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

Update for Crab Plan Team modeling workshop

Caitlin Stern[1,2], Emily Ryznar[3,4], and Jon Richar[3,5]
[1]Alaska Department of Fish and Game
[2]caitlin.stern@alaska.gov
[3]NOAA Fisheries
[4]emily.ryznar@noaa.gov
[5]jon.richar@noaa.gov

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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 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*.

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.
- 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().

For each stock, we present a range of models to show the effects of choices at each of these decision points. After fitting models, we used the following steps for model evaluation:

- Run the sdmTMB::sanity() function. Output of this function for a model that passes all sanity checks looks like this:

✓ Non-linear minimizer suggests successful convergence

✓ Hessian matrix is positive definite

✓ No extreme or very small eigenvalues detected

✓ No gradients with respect to fixed effects are >= 0.001

✓ No fixed-effect standard errors are NA

✓ No standard errors look unreasonably large

✓ No sigma parameters are < 0.01

✓ No sigma parameters are > 100

✓ Range parameter doesn't look unreasonably large

- If a model passed all the sanity checks, we used the R package *DHARMa* (Hartig 2022) to calculate the DHARMa residuals using the function DHARMa::dharma_residuals(). Models that did not pass the sanity checks were excluded from further consideration.
- We tested for quantile deviations, under/overdispersion, outliers, and zero inflation using the functions DHARMa::testQuantiles(), DHARMa::testDispersion(), DHARMa::testOutliers(), and DHARMa::testZeroInflation(), respectively.
- We evaluated model predictive density (the predictive ability of the model for new observations; Anderson *et al.* 2024) using the function sdmTMB_cv(). This function measures model predictive density by holding out subsets of the data in turn and using each as a test set. These subsets of data are termed "folds" and the number of folds to use can be specified using the k_folds argument. To compare models, we ran this function with the same number of folds specified for each model, then extracted the summed log-likelihood value for each model.

Tanner crab

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: 100 knots, 50 knots, and 30 knots (Figures 11 - 9). We used a prediction grid with resolution of 5 km^2 (Figure 8).

St. Matthew Island blue king crab

For model fitting, we used spatial meshes at three resolutions: 120 knots, 90 knots, and 50 knots (Figures 14 - 12). We used a prediction grid with a resolution of 4 km^2 (Figure 15).

Results

Tanner crab

Tanner crab

Norton Sound red king crab

Model diagnostics

The DHARMa residuals diagnostic plots show evidence of quantile deviations for all three NSRKC models (Figures **??** - **??**). 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.

Model predictive density

Predictive density (log-likelihood) values for NSRKC models are shown in table **??**. Predictive density values closer to zero indicate better out-of-sample predictive skill. Models with missing predictive density values are models that did not pass all sanity checks. The three models with the best out-of-sample predictive skill were models **add info here**.

Predicted abundance

Heat maps of predicted NSRKC abundance for the three models with the best out-of-sample predictive skill are show in figures **??** - **??**.

St. Matthew Island blue king crab

Model diagnostics

Examination of DHARMa residuals showed similar patterns for the three SMBKC models (Figures **??** - **??**). All three models showed evidence of underdispersion, with observed data less dispersed than expected under

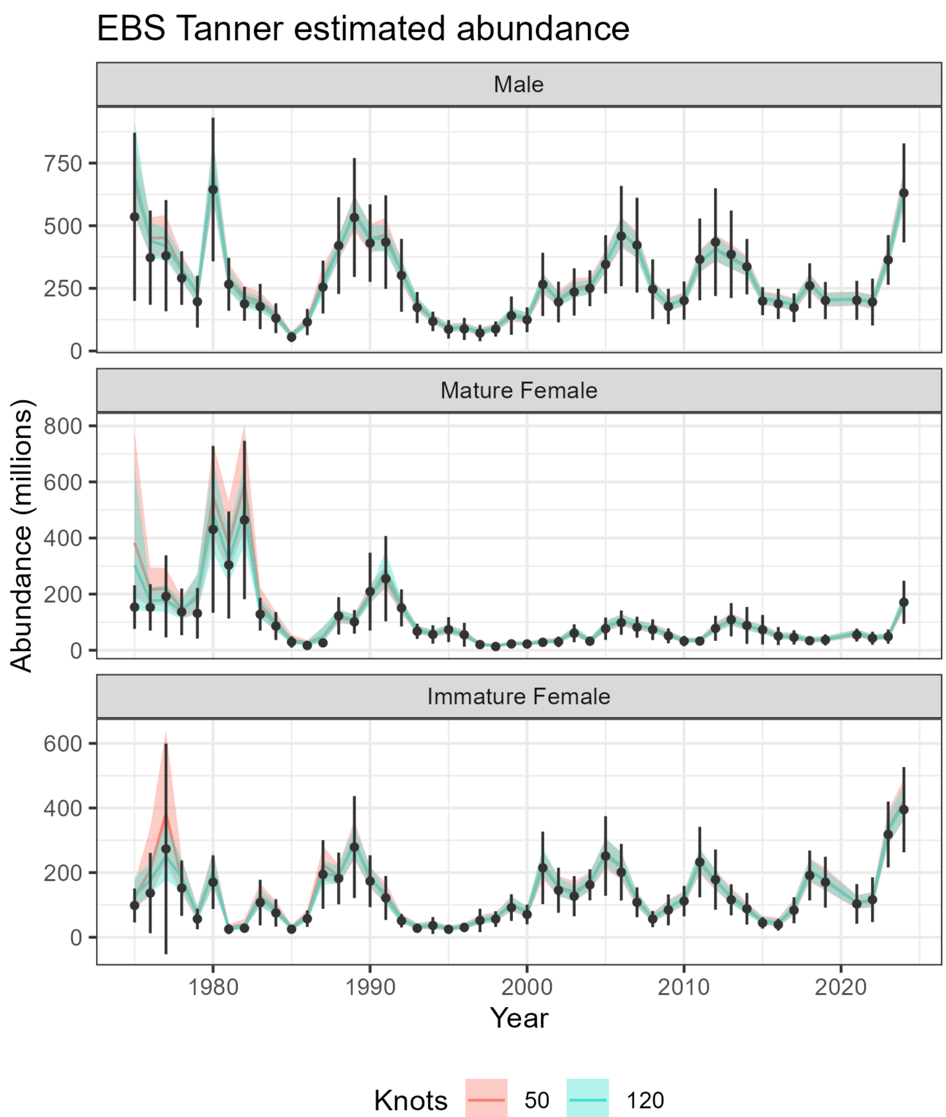

Figure 1: Estimated abundance (millions) for Eastern Bering Sea Tanner crab (Chionoecetes bairdi). Colored lines represent abundance (±95% CI) estimated by sdmTMB, with pink and blue denoting models fit with a 50- and 120-knot mesh, respectively. Black points represent abundance (±95% CI) estimated by the NMFS summer bottom trawl survey.

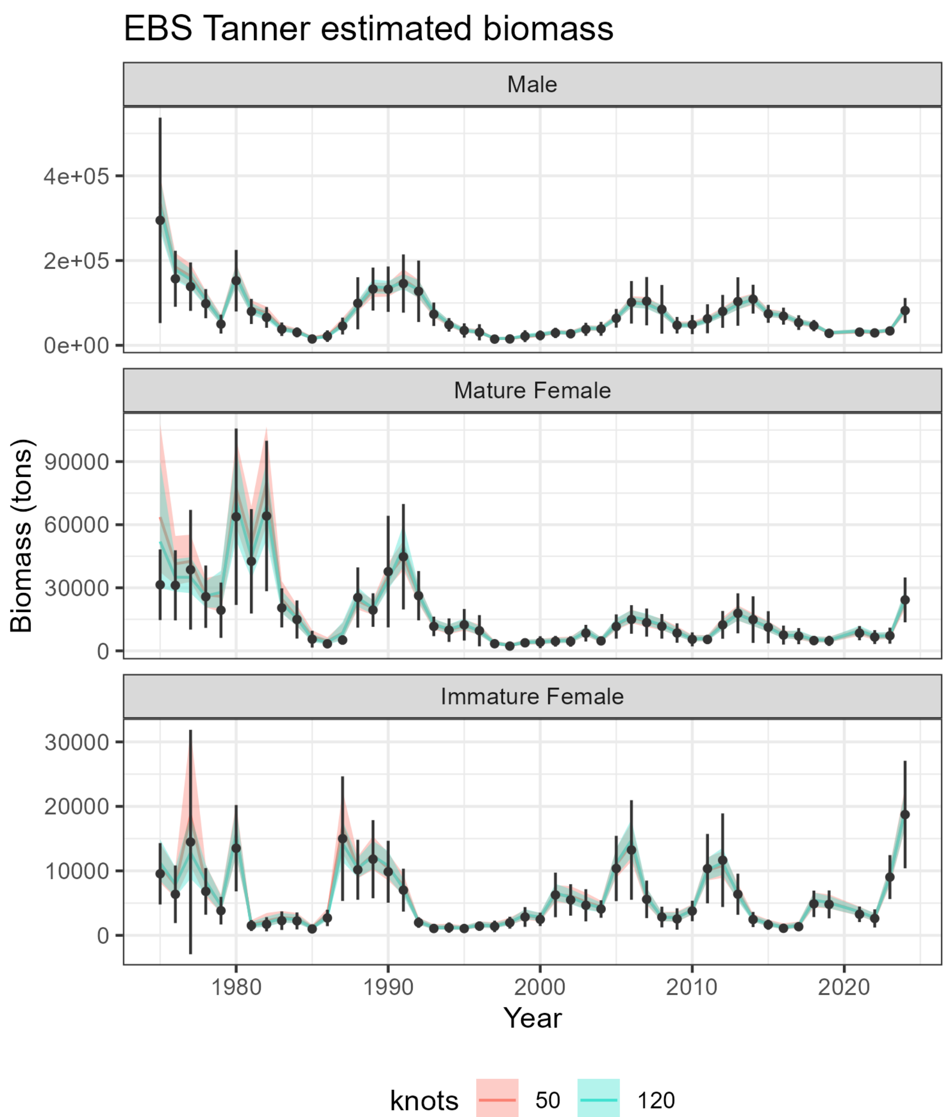

Figure 2: Estimated biomass (tons) for Eastern Bering Sea Tanner crab (Chionoecetes bairdi). Colored lines represent abundance (±95% CI) estimated by sdmTMB, with pink and blue denoting models fit with a 50- and 120-knot mesh, respectively. Black points represent abundance (±95% CI) estimated by the NMFS summer bottom trawl survey.

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 **??** - **??**.

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 **??**).

Conclusions

Acknowledgements

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Tables

Table 1: Norton Sound red king crab fitted model predictive density (log-likelihood) values, estimated using sdmTMB cross-validation with 3 folds, for models fitted with Tweedie, delta gamma, or delta lognormal model familes; spatial random fields estimated using independent and identically distributed (IID), random walk (RW), or first-order autoregressive (AR1) methods; and spatial resolution of 30, 50, or 100 knots. Predictive density (log-likelihood) values closer to zero represent better out-of-sample predictive skill. Model configurations with missing log-likelihood values represent models that did not pass sanity checks.

Family	Estimation method	Knots	Log-likelihood
Tweedie	IID	100	-5906
Tweedie	IID	50	-5813
Tweedie	IID	30	-5730
delta gamma	IID	100	
delta gamma	IID	50	-5607
delta gamma	IID	30	-5567
delta lognormal	IID	100	-5369
delta lognormal	IID	50	-5381
delta lognormal	IID	30	-5400
Tweedie	RW	100	
Tweedie	RW	50	
Tweedie	RW	30	
delta gamma	RW	100	
delta gamma	RW	50	
delta gamma	RW	30	
delta lognormal	RW	100	
delta lognormal	RW	50	
delta lognormal	RW	30	
Tweedie	AR1	100	
Tweedie	AR1	50	
Tweedie	AR1	30	
delta gamma	AR1	100	
delta gamma	AR1	50	
delta gamma	AR1	30	
delta lognormal	AR1	100	
delta lognormal	AR1	50	
delta lognormal	AR1	30	

Figures

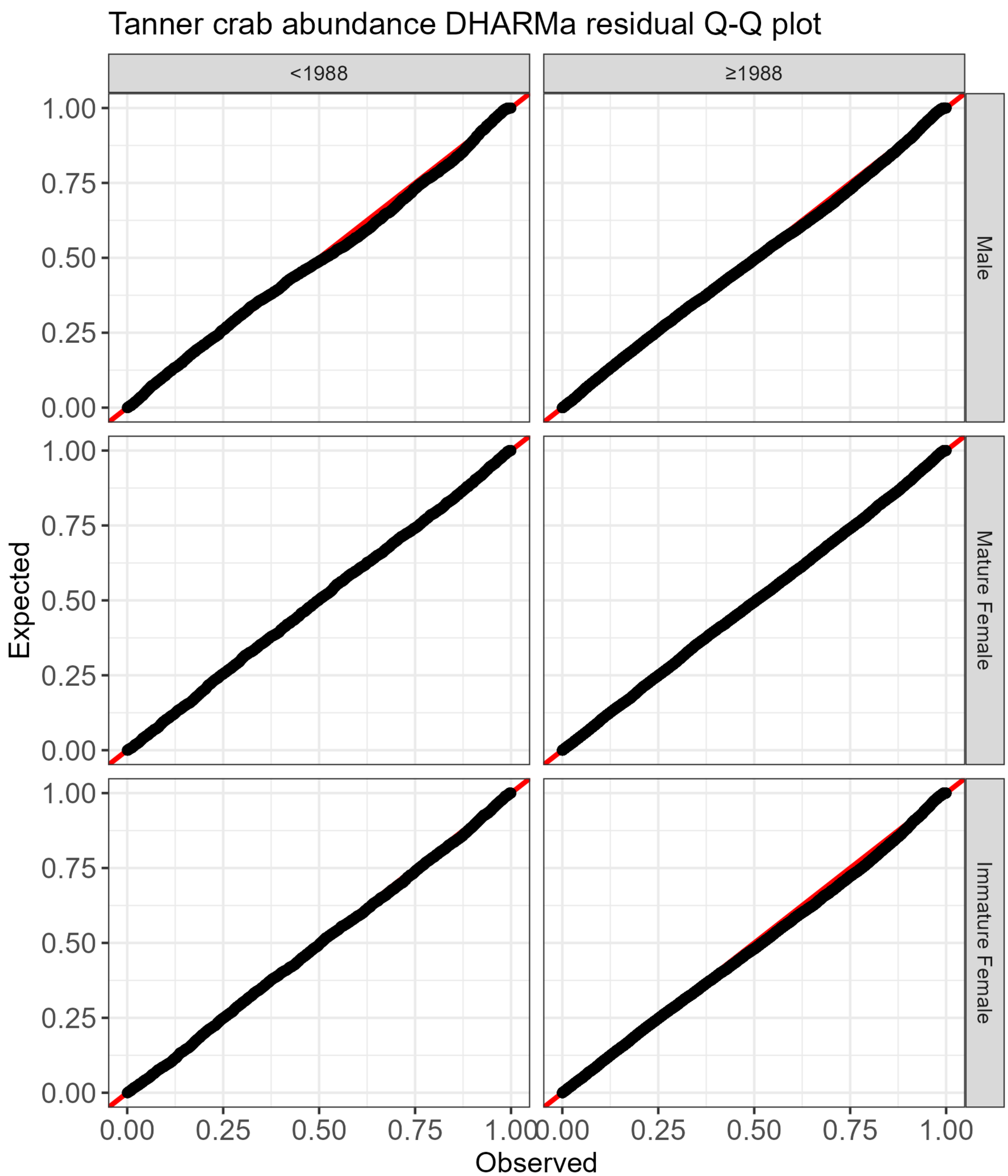

Figure 3: Q-Q plot of DHARMa residuals for EBS-wide abundance models fit using NMFS summer bottom trawl survey data before 1988 (left) and 1988 onward (right) using 120 knots in the model mesh.

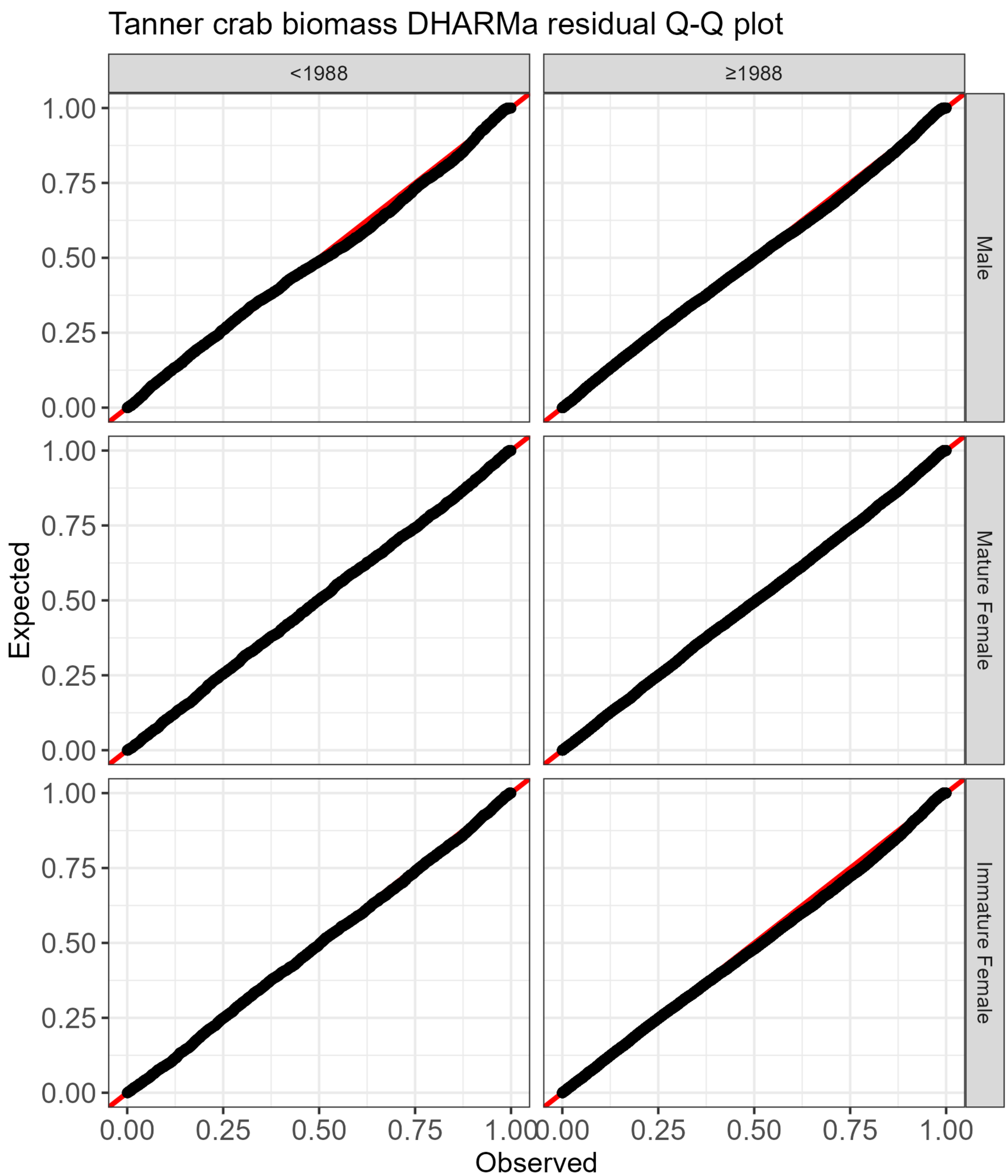

Figure 4: Q-Q plot of DHARMa residuals for EBS-wide biomass models fit using NMFS summer bottom trawl survey data before 1988 (left) and 1988 onward (right) using 120 knots in the model mesh.

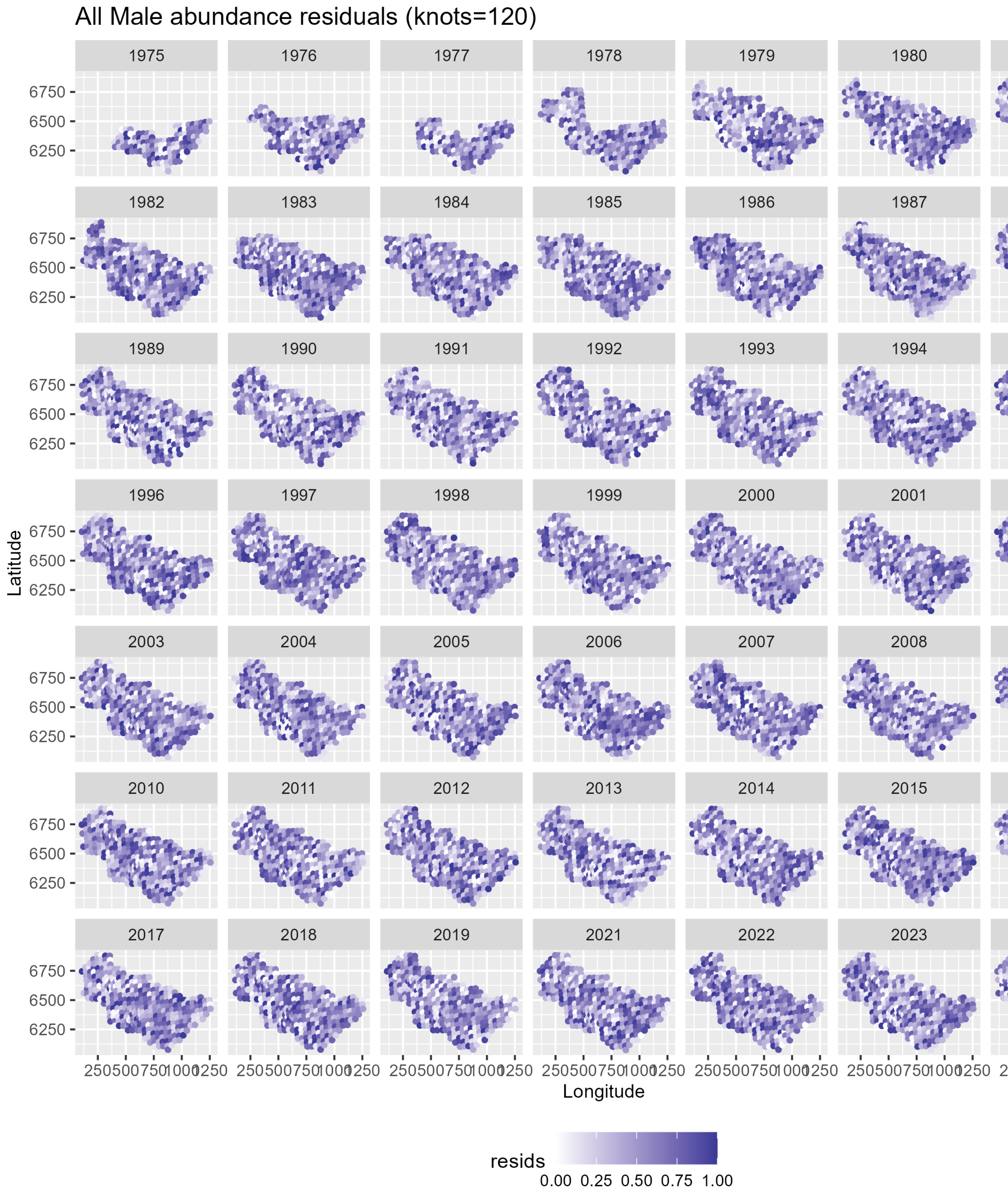

Figure 5: Spatial plot of DHARMa residuals for EBS-wide male abundance models fit using NMFS summer bottom trawl survey data before 1988 and 1988 onward. Predictions from both these periods/models are combined in this figure.

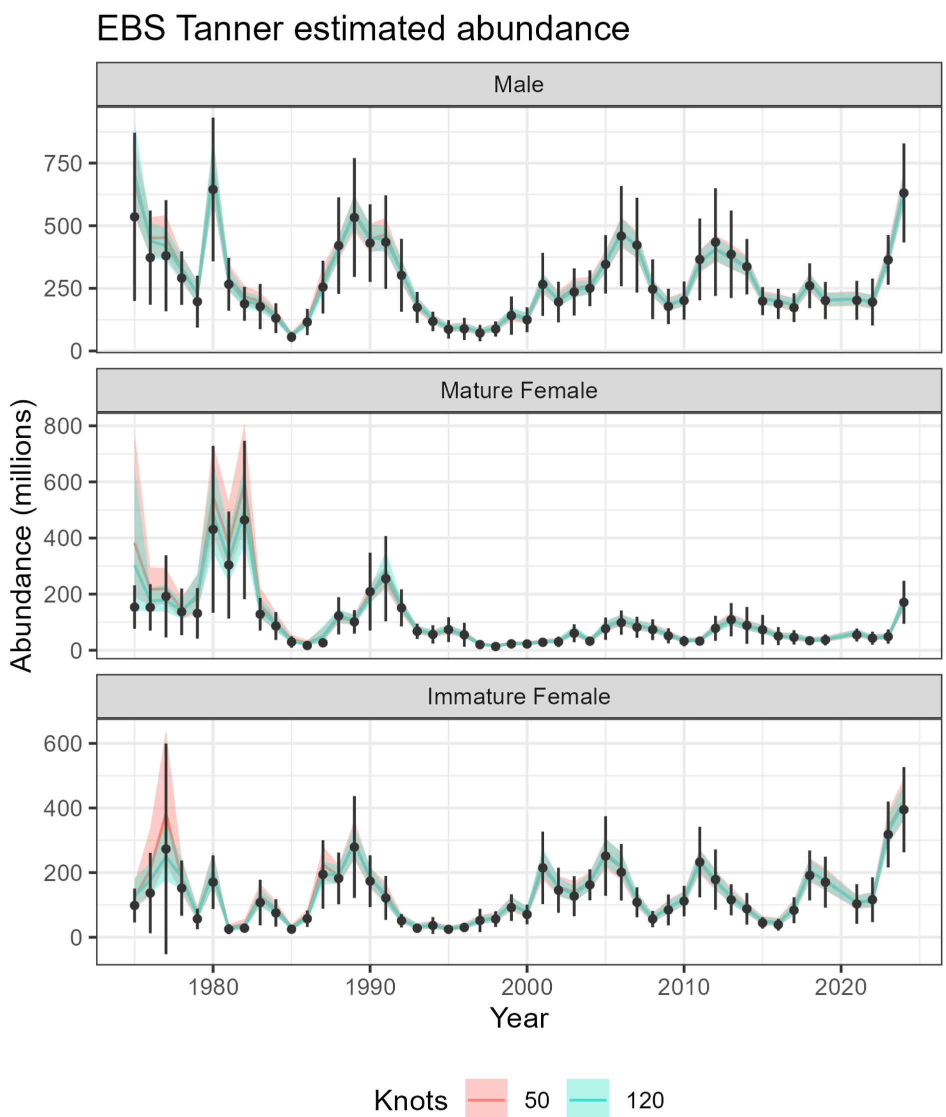

Figure 6: Estimated abundance (millions) for Eastern Bering Sea Tanner crab (Chionoecetes bairdi). Colored lines represent abundance (±95% CI) estimated by sdmTMB, with pink and blue denoting models fit with a 50- and 120-knot mesh, respectively. Black points represent abundance (±95% CI) estimated by the NMFS summer bottom trawl survey.

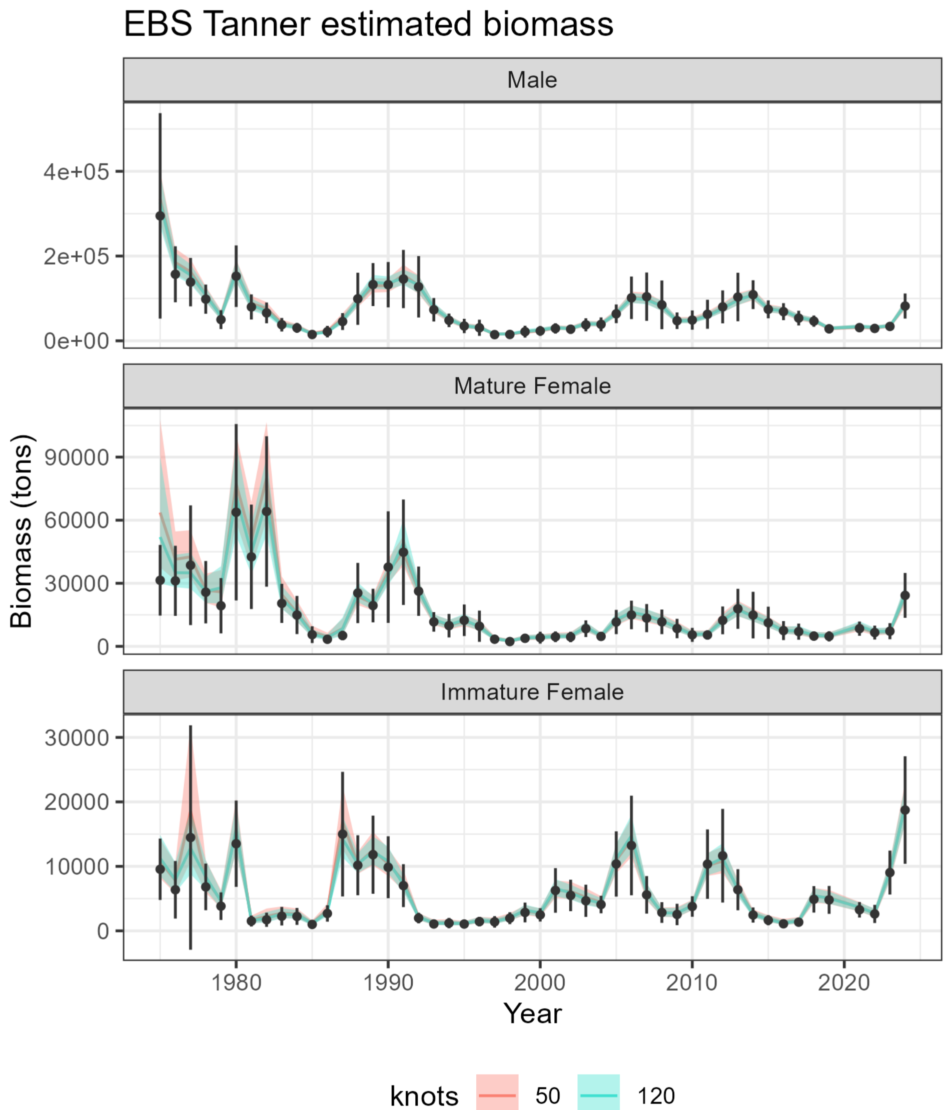

Figure 7: Estimated biomass (tons) for Eastern Bering Sea Tanner crab (Chionoecetes bairdi). Colored lines represent abundance (±95% CI) estimated by sdmTMB, with pink and blue denoting models fit with a 50- and 120-knot mesh, respectively. Black points represent abundance (±95% CI) estimated by the NMFS summer bottom trawl survey.

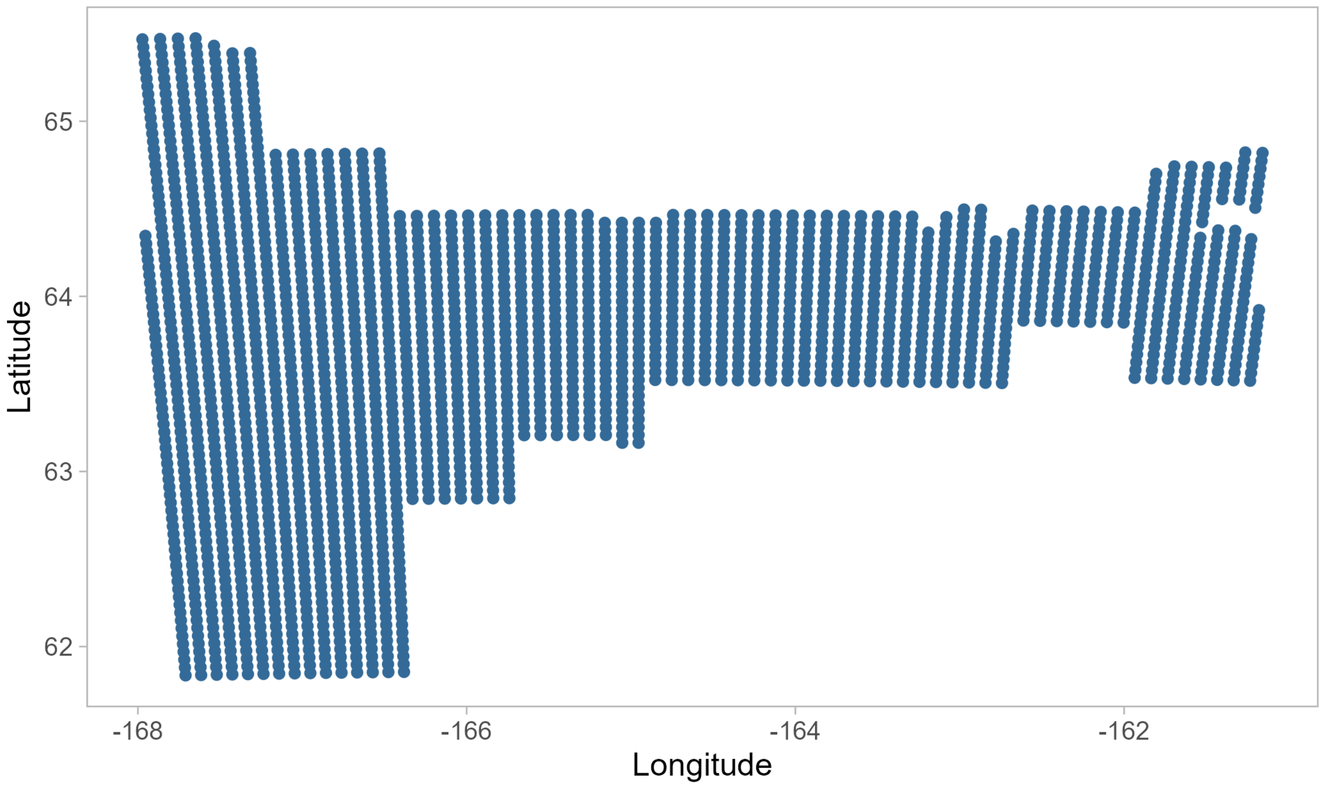

Figure 8: Prediction grid used for Norton Sound red king crab spatial abundance predictions. Spatial resolution is 5 km^2.

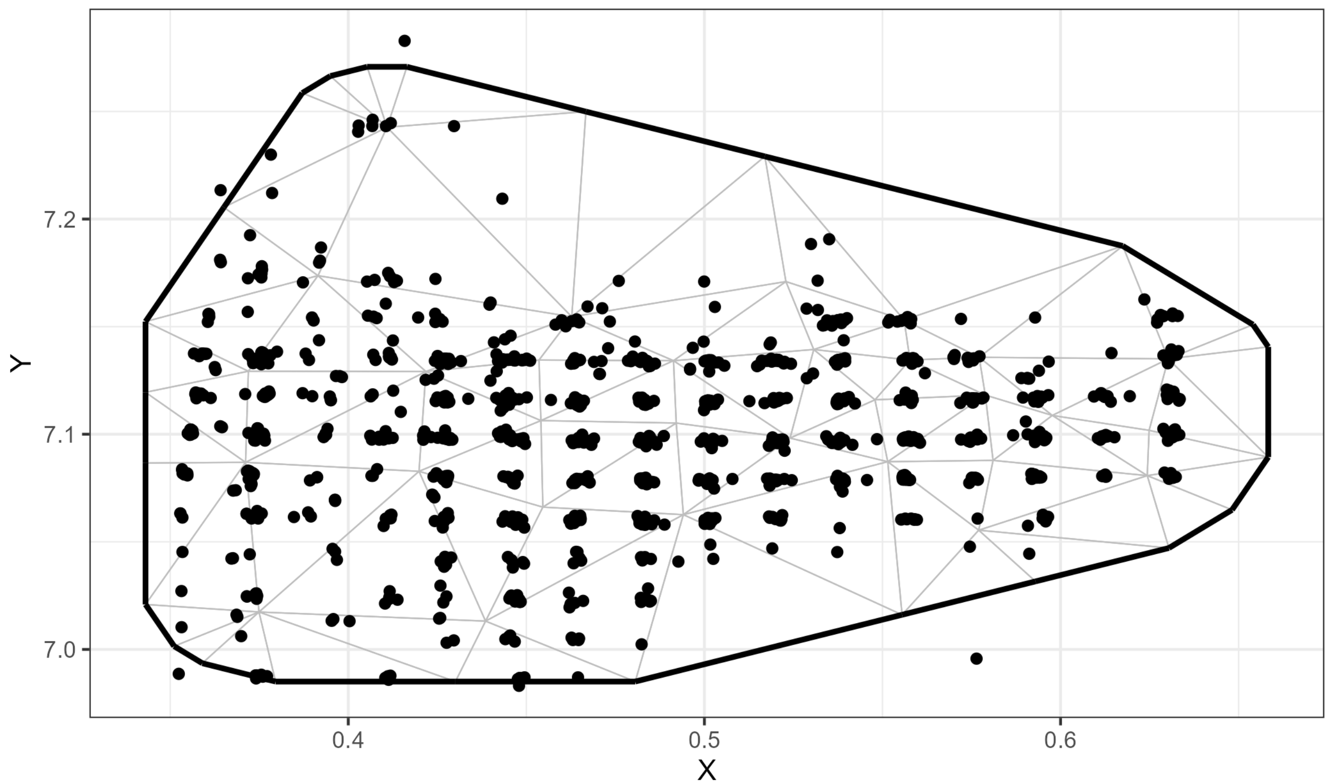

Figure 9: Spatial mesh with 30 knots used for fitting Norton Sound red king crab spatial models. Points represent observations and vertices represent knot locations.

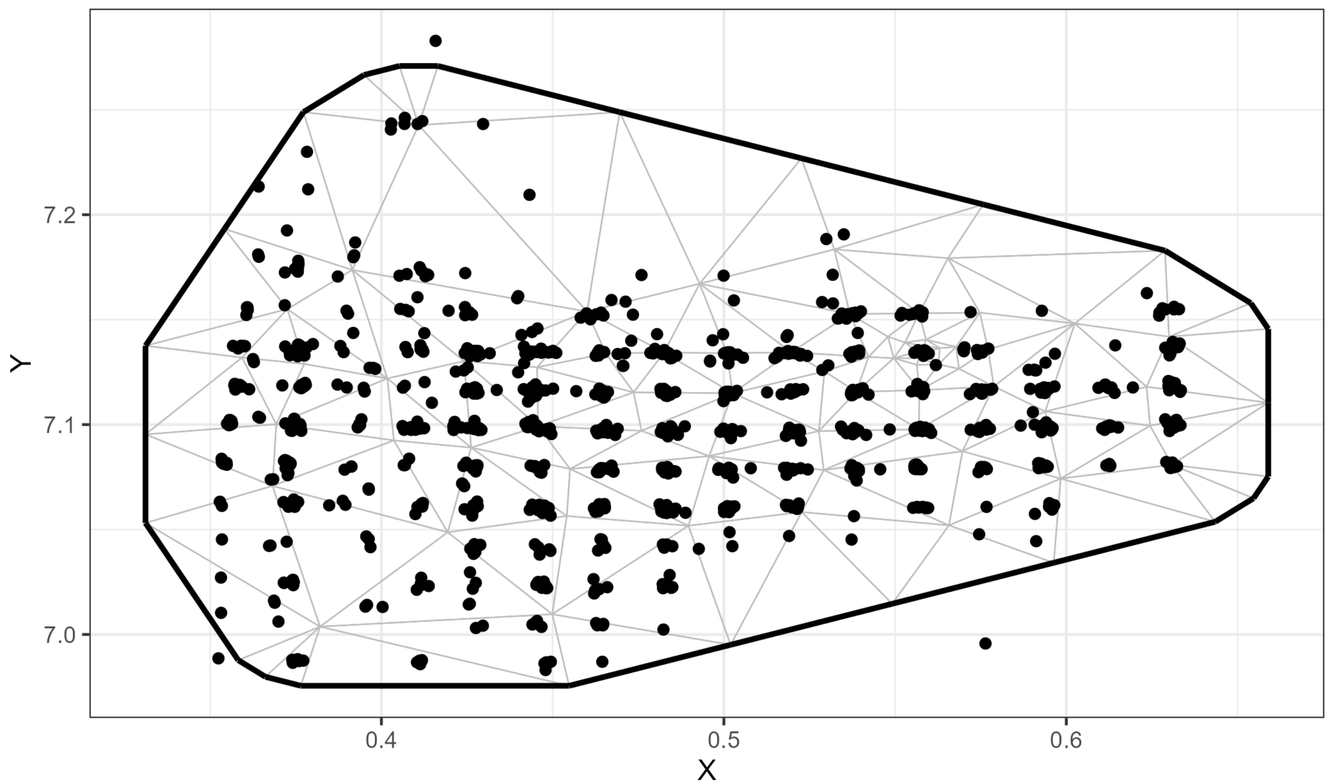

Figure 10: Spatial mesh with 50 knots used for fitting Norton Sound red king crab spatial models. Points represent observations and vertices represent knot locations.

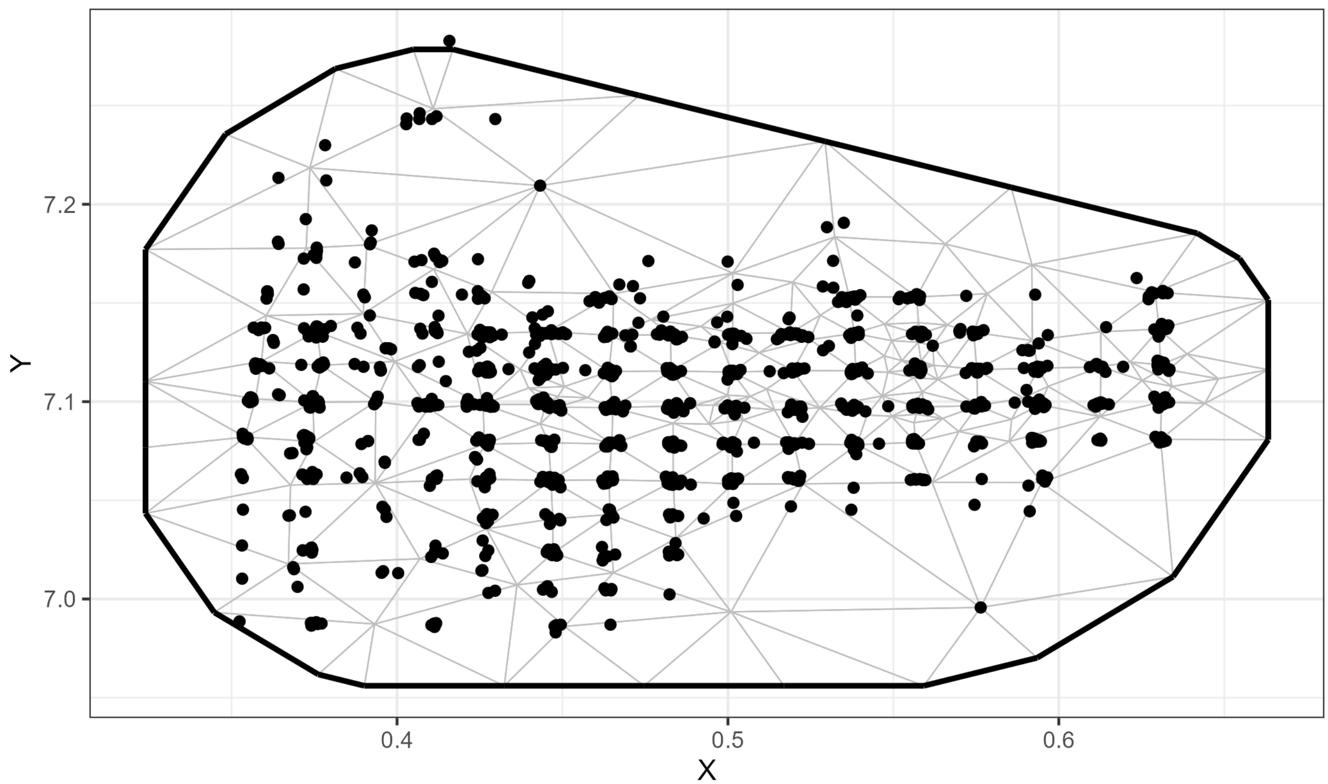

Figure 11: Spatial mesh with 100 knots used for fitting Norton Sound red king crab spatial models. Points represent observations and vertices represent knot locations.

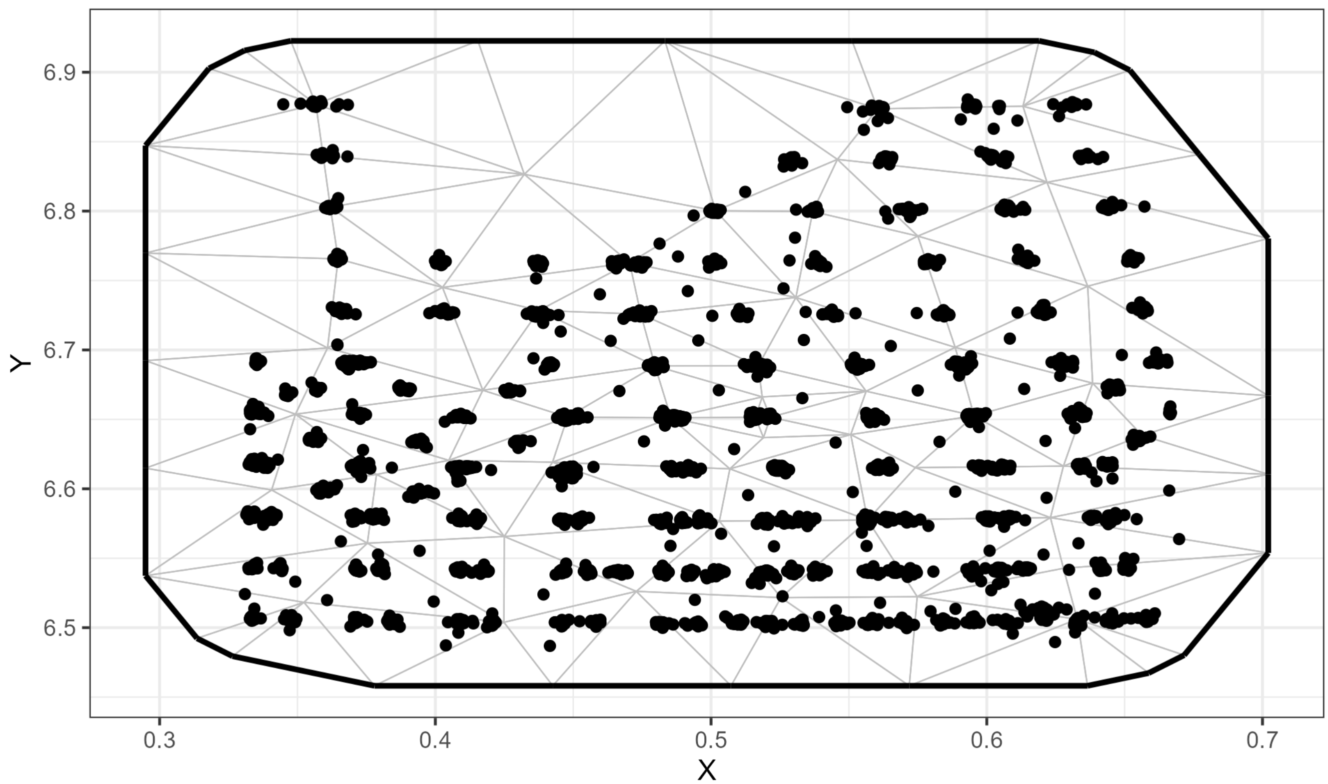

Figure 12: Spatial mesh with 50 knots used for fitting St. Matthew Island blue king crab spatial models. Points represent observations and vertices represent knot locations.

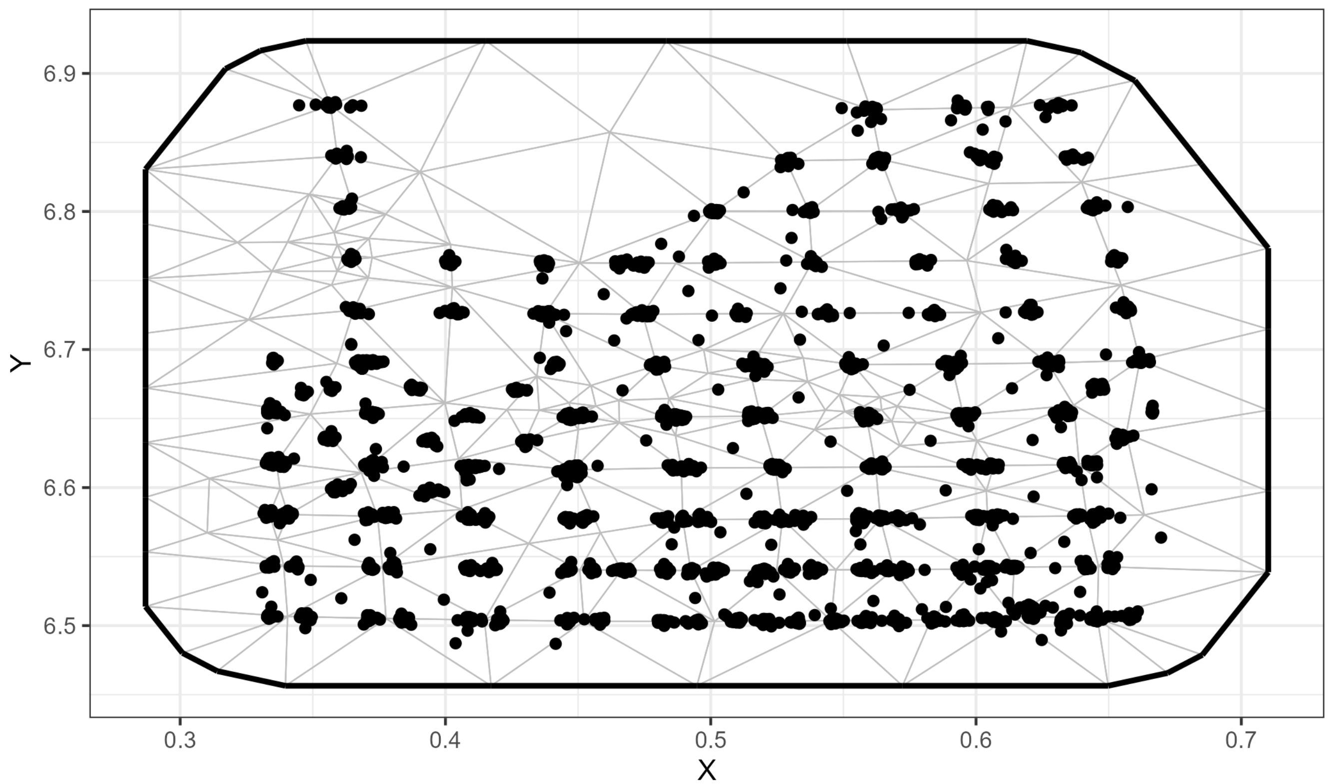

Figure 13: Spatial mesh with 90 knots used for fitting St. Matthew Island blue king crab spatial models. Points represent observations and vertices represent knot locations.

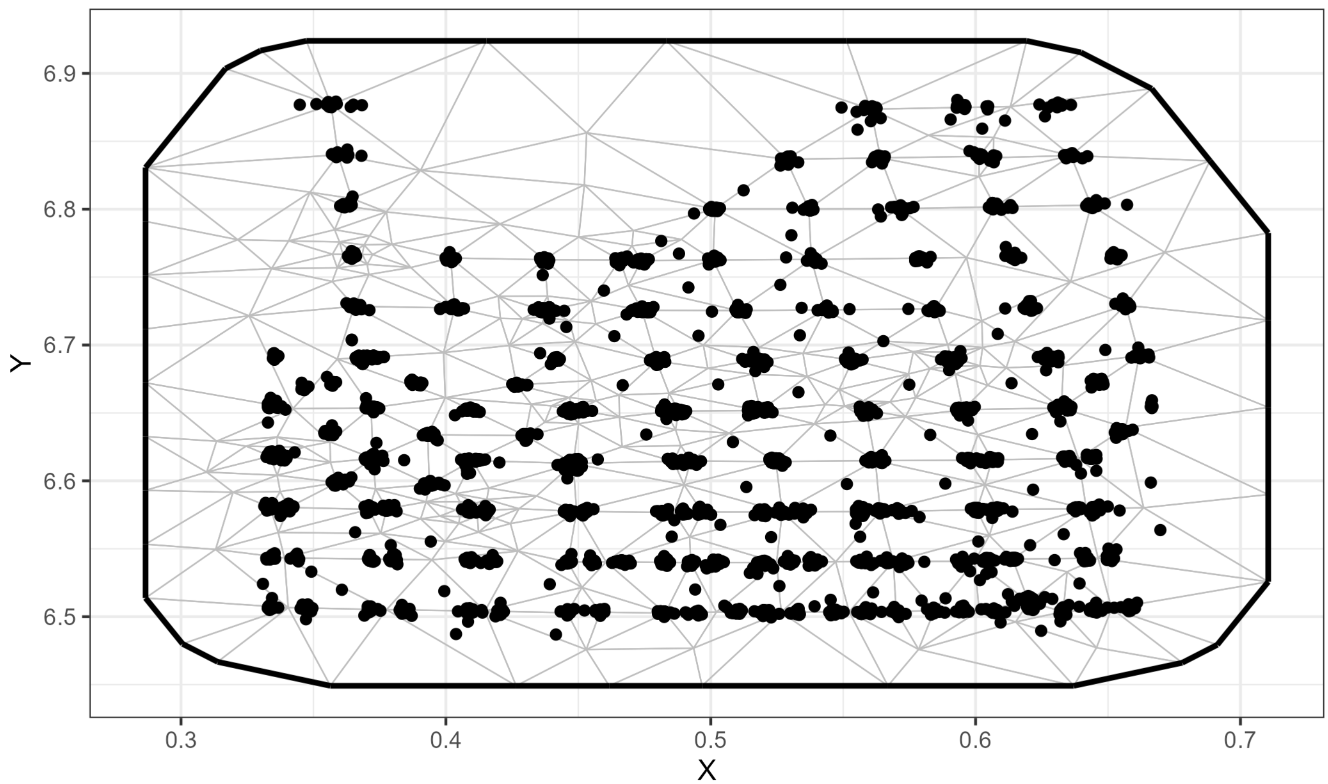

Figure 14: Spatial mesh with 120 knots used for fitting St. Matthew Island blue king crab spatial models. Points represent observations and vertices represent knot locations.

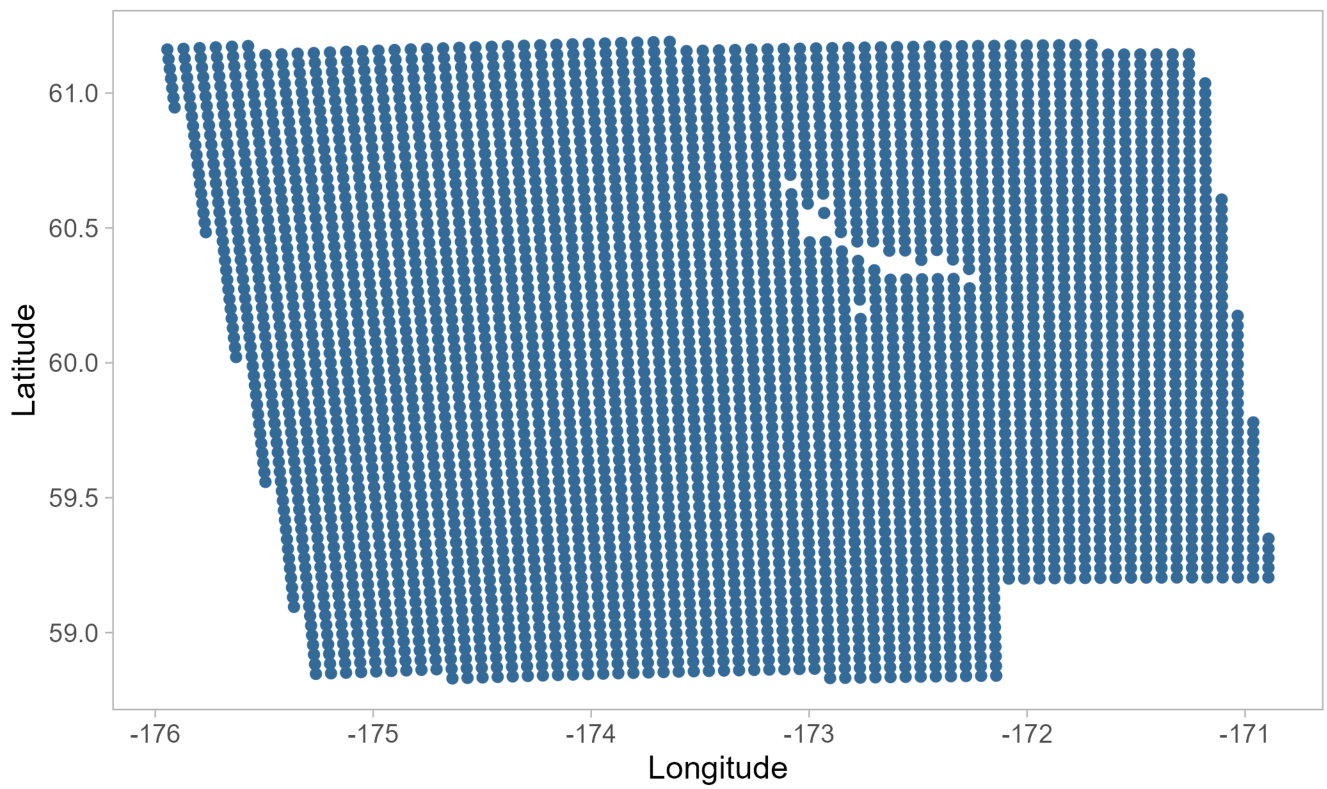

Figure 15: Prediction grid used for St. Matthew Island blue king crab spatial abundance predictions. Spatial resolution is 4 km^2.