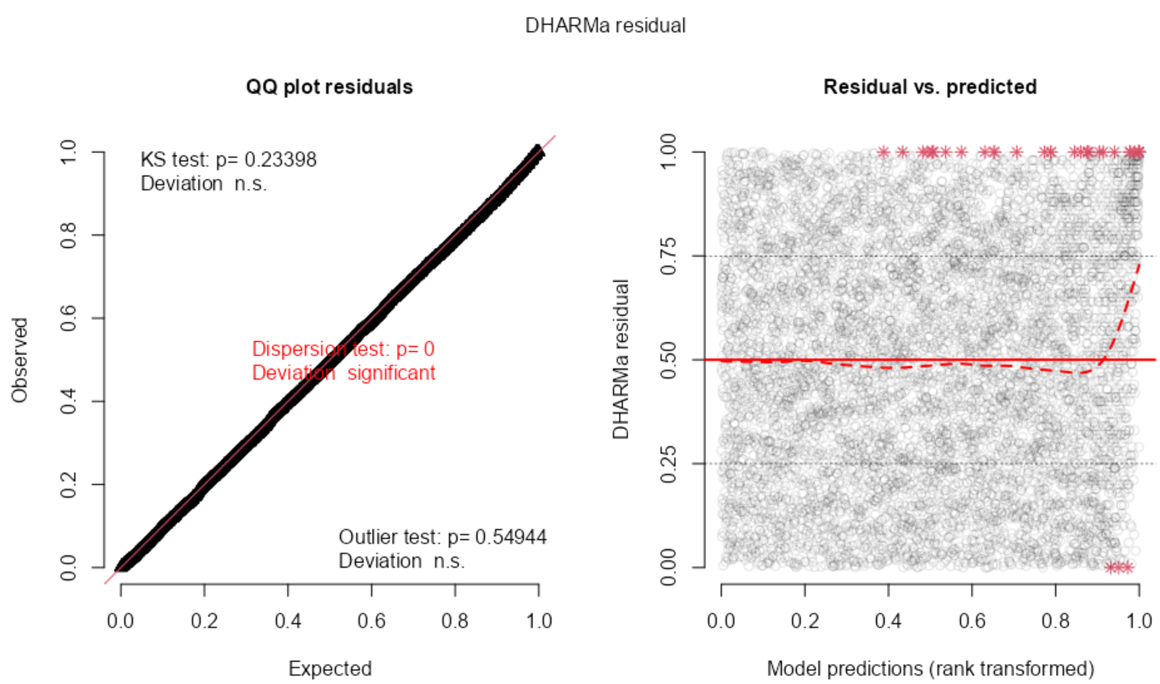


Figure 32: Model diagnostic plots using DHARMa residuals for the model with 120 knots.

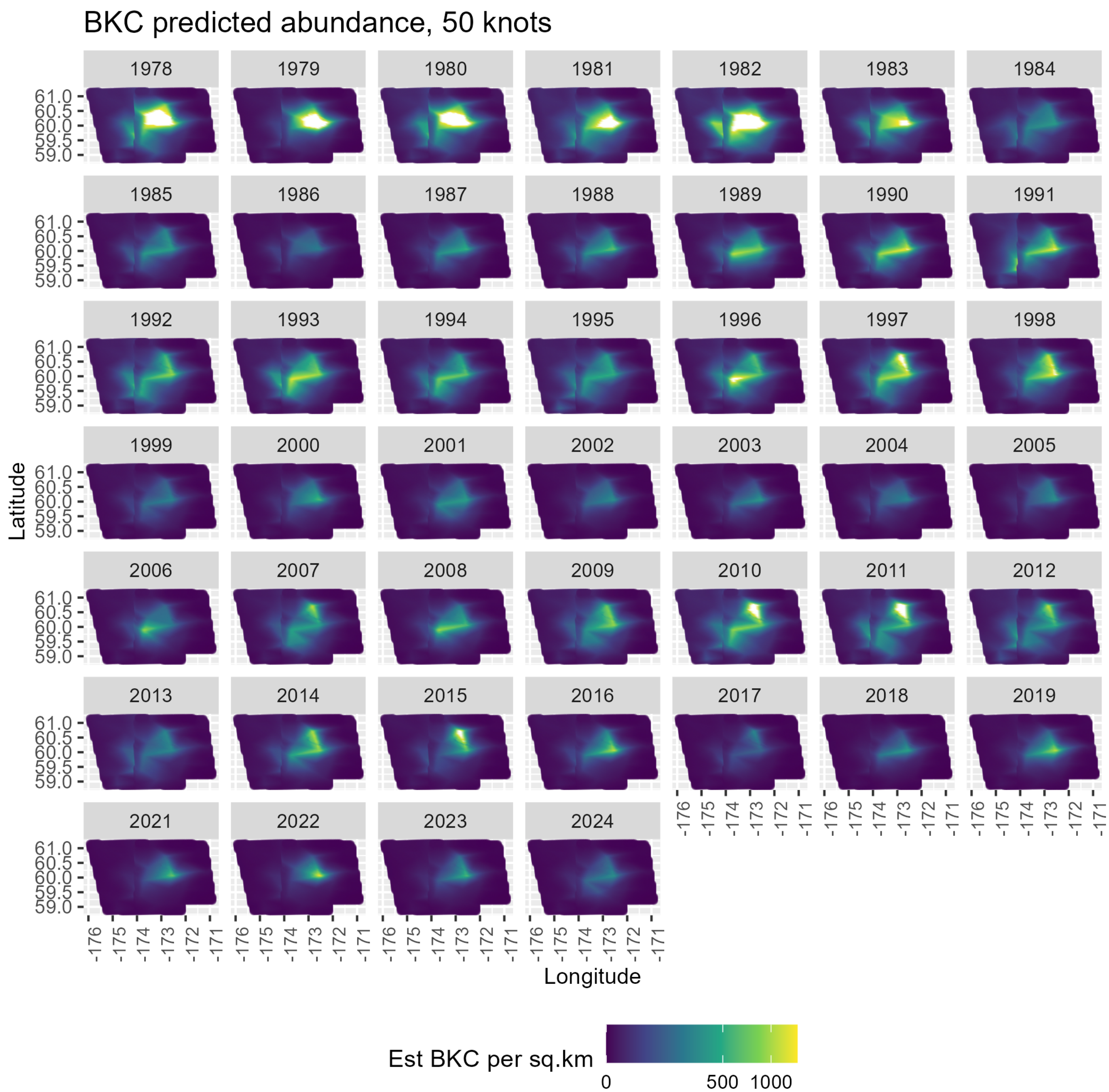


Figure 33: Heat map of St. Matthew Island blue king crab predicted abundance generated using the model with 50 knots.

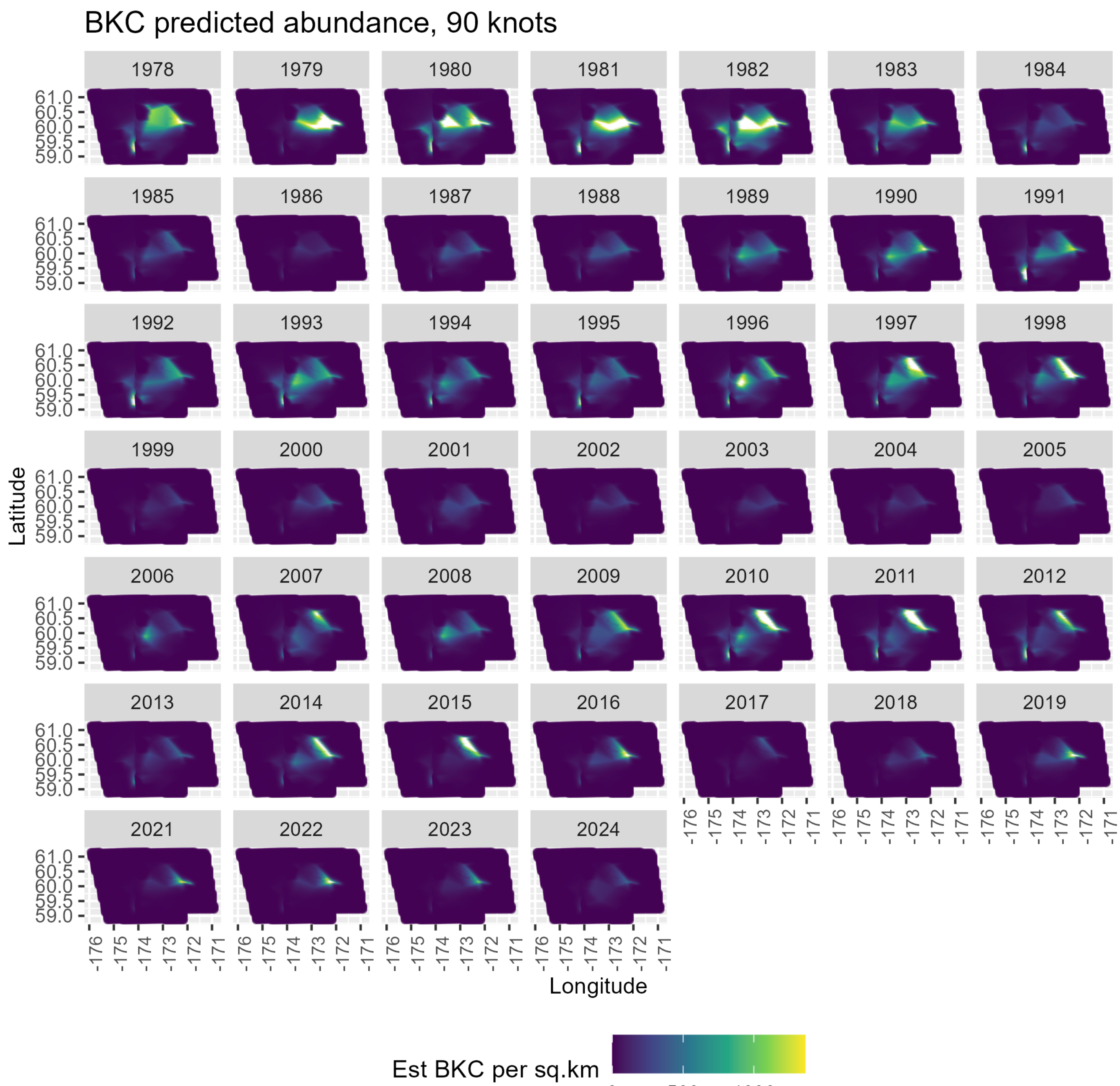


Figure 34: Heat map of St. Matthew Island blue king crab predicted abundance generated using the model with 90 knots.

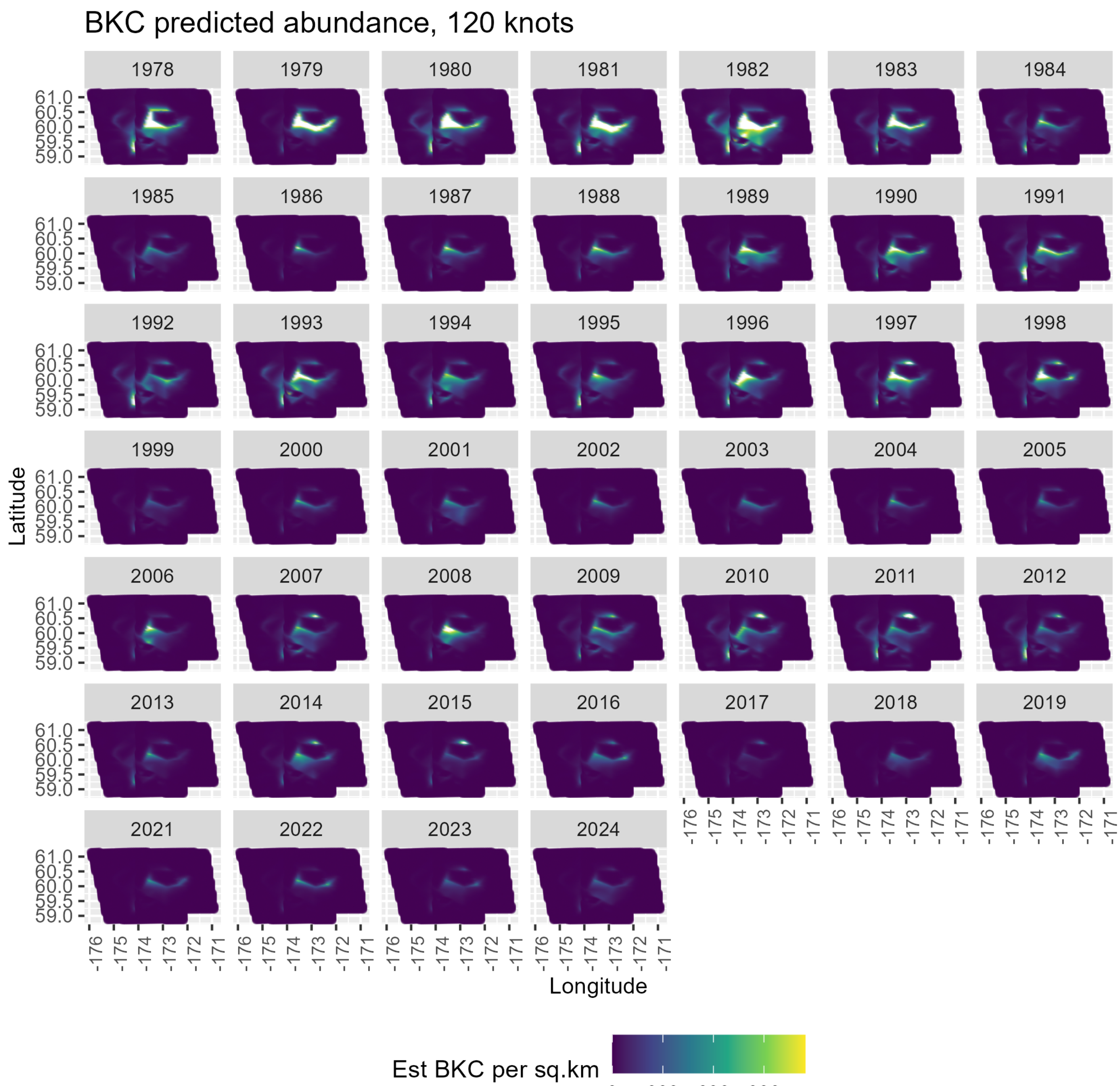


Figure 35: Heat map of St. Matthew Island blue king crab predicted abundance generated using the model with 120 knots.

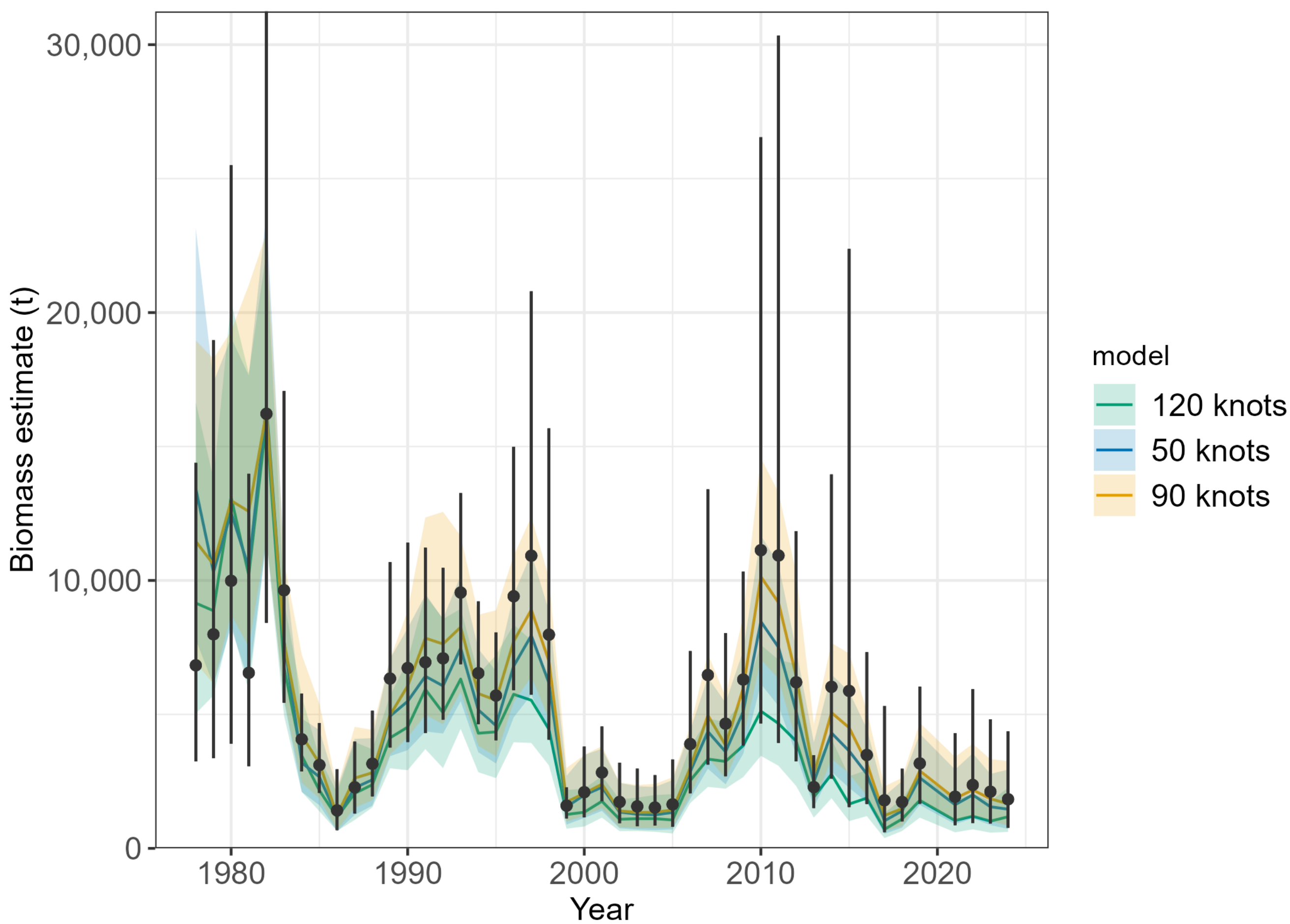


Figure 36: Estimated biomass (t) for St. Matthew Island blue king crab. Colored lines represent biomass (±95% CI) estimated using sdmTMB. Black points represent biomass (±95% CI) estimated by the NMFS EBS bottom trawl survey.

Appendix