Improving seasonal predictions of Bristol Bay red king crab spatial distributions with movement-integrated SDMs

Crab Plan Team Research Update

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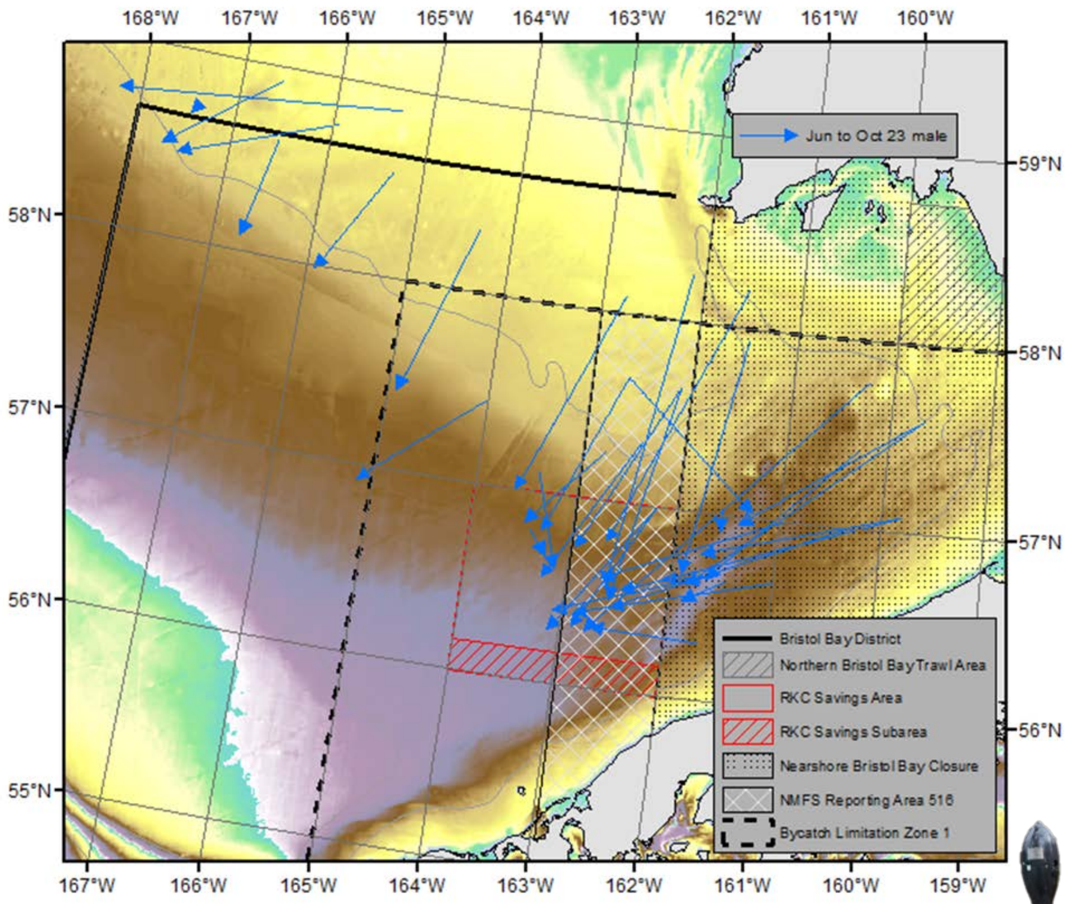
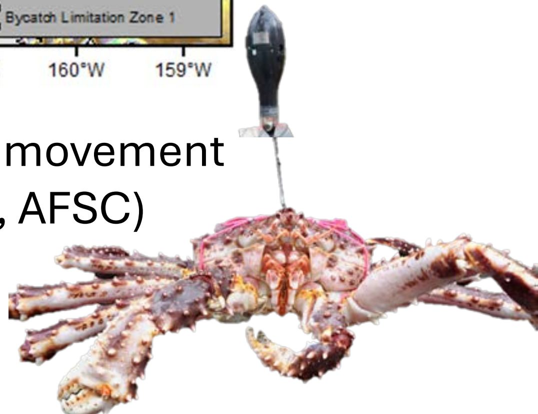
BBRKC seasonal migrations

- BBRKC can move 100s of km seasonally
- Movement patterns vary by sex and maturity stage
- Capacity for spatially resolved and comprehensive predictions of BBRKC seasonal distributions is lacking
- Today: **Developing spatially resolved seasonal distribution projections for mature male BBRKC**

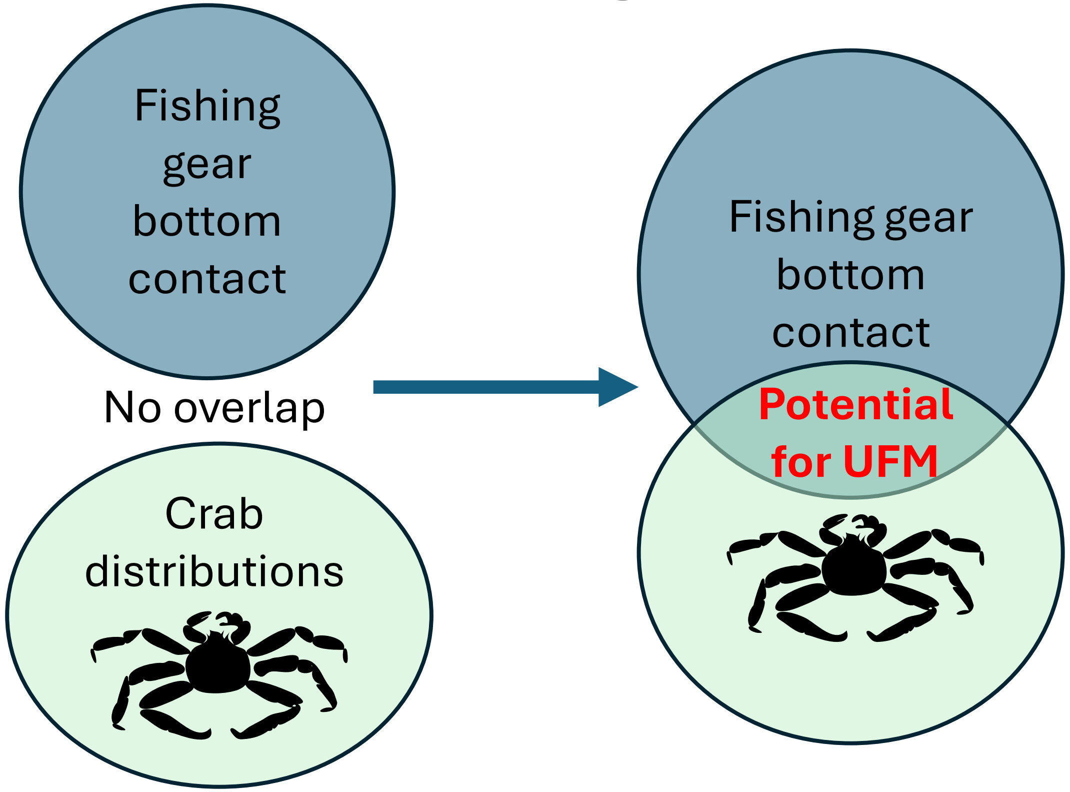


Mature male BBRKC summer-fall movement patterns (Image: Leah Zacher, AFSC)



Knowledge of seasonal BBRKC distributions essential to understanding scale of *unobserved fishing mortality*

- **Unobserved fishing mortality (UFM)**
  - When fishing gear touching the seafloor strikes and kills crabs without retaining them
- Estimating UFM impacts on a large scale requires understanding **overlaps** between crabs and fishing distributions
- Problem: where are the crabs when the fisheries are operating?



*Overlaps can tell us about **co-occurrence** between BBRKC and fishing gear bottom contacts, not UFM explicitly

Data challenges for predicting seasonal BBRKC distributions

Existing data on seasonal BBRKC distributions varies across

- Gear types
- Sampling designs
- Spatial coverage

Variability in data challenges our ability to predict seasonal distributions of BBRKC in a spatially comprehensive way across Bristol Bay.

Movement-integrated SDMs may be useful for deriving fisheries-independent projections of distributions throughout the year

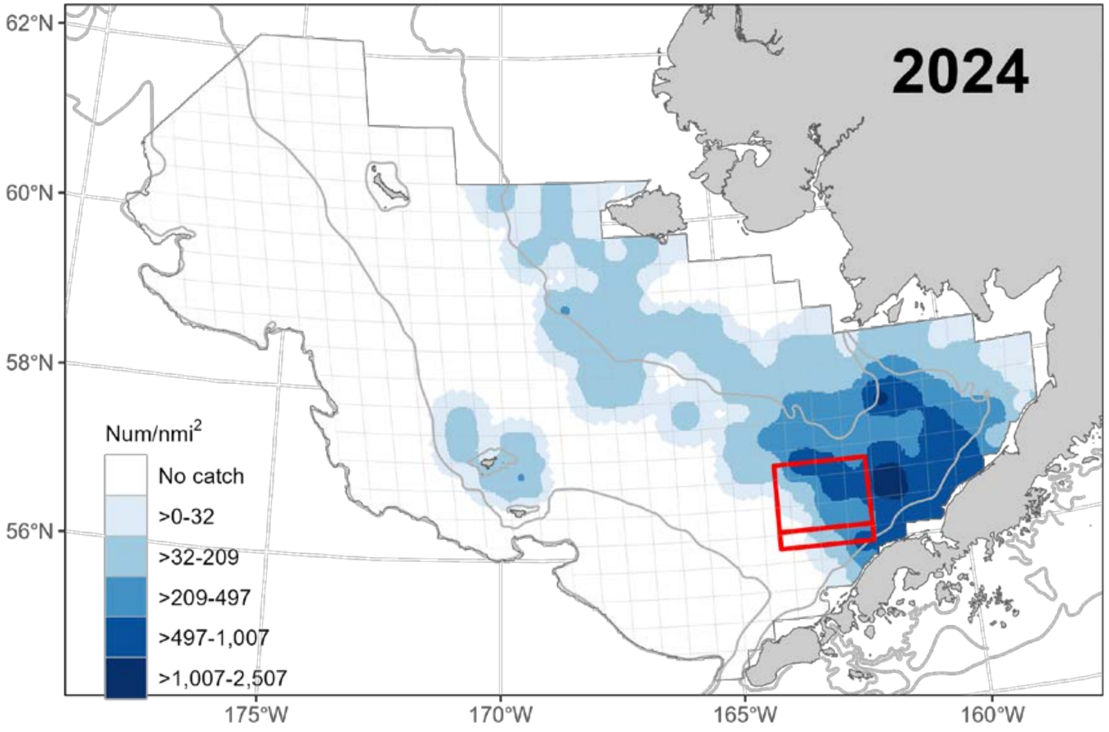
Movement-integrated ("hybrid") species distribution models

Combines model outputs from two separate models to project crab densities over space and time:

1. **Species distribution model** (SDM): estimates the densities of animals across a region

- Used to estimate the initial density surface that is the starting point for projections

- Type of SDM is less important: spatial GLMM, GAM, BRT etc



Predicted RKC densities from summer survey tows

Movement-integrated ("hybrid") species distribution models

2. A **movement model**: estimates where animals are and can predict where they're likely to go

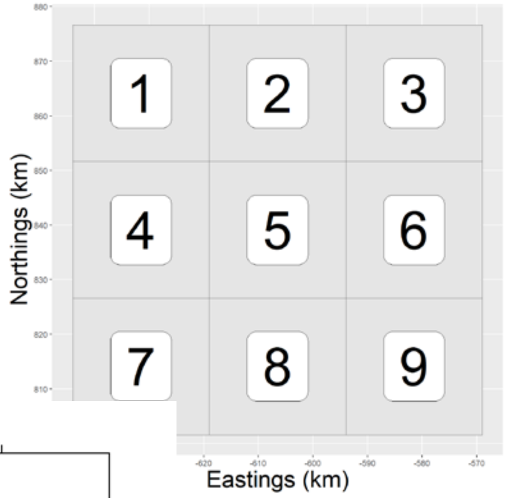
Output is *movement fraction matrix*[1,2] $\boldsymbol{M}$

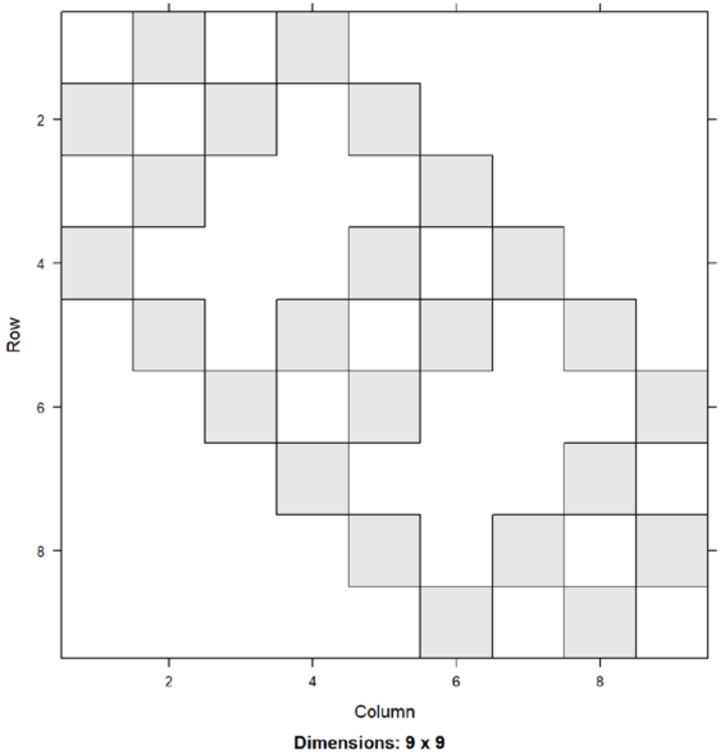
- Also called a movement probability matrix
- Describes fraction of population moving from one location (grid cell) to any other location over a time interval

The movement fraction matrix $\boldsymbol{M}$ is calculated by integrating an instantaneous movement rate matrix $\dot{\boldsymbol{M}}$ over a time interval

- Integration done by taking the exponential of $\dot{\boldsymbol{M}}$

Arbitrary spatial grid (right) and its adjacency structure (below)





[1]Thorson & Kristensen 2024; Thorson et al. 2021

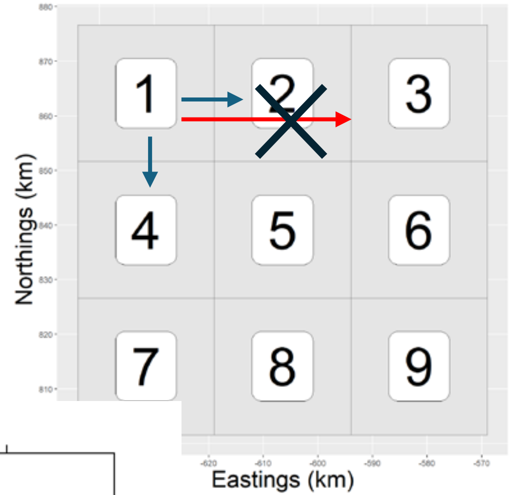
Movement-integrated ("hybrid") species distribution models

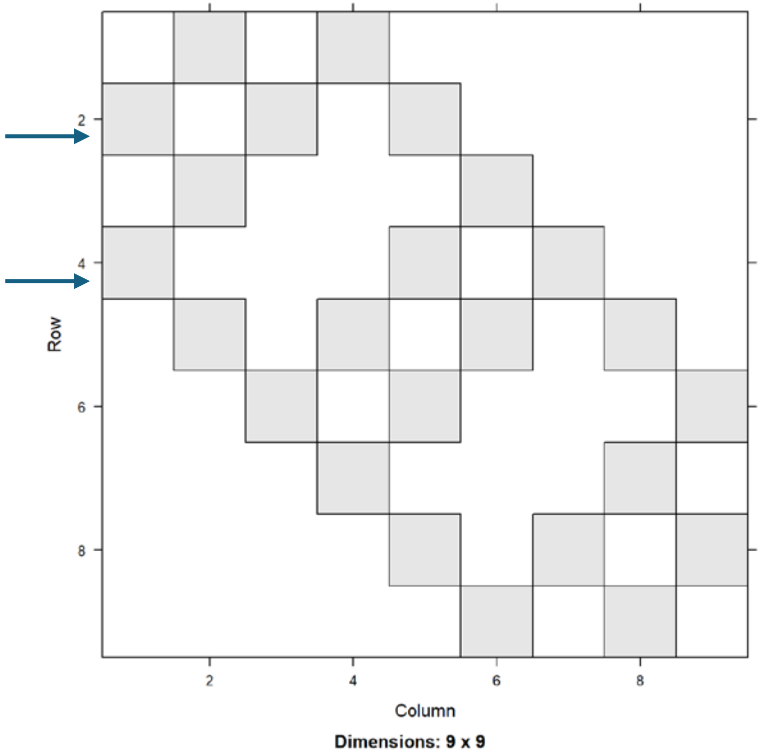
The instantaneous movement matrix $\dot{\boldsymbol{M}}$ is the sum of three different rate matrices: $\dot{\boldsymbol{M}} = \dot{\boldsymbol{T}} + \dot{\boldsymbol{A}} + \dot{\boldsymbol{D}}$

- Taxis $\dot{\boldsymbol{T}}$ - captures directional movement towards preferred habitat
- Drift (advection) $\dot{\boldsymbol{A}}$ - directional movement in response to environmental gradients (e.g., currents)*
- Diffusion $\dot{\boldsymbol{D}}$ - movement not captured by taxis or drift; a residual term

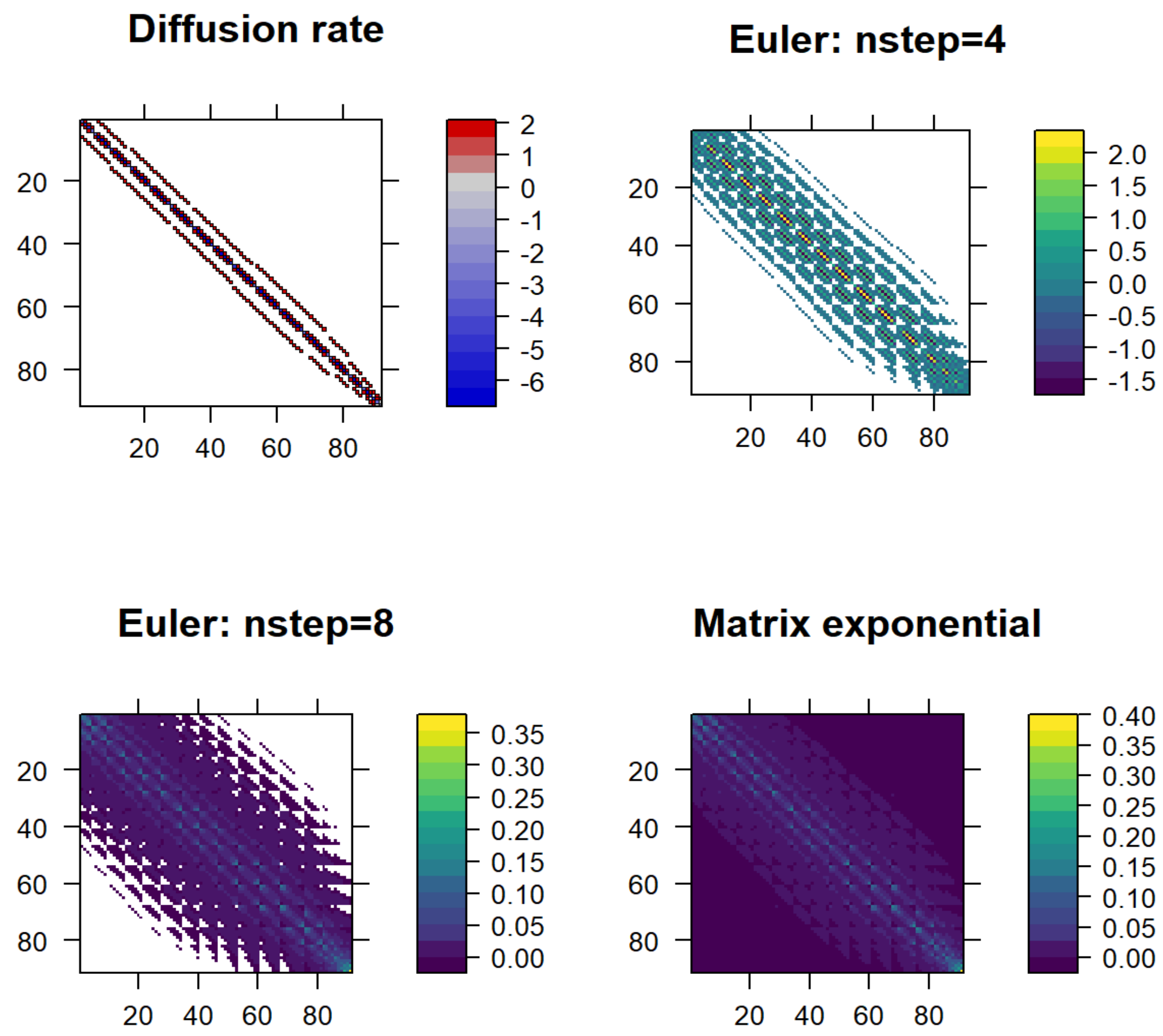
All rate matrices are structured as adjacency matrices – individuals can only move between cells in instantaneous time

Arbitrary spatial grid (right) and its adjacency structure (below)





Movement-integrated (“hybrid”) species distribution models



Thorson & Kristensen 2024

Visual of saturation of the adjacency structure as time progresses and individuals diffuse (no taxis/drift here)

Integration via exponentiating the rate matrix $\dot{\boldsymbol{M}}$ calculates probability that an individual at any given location can reach any other location over the interval

- This is the movement fraction matrix $\boldsymbol{M}$

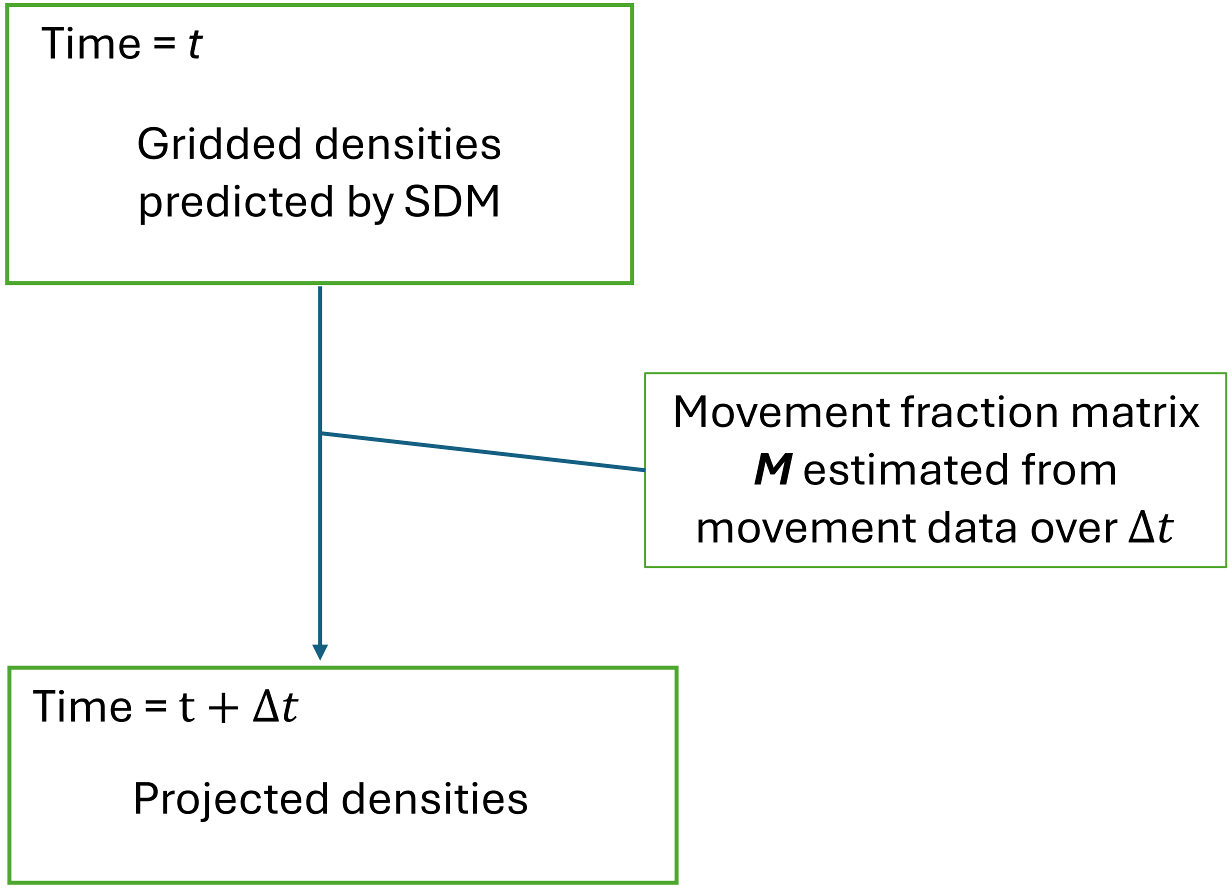
Using movement probabilities to project densities through time

1. We have a vector of densities from the SDM at time t, $\boldsymbol{n_t}$

2. We have a movement fraction matrix $\boldsymbol{M}$, representing overall movement over the interval Δt

3. To project densities forward to $t + \Delta t$:

$$\boldsymbol{n}_{t+\Delta t}^{T} = \boldsymbol{n}_{t}^{T}\boldsymbol{M}$$



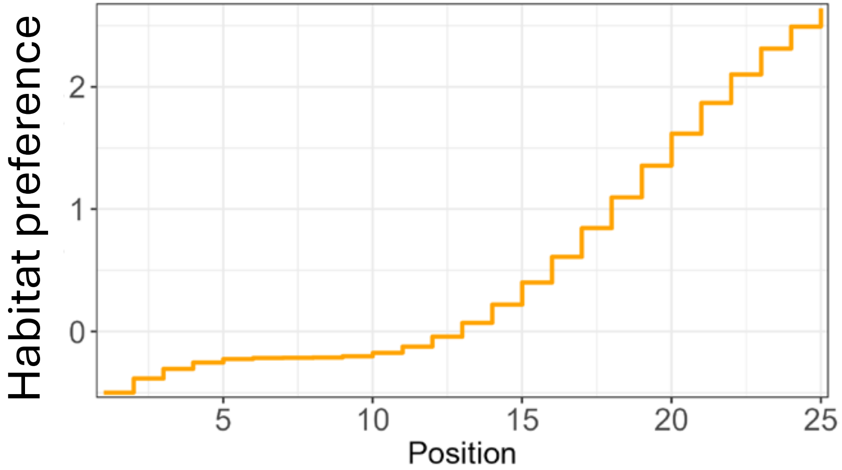
Diffusion-taxis model for BBRKC

Our model for BBRKC considered $\dot{\boldsymbol{M}}$ to be only function of diffusion and taxis

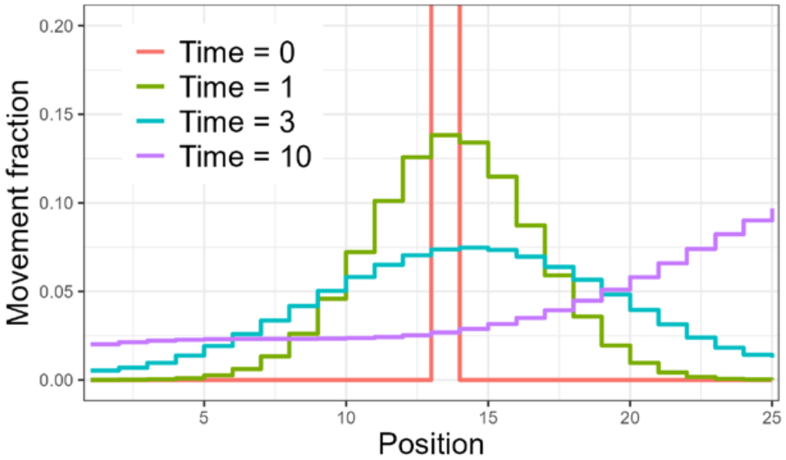
Taxis is a function of differences in habitat preferences

- When time integrated, we expect movement "up" habitat preference gradients

Preference functions must be estimated from observed movement in relation to environmental drivers



Hypothetical habitat preference curve in 1D



Movement fractions through time in the presence of a preferred habitat gradient

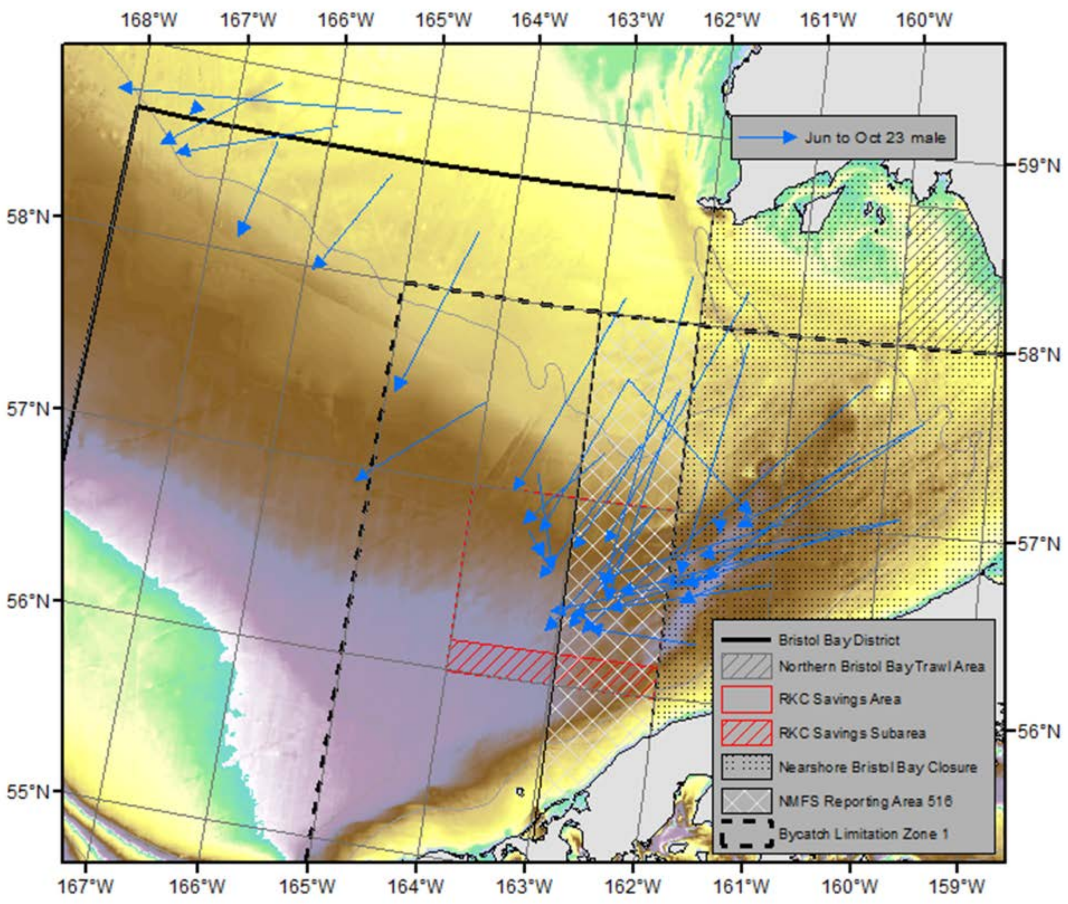
Diffusion-taxis model for BBRKC

Used movement data from mature male crabs tagged in June 2023

- Tags released in October

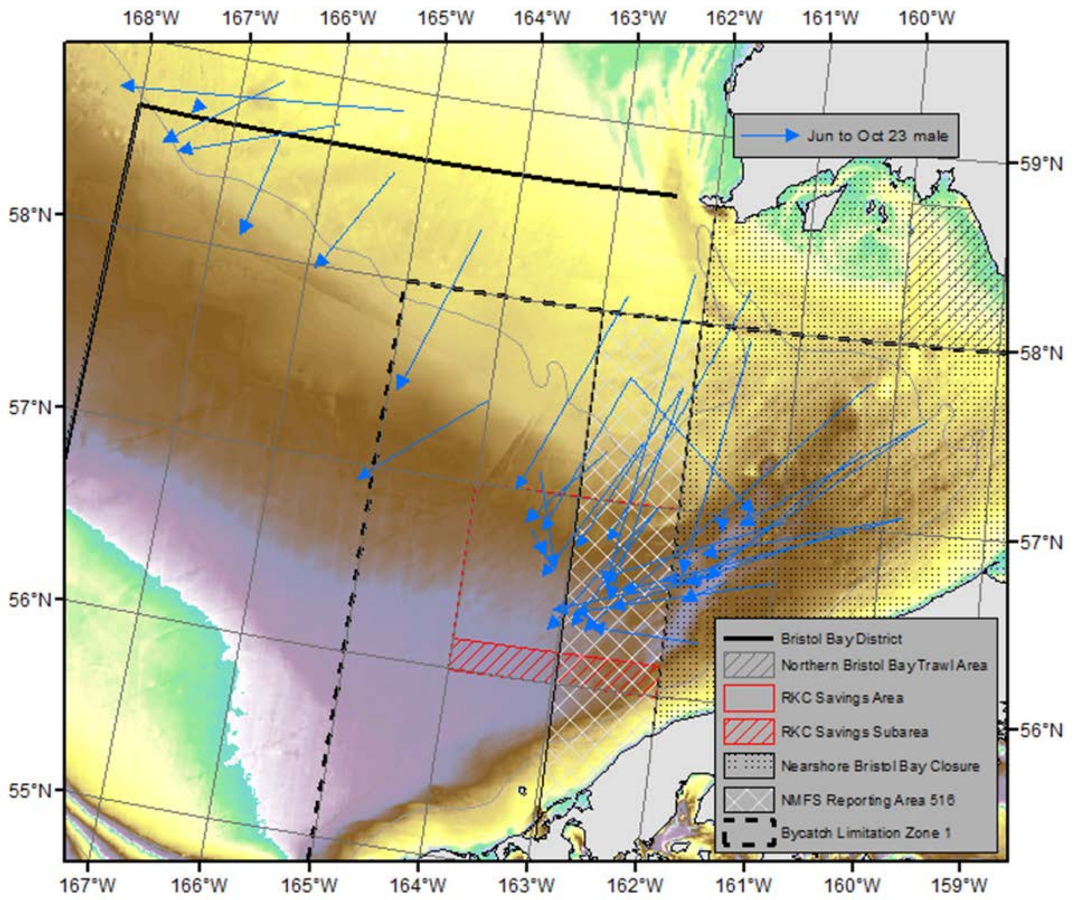
Projected summer 2023 densities forward into the fall

Modeled habitat preference as non-linear interaction between depth and October bottom temperatures (N = 37 tags)

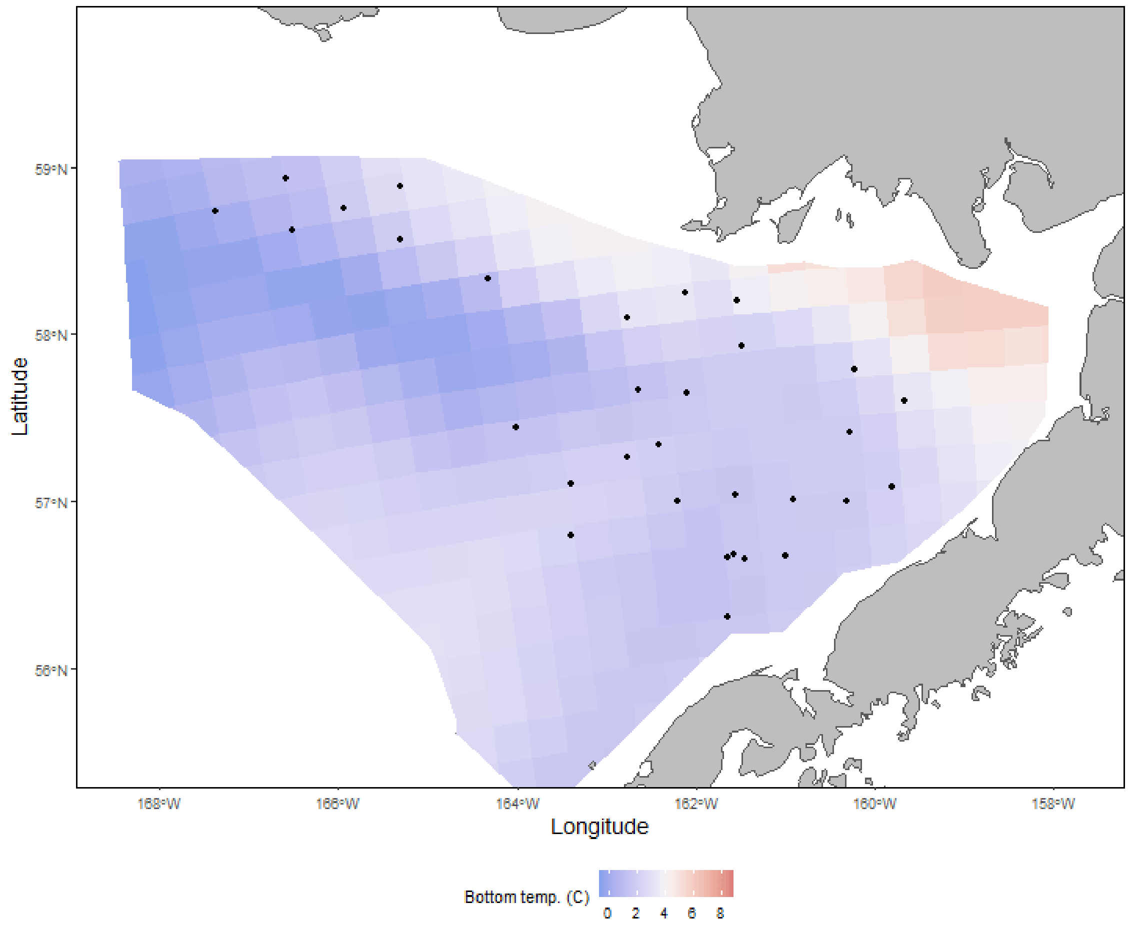


Mature male BBRKC summer-fall movement patterns (Image: Leah Zacher, AFSC)

Environmental covariates in relation to movement

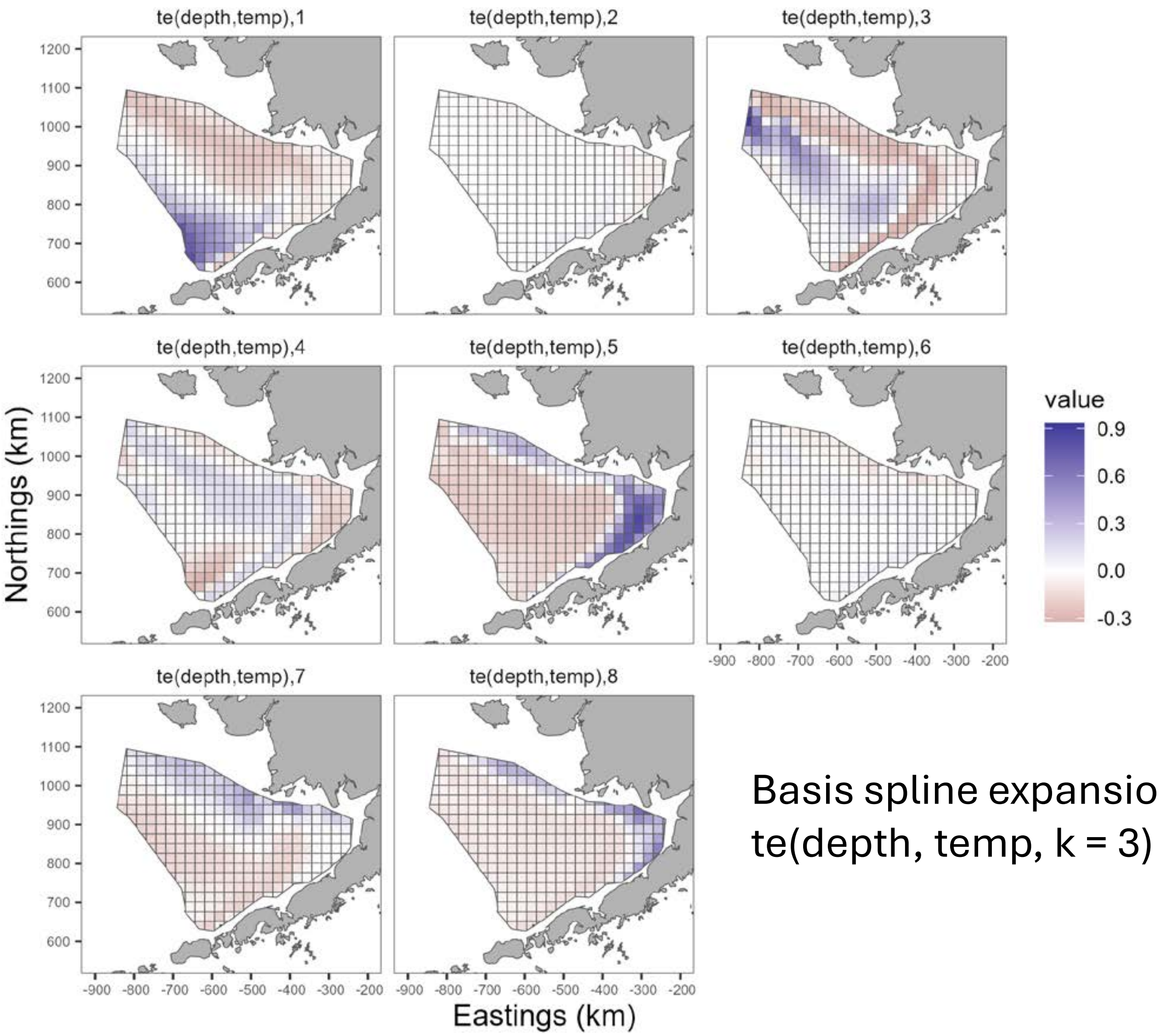


Movement in relation to depth



Movement in relation to June-October bottom temperature transition (ROMS)

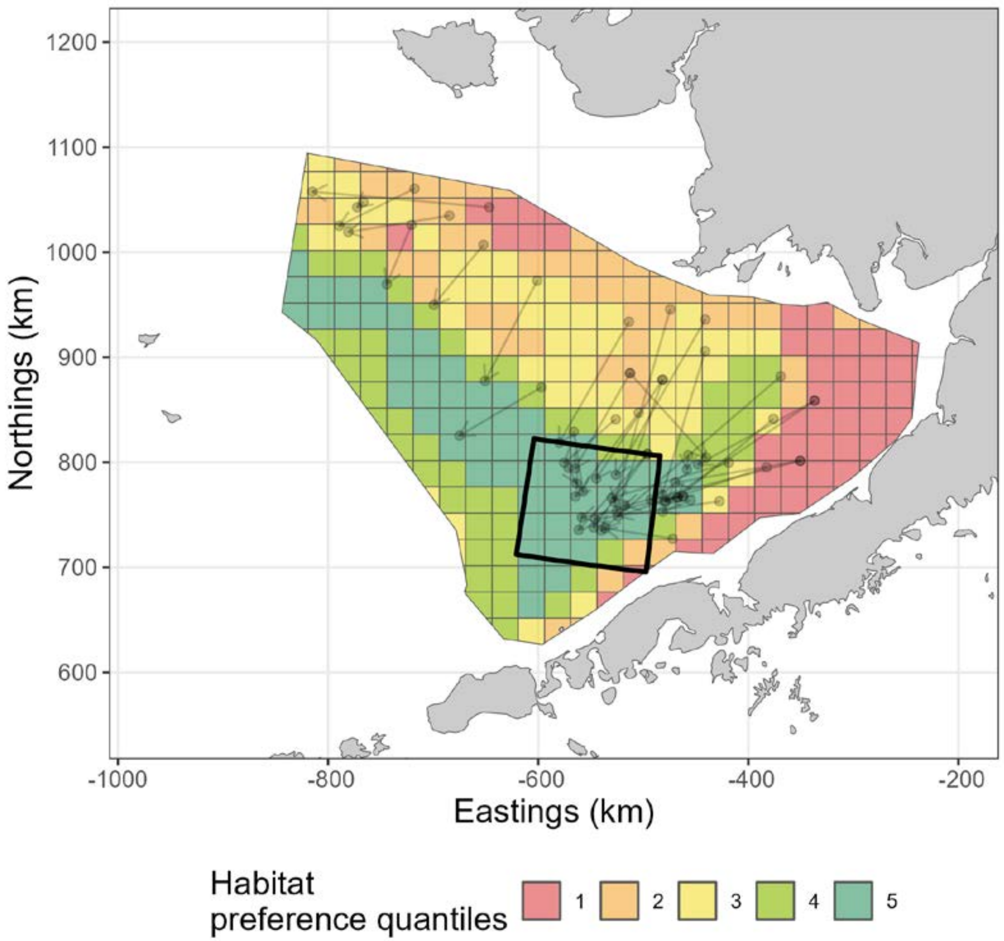
Habitat preference function estimation



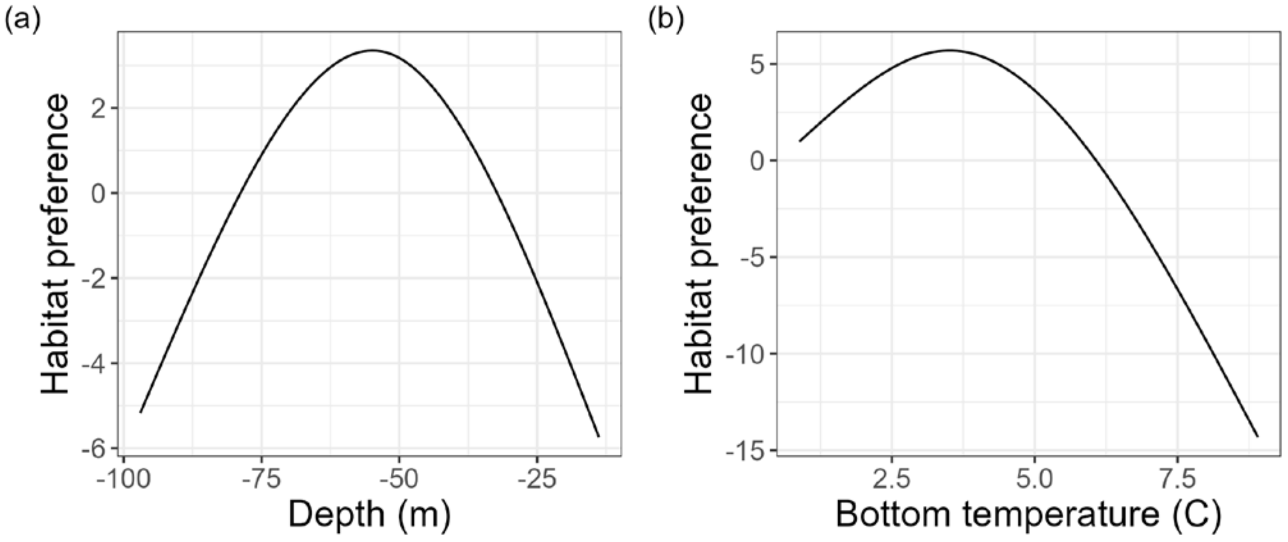
Basis spline expansion for te(depth, temp, k = 3)

- The habitat preference function is a 2D tensor product interaction between depth and bottom temperature "te(depth, temp, k = 3)"
- Fitted using maximum likelihood in R
- The returned habitat preference surface maximizes the likelihood of crabs moving from initial to final locations
- AIC suggests model including both depth and temp (AIC = 270) is better fit than depth alone (AIC = 309)

Habitat preferences for migrating mature male BBRKC

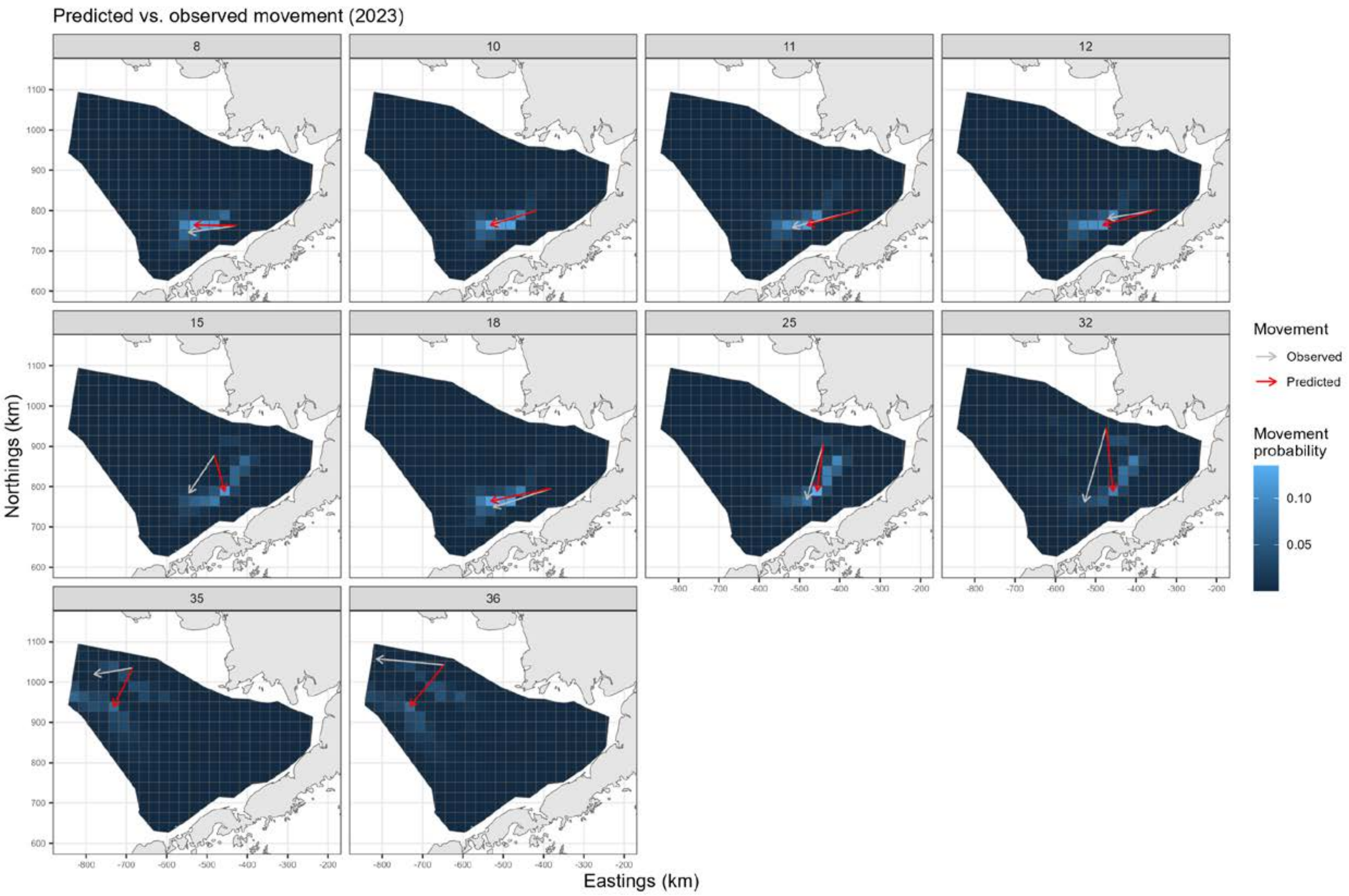


- Habitat preferences visualized over space. Green is “better”
- Not where crabs are or will be – “preferred habitat”

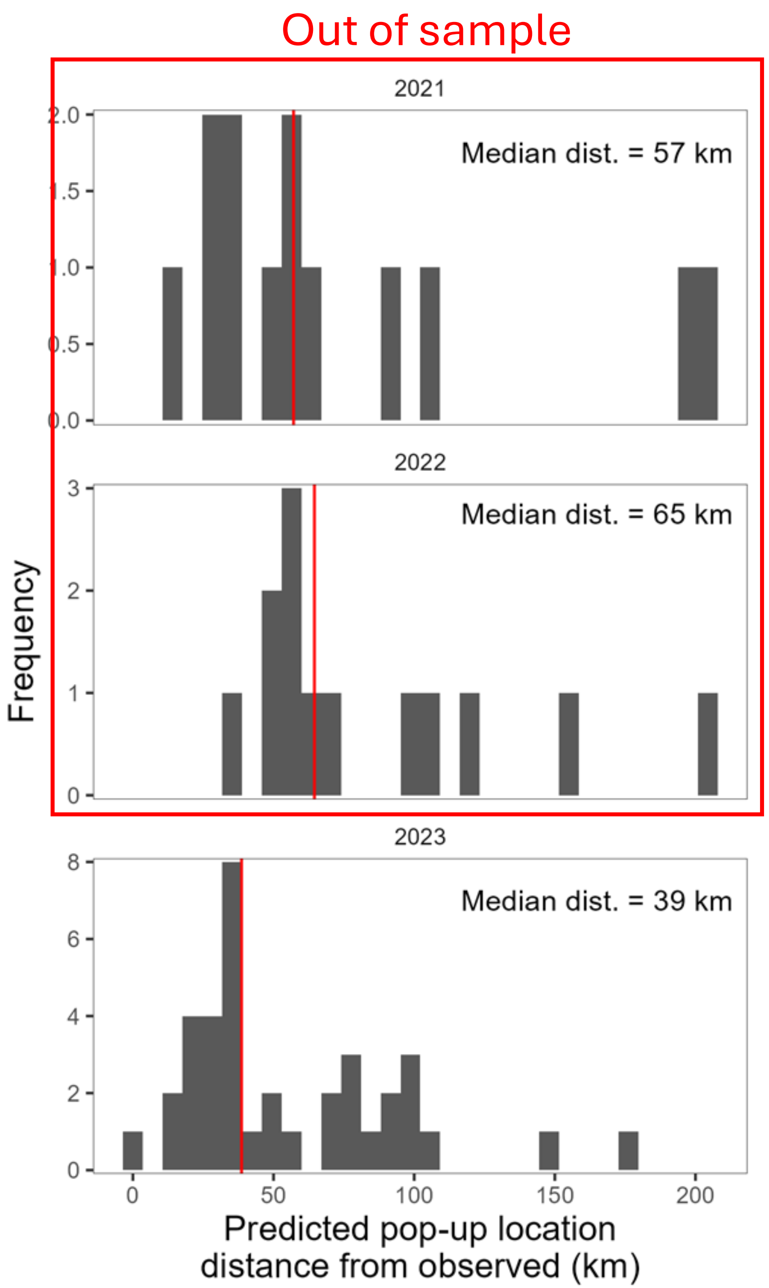


Marginal habitat preference functions. BBRKC are likely to travel up habitat preference gradient over the June-October period into regions where peaks occur

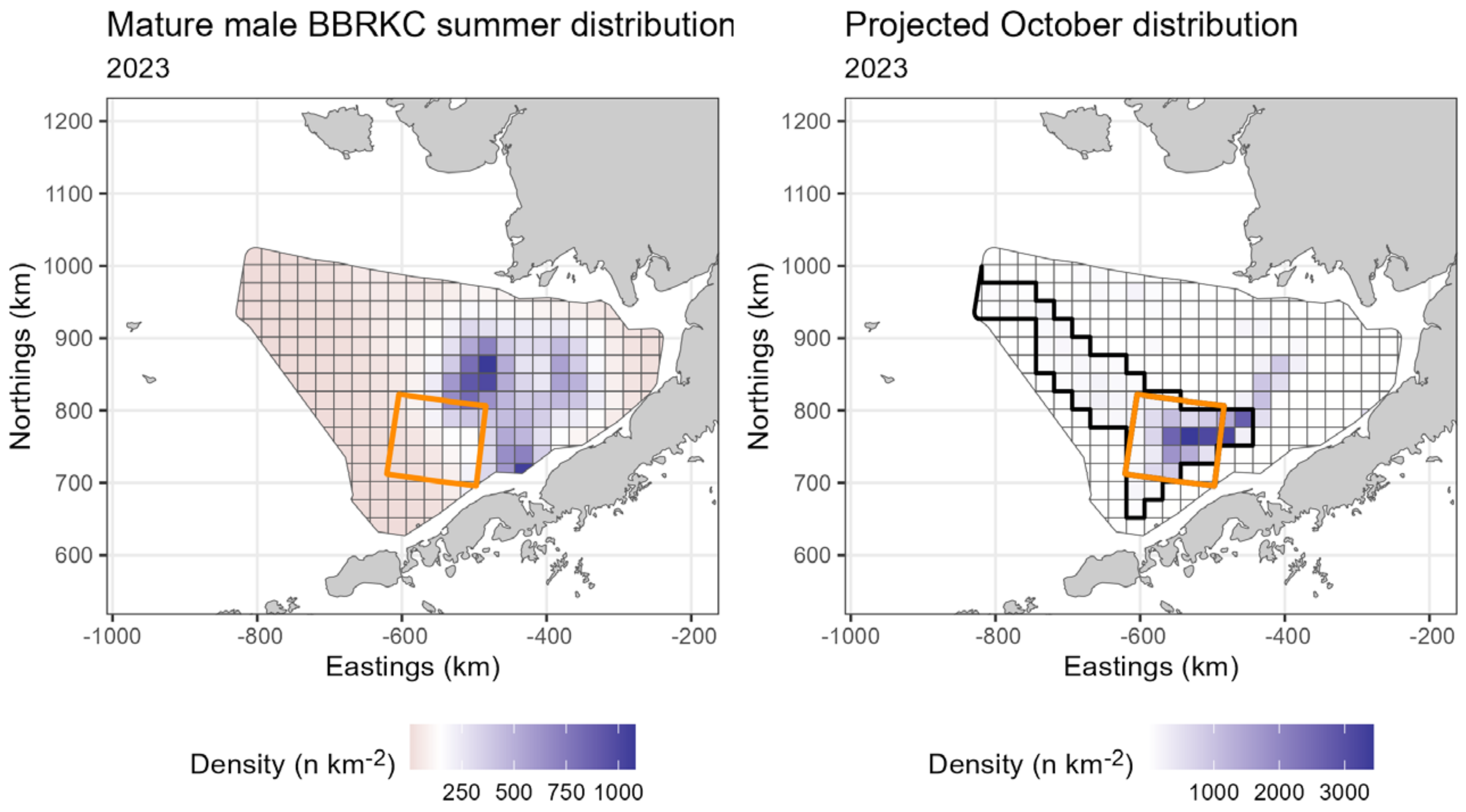
Movement model: predicted vs. observed



A subset of predicted movement probabilities (red) for cells with associated tagged crabs (observed tracks in grey).



June distributions and October projections

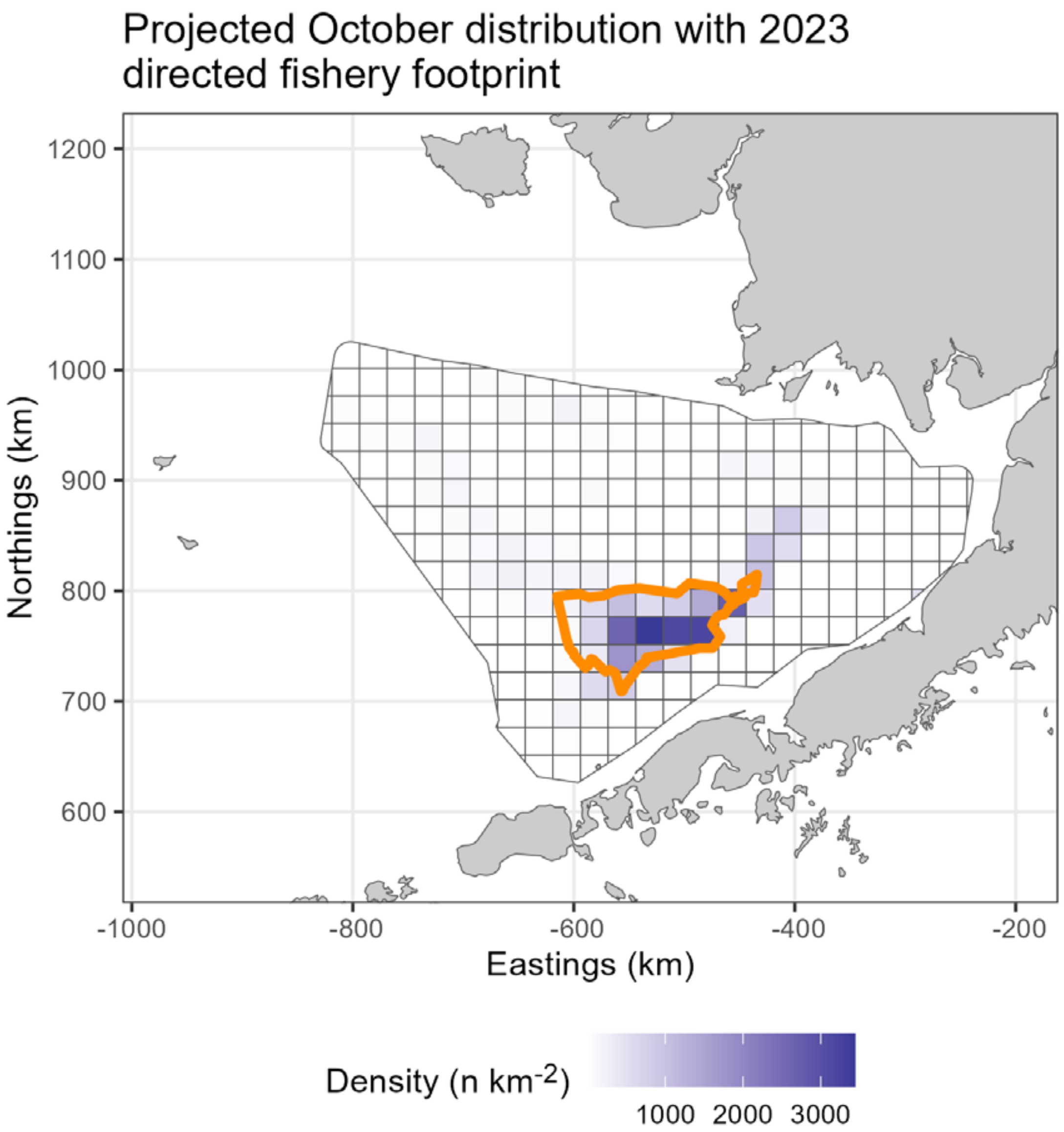


Tweedie GLMM with spatial random field for predicting June distributions (sdmTMB)

~8% of all BBRKC fell within RKCSA using summer density predictions

~52% of all BBRKC fell within RKCSA using projected fall densities

Projected October densities vs. directed BBRKC fishery (Oct-Jan)



Outer boundary around the region where RKC catches were recorded in 2023

Passes sanity check

Takeaways and future directions

- Movement-integrated SDM gives reasonable projections of mature male BBRKC densities for fall season based on movement data
  - Still need to characterize uncertainty in projections and preference functions
  - Further stress testing for goodness of fit

- Highlights value of crab tagging work, could be a useful tool for evaluating overlaps between fishing gear bottom contacts and RKC distributions outside summer season

- Apply approach to mature female crab tagging data over the next year. Evaluate overlaps with fishing gear bottom contacts.

Thank you!

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BSFRF Bering Sea Fisheries Research Foundation