

# Ecosystem & Socioeconomic Profile Indicator Analysis Update

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# **Goal for today: Propose new methodology for indicator importance analysis- dynamic structural equation modeling**

## Outline:

- Overview of causal modeling framework and dynamic structural equation modeling (DSEM)
- Review preliminary snow crab recruitment and mortality DSEM models
- Application of DSEM results to ESP indicator categorization and risk table framework
- Discussion on approach for September ESP report cards:

ESP Indicator Analysis

Estimate  
causal effects

**Causal Modeling  
Framework**

Specify a  
dynamic  
structural  
equation model

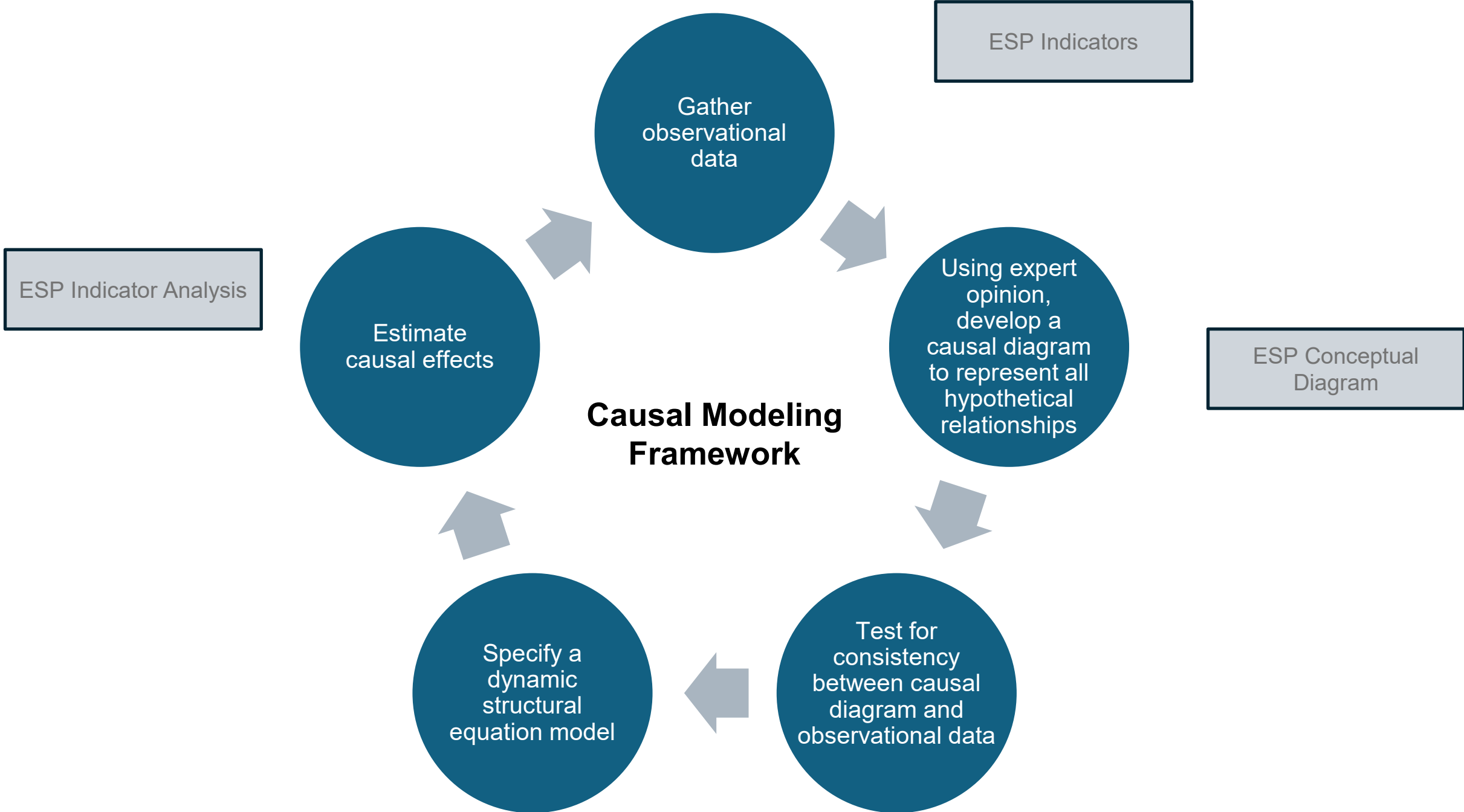
Gather  
observational  
data

Test for  
consistency  
between causal  
diagram and  
observational data

Using expert  
opinion,  
develop a  
causal diagram  
to represent all  
hypothetical  
relationships

ESP Indicators

ESP Conceptual  
Diagram



# Dynamic Structural Equation Modeling (DSEM) overview

**INPUT:** Defines a GLMM for a  $T \times J$  matrix by organizing every variable ( $J$ ) across every time step ( $T$ )

**LOGIC:** Constructs a Gaussian Markov Random Field by converting a system of equations representing a hypothesized network of interactions (e.g., climate  $\rightarrow$  prey  $\rightarrow$  recruitment) into a precision matrix

**OUTPUT:** Estimates latent states and causal links while imputing missing data and accounting for autocorrelation

“Dynamic structural equation models synthesize ecosystem dynamics constrained by ecological mechanisms”, Thorson et al. (2024)

# Benefits of DSEM vs. Bayesian Adaptive Sampling

- Integration of simultaneous and lagged effects
- Interpolates missing data within state-space framework
- Handles correlated datasets common in environmental time series
- Can model unobserved or latent variables
- Can test indirect effects and evaluate importance of different ecological pathways
- Flexible data distributions
- Potential for incorporation of non-stationary and non-linear functions (Thorson and Kristensen, *in review*)
- Includes prior scientific expertise through causal diagrams and model structure
- Causal diagrams improve interpretability for stakeholders
- Shifts focus from data associations to causality/mechanistic understanding

## Methods for snow crab DSEM indicator analysis:

Step 1: Develop causal diagrams for drivers of snow crab recruitment and mortality

Step 2: Fit dynamic structural equation model models using dsem R package

- Scale all variables and model as AR1 process
- Observation error set to 0.1
- Use same background dataset in the model fitting process so that models are fit to same set of data and AIC can be used for comparison
- Assume linear relationships among variables
- Specify biologically-plausible lag for each causal pathway

Step 3: Model evaluation

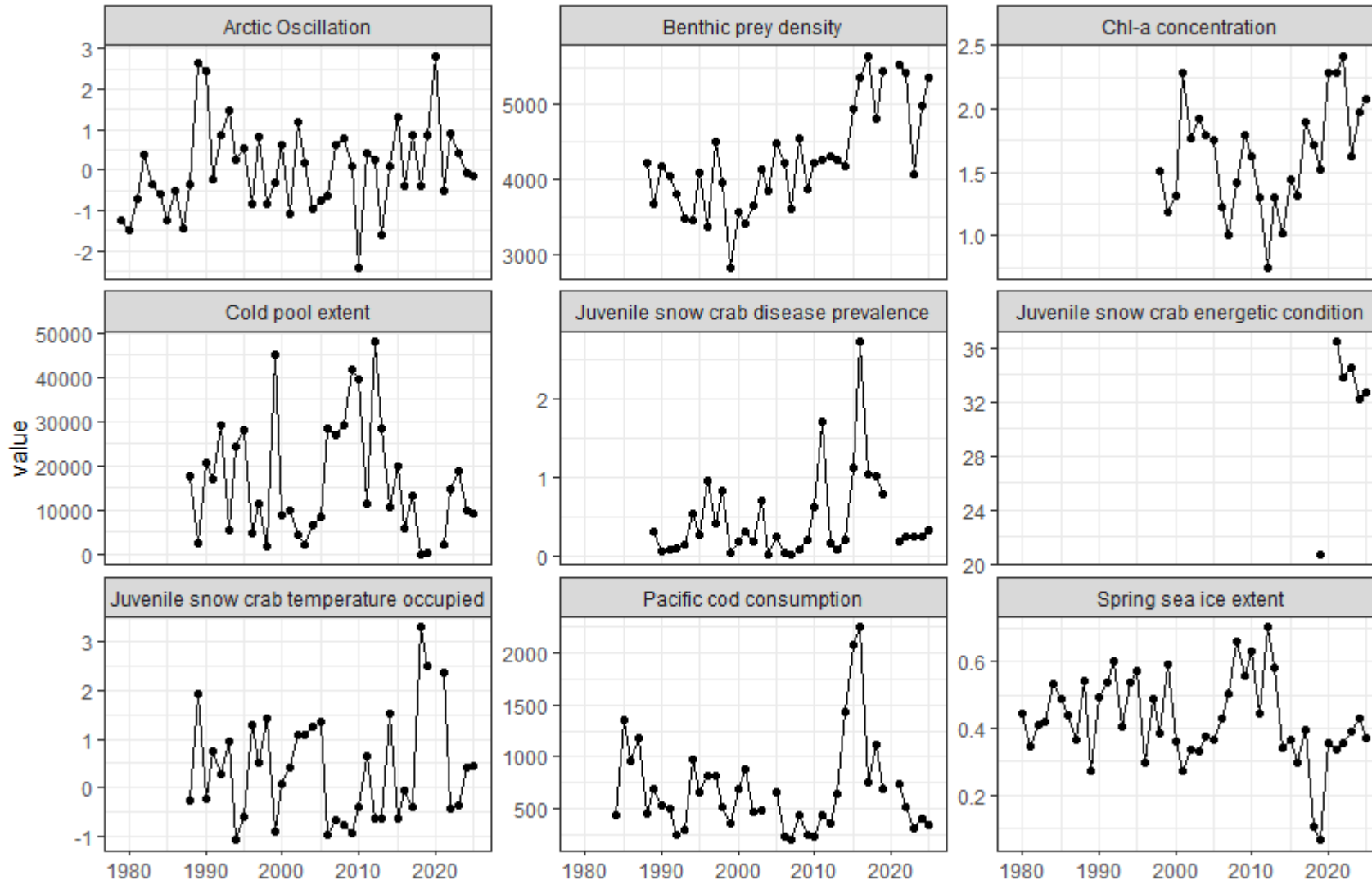
- Estimate effect sizes for each link (betas), determine significance with two-sided Wald test
- Compare marginal AIC across models
- Compare reduction in unexplained recruitment variance,  $\sigma^2_{R,\text{unexplained}^2}$

Approach similar to pollock ESP DSEM:  
“Causal models as a scientific framework for next-generation ecosystem and climate-linked stock assessments”, Champagnat et al. 2026

# Step 1: Selecting relevant ecosystem indicators for recruitment DSEM



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Most indicators are developed from the EBS bottom trawl survey so we have good temporal coverage (1988+)

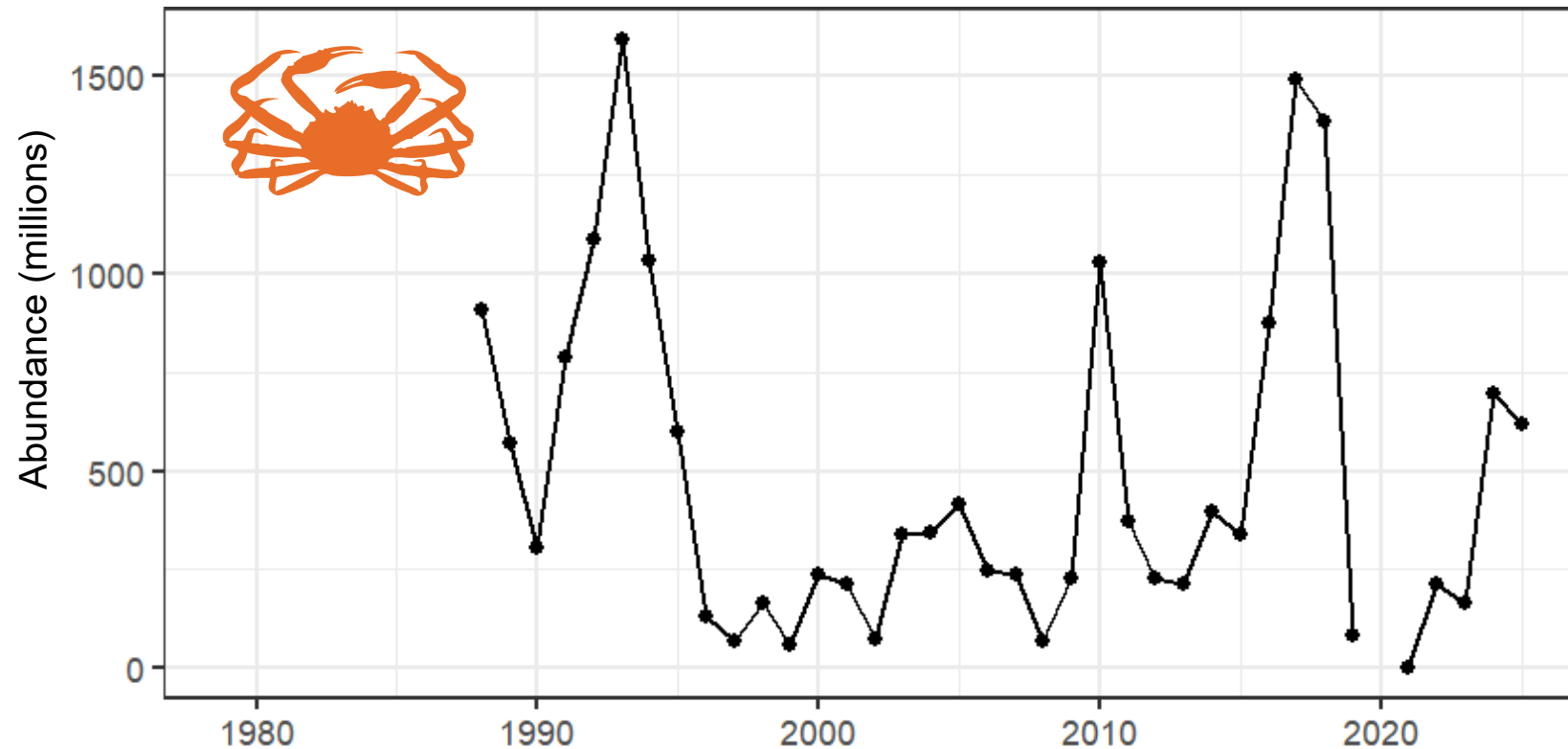
Snow crab energetic condition monitoring wasn't started until 2019

# Step 1: Selecting relevant ecosystem indicators for recruitment DSEM

## Response Variable: Snow Crab Recruitment

Abundance of 40-50mm immature male snow crab from EBS bottom trawl survey (1988-2025)

Lags informed by assumption that this size class is ~4.5-5.7 years post-settlement



# Base Recruitment Models:

**Random recruitment variation (IID):**  
Snow crab recruitment (IID) + AR1 ESP  
indicators



**Autocorrelated recruitment variation (AR1):**  
Snow crab recruitment (AR1) + AR1 ESP  
indicators



# Base Recruitment Models:

**Random recruitment variation (IID):**  
Snow crab recruitment (IID) + AR1 ESP indicators

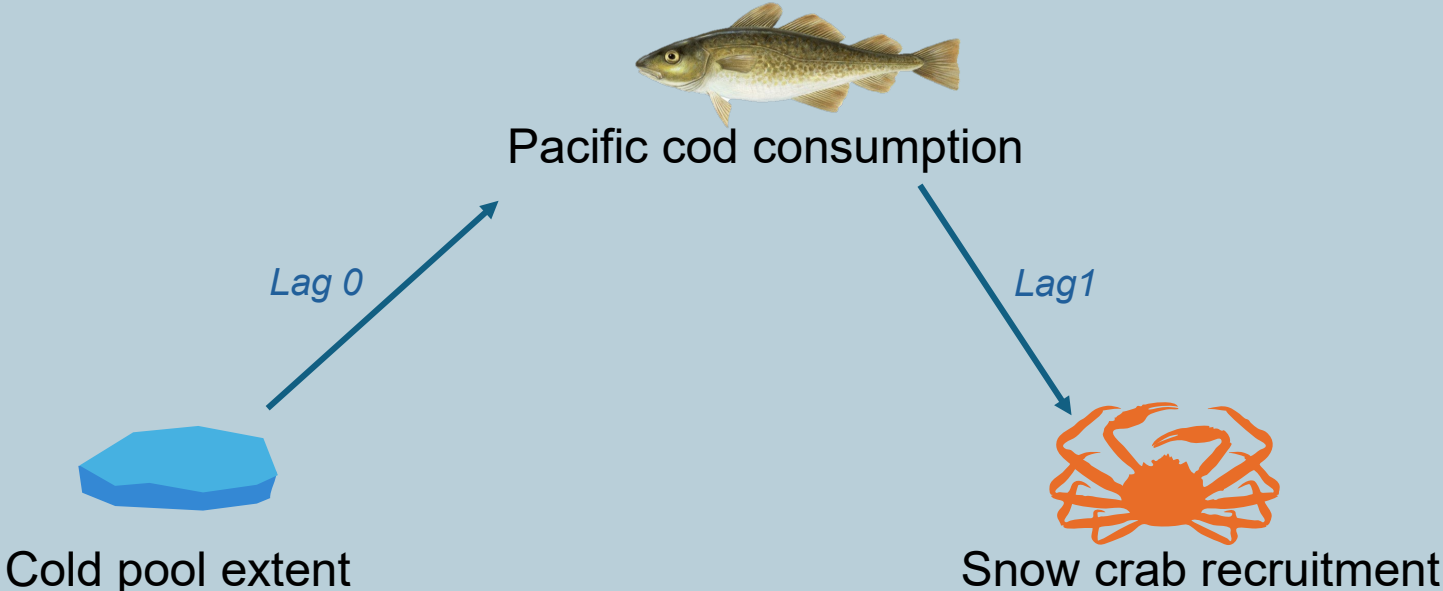


**Autocorrelated recruitment variation (AR1):**  
Snow crab recruitment (AR1) + AR1 ESP indicators



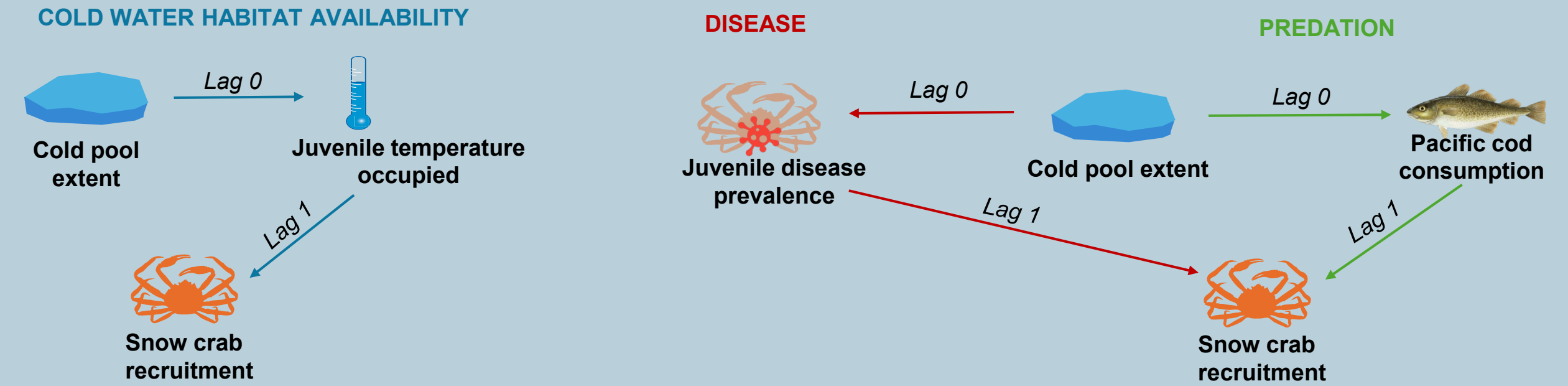
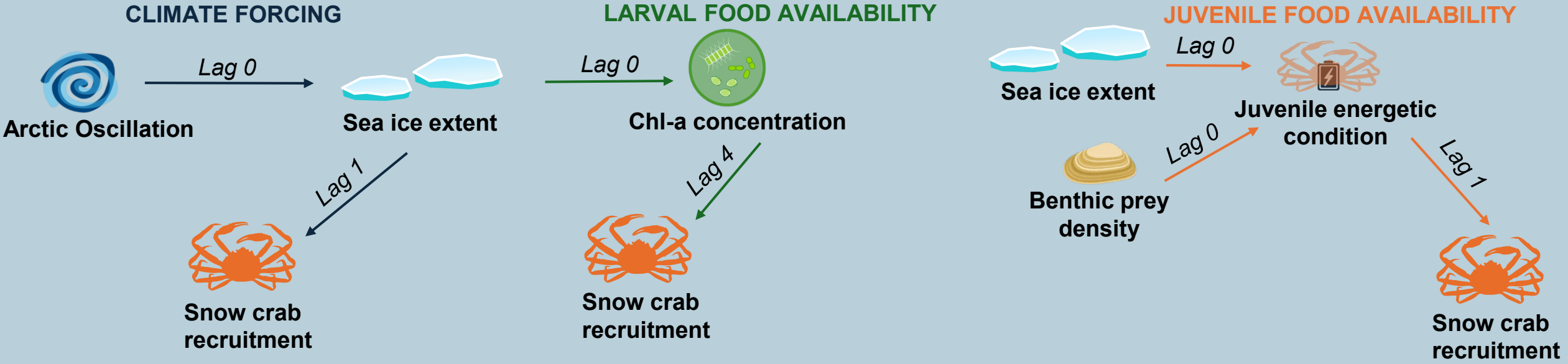
# Structural Causal Recruitment Models: Lagged causal pathways + AR1 ESP indicators

Example causal model:



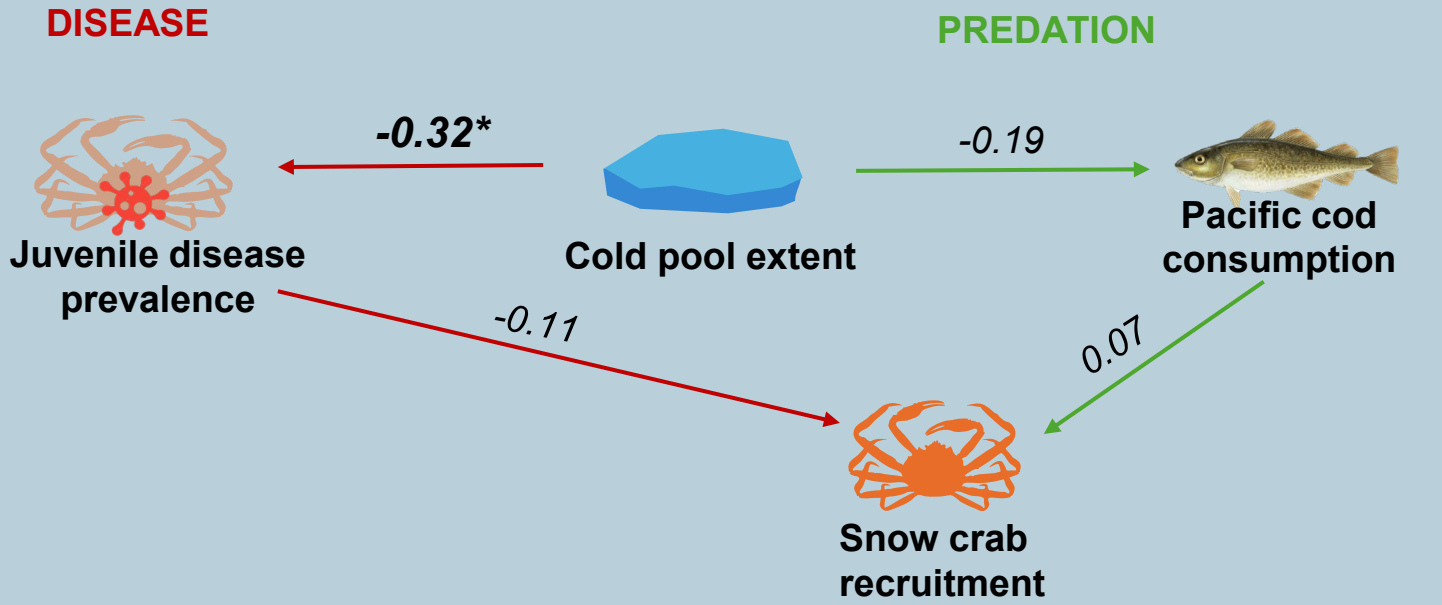
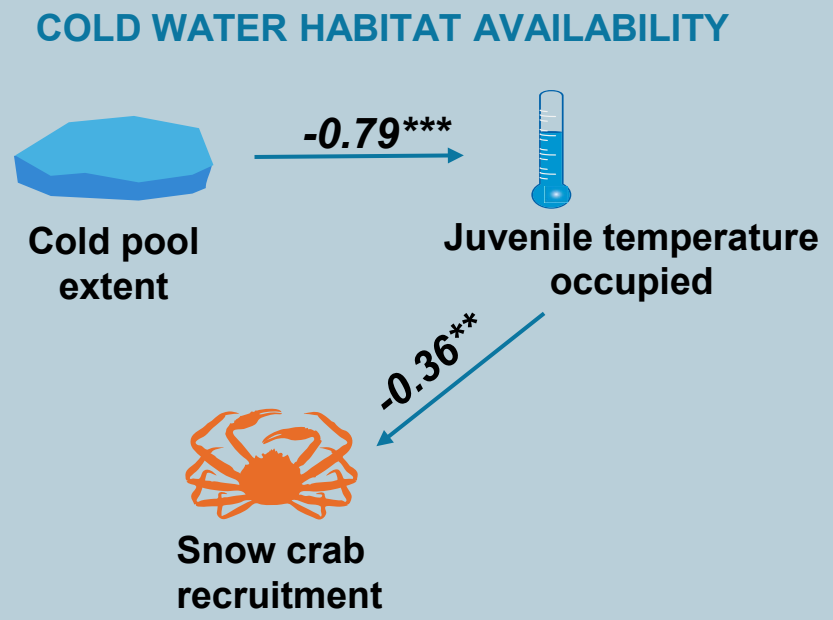
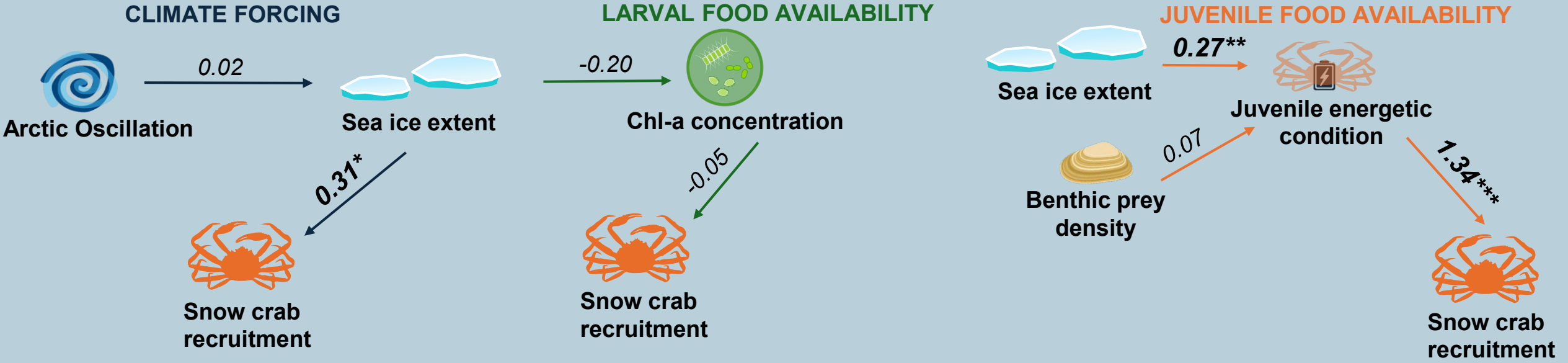
# Structural Causal Recruitment Models:

Lagged causal pathways + AR1 ESP indicators



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# Structural Causal Recruitment Models:

## Random recruitment variation (IID):

Snow crab recruitment (IID)  
+ AR1 ESP indicators



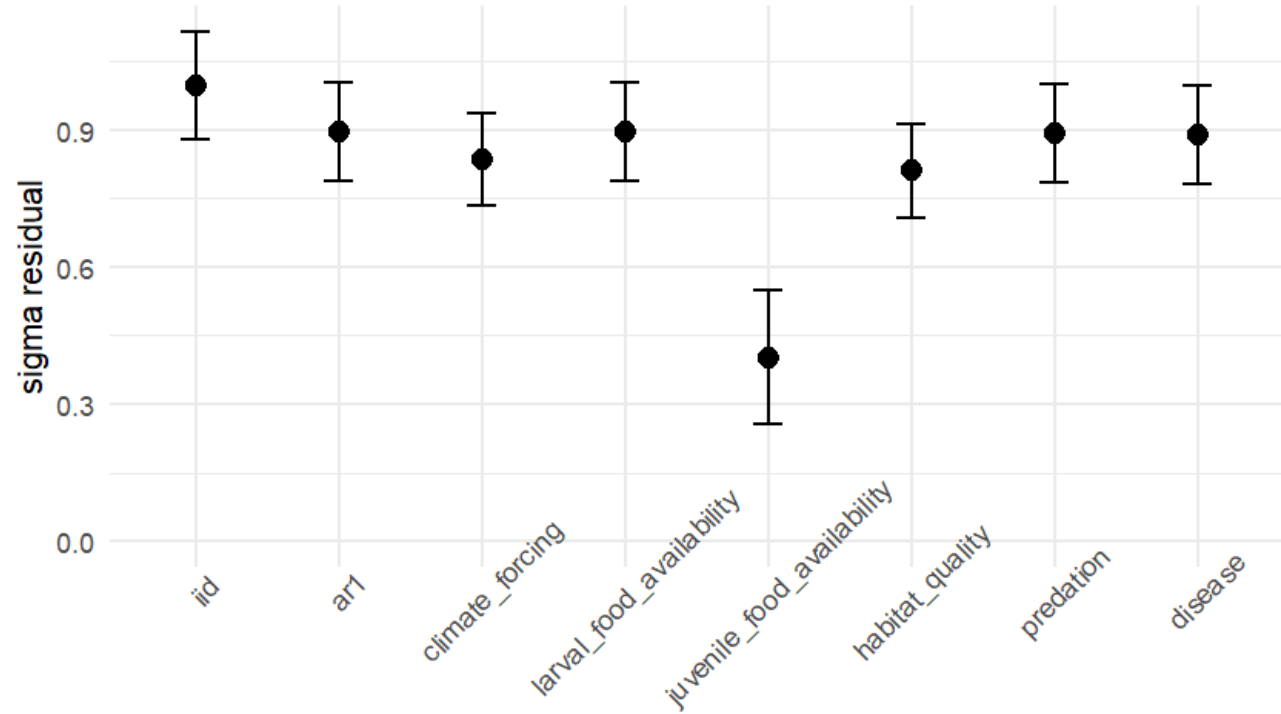
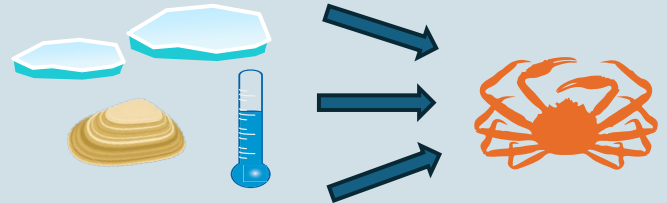
## Autocorrelated recruitment variation (AR1):

Snow crab recruitment (AR1)  
+ AR1 ESP indicators



## Ecosystem causal drivers:

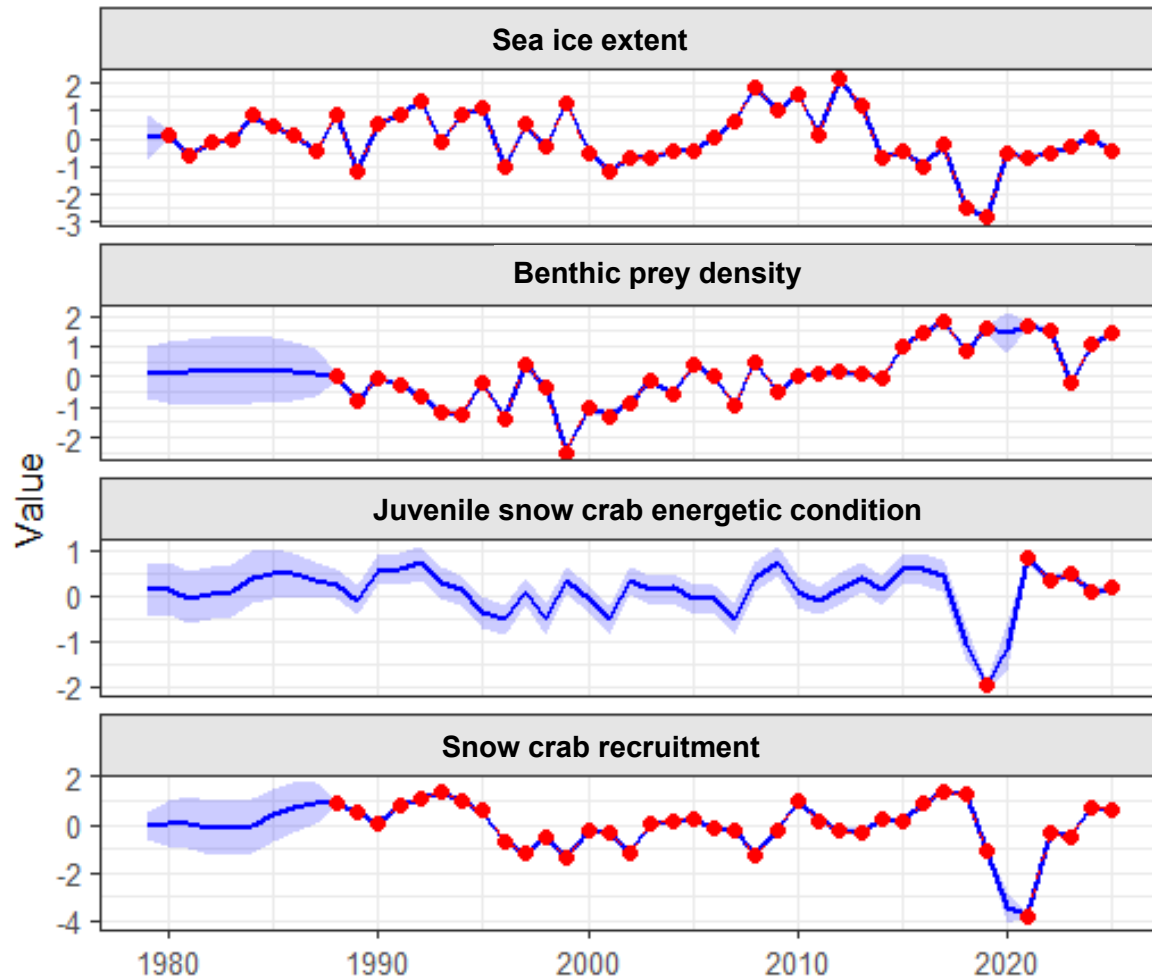
Lagged causal recruitment pathways +  
AR1 ESP indicators



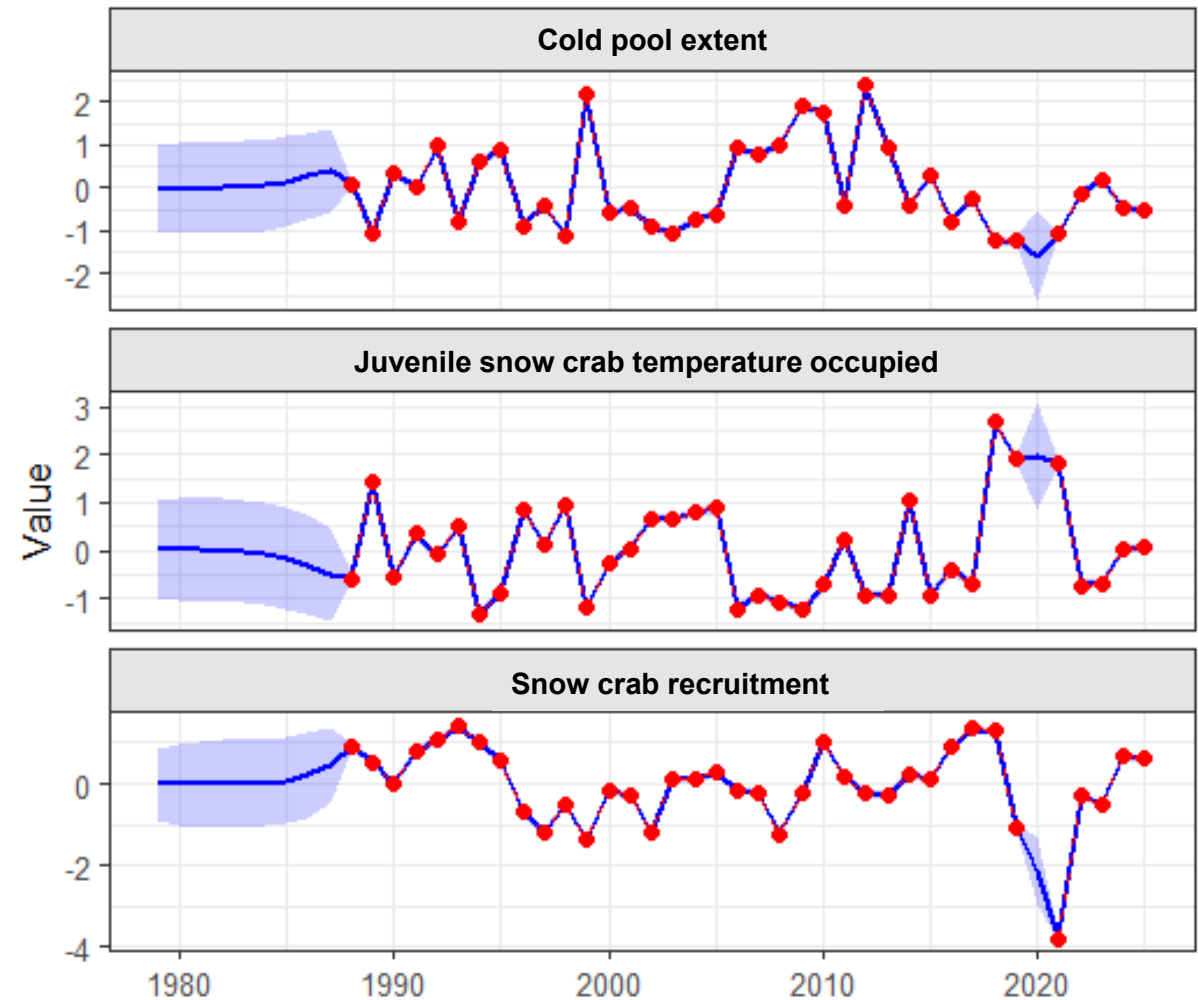
Including sea ice and energetic condition causal pathways (juvenile food availability model) results in an 84% decrease in estimated recruitment variance relative to the IID model

# Estimated latent variables

## JUVENILE FOOD AVAILABILITY MODEL



## COLD WATER HABITAT AVAILABILITY MODEL

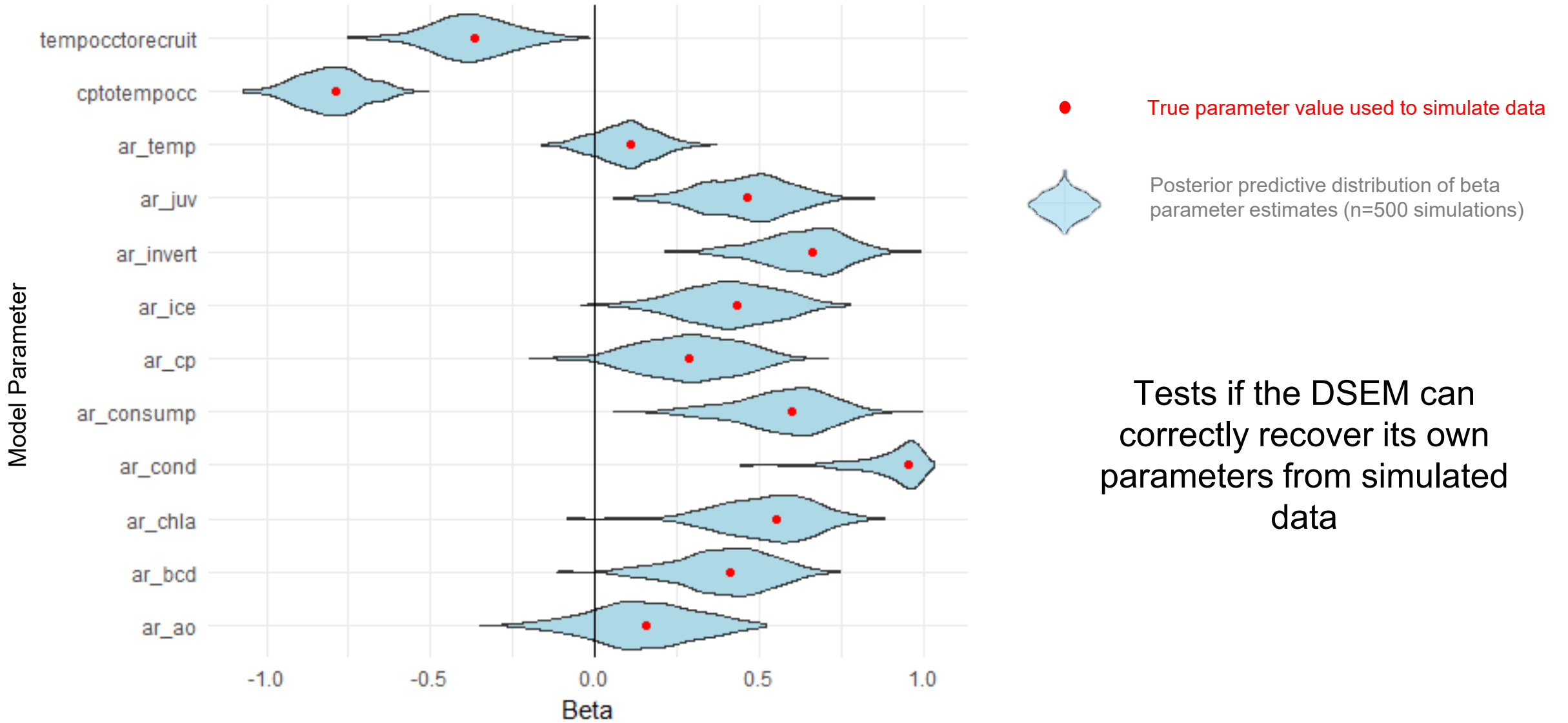


The strong causal effect of energetic condition is driven by a single data point (2019), and captures heatwave/collapse conditions that likely do not generalize to the historical period

## Potential diagnostics for DSEM models:

- Residual diagnostics
- OOS predictive performance
- Self-test simulations for parameter recovery
- Sensitivity analyses for:
  - Observation error
  - Lag structure

# Diagnostics: Example of self-test simulation



# Diagnostics: Bias and RMSE across simulations

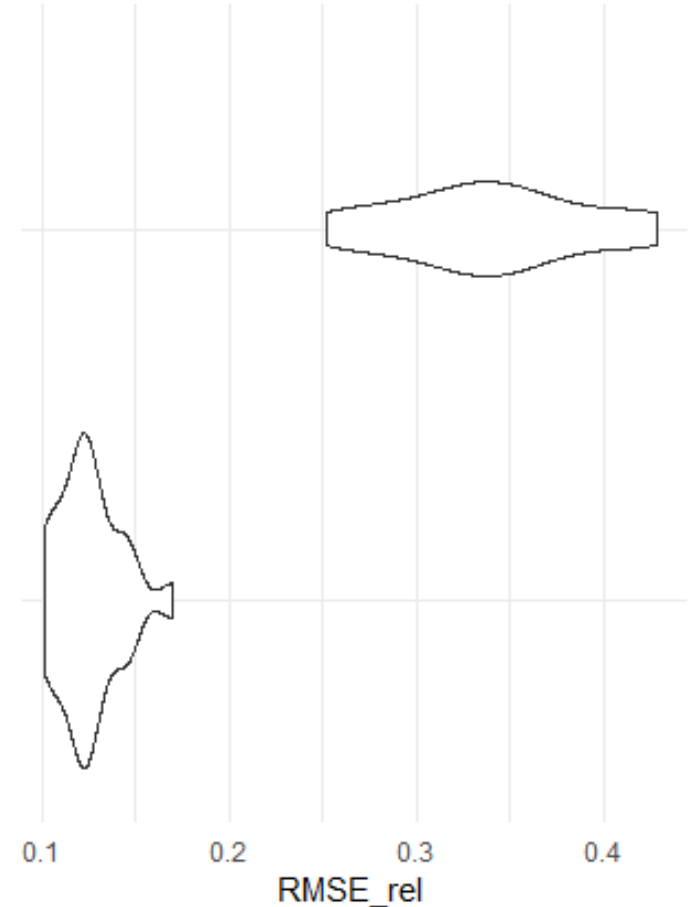
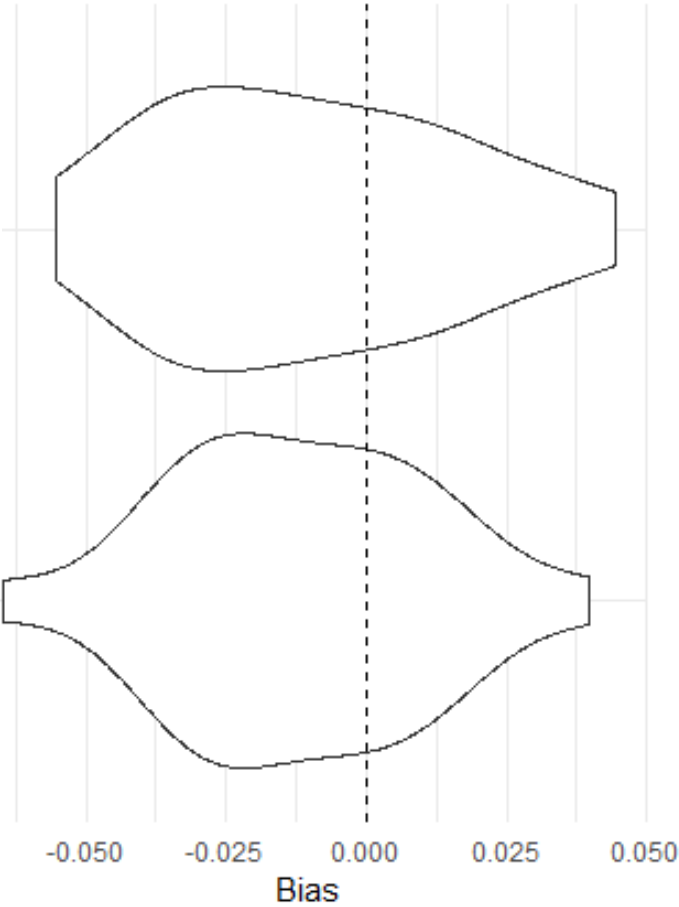
Causal Pathway:

Bias

Relative RMSE

Temperature occupied -> recruitment

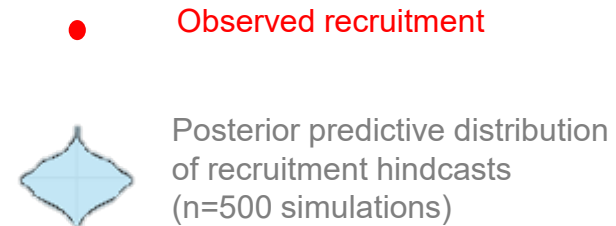
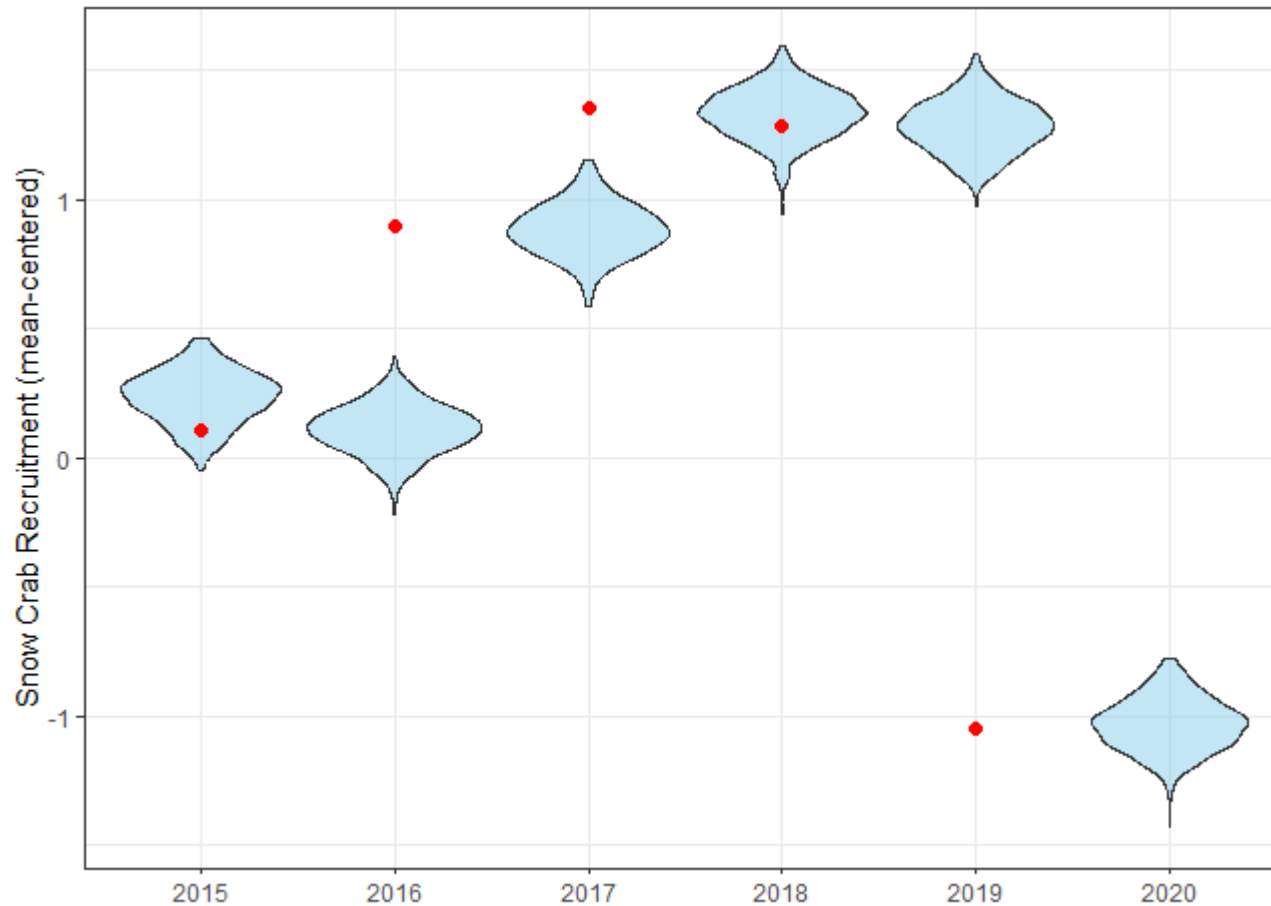
Cold pool -> Temperature occupied



Tests if the model is unbiased (i.e. recovers true parameters correctly), and quantifies overall estimation error

# Diagnostics: OOS predictive performance

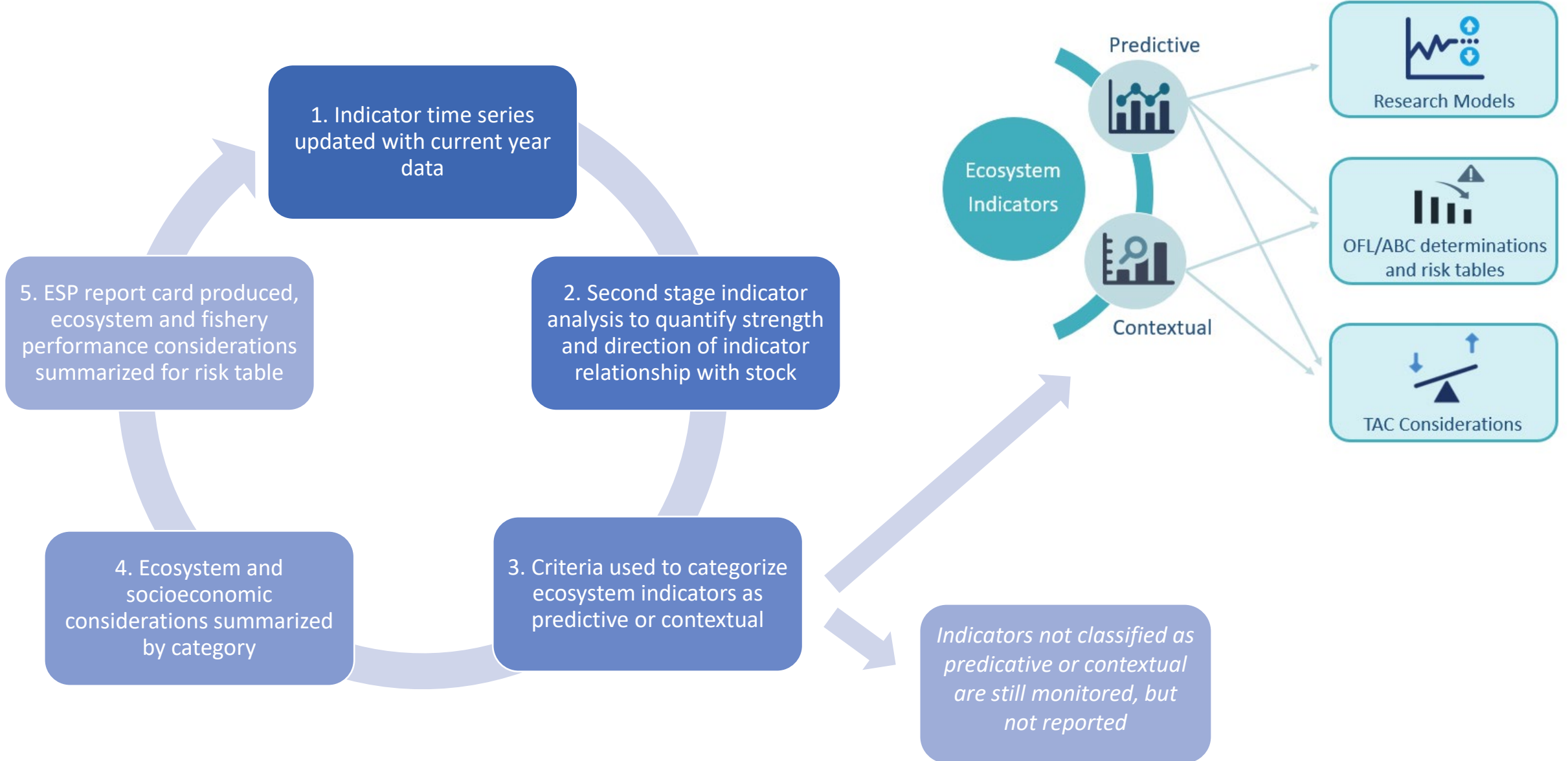
## Recruitment retrospective forecast skill for 2015-2020



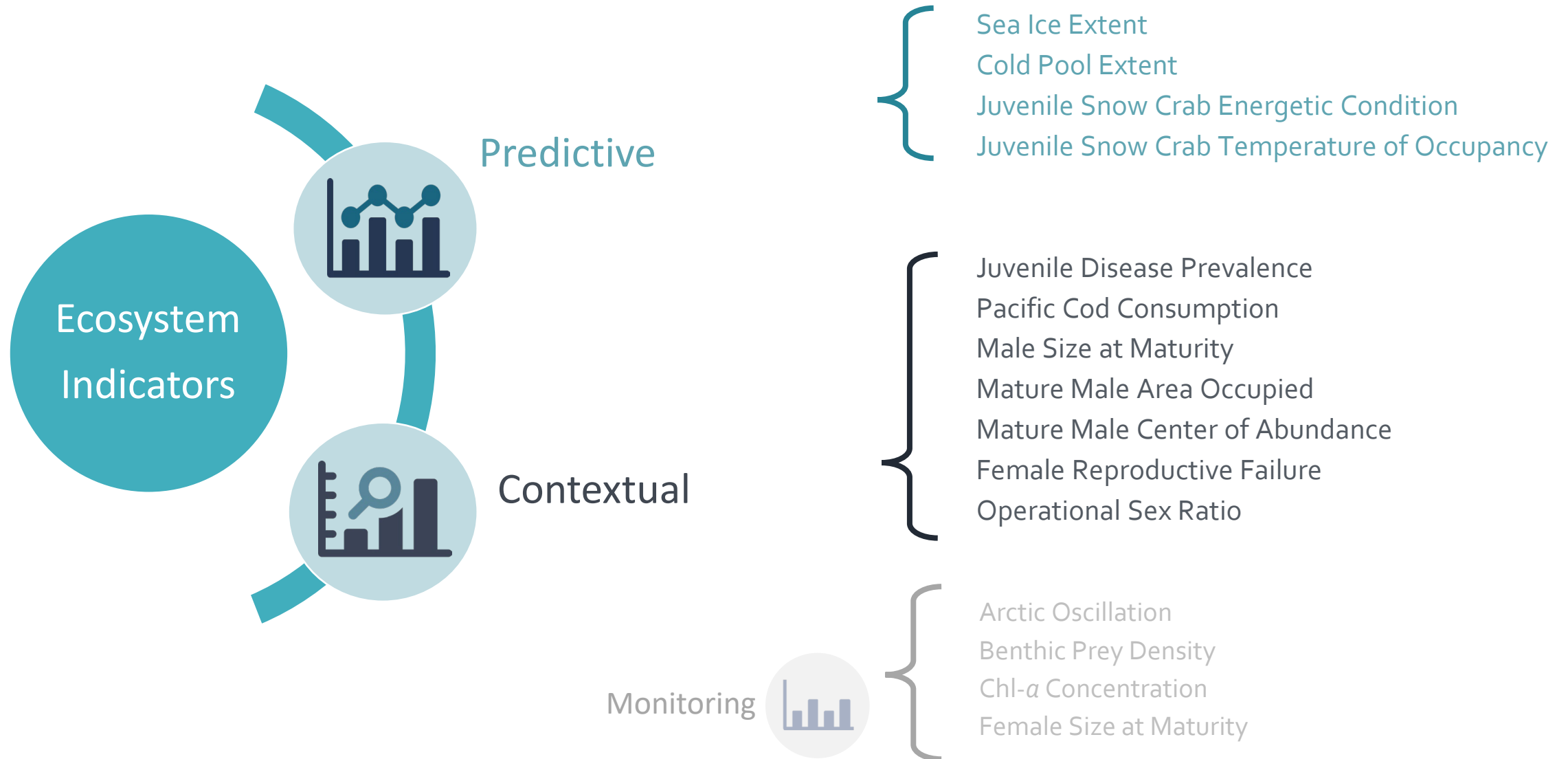
Tests for:

- Predictive skill of DSEM over time
- Stability of estimated causal relationships as the training window changes

# Annual workflow for ESP report cards



# Implementation of DSEM indicator analysis results in ESP report card



# Implementation of DSEM indicator analysis results into risk table

## Risk Table Summary for Bristol Bay Red King Crab

The following is a synthesis and interpretation of the most recent ecosystem and socioeconomic information available for Bristol Bay red king crab (BBRKC) from the ecosystem and socioeconomic profile (ESP, Fedewa et al., 2025) and the Eastern Bering Sea Ecosystem Status Report (ESR, [Siddon, 2024](#); Siddon, 2025, in press). This information may be helpful for evaluating risk table score levels and is organized below by the proposed risk table categories.

We identified two predictive ecosystem indicators that quantitatively predict BBRKC recruitment using a Bayesian Adaptive Sampling approach for indicator selection and importance: **pH and wind stress** (see Fedewa et al., 2025 for more details). These indicators are emphasized in **BOLD** below. The final model including pH and wind stress explained a moderate amount of variation in BBRKC recruitment ( $R^2 = 0.39$ ), however, we note that large credible intervals suggest a large degree of uncertainty in the estimated effect sizes.

### Category Summary:

Assessment-related Considerations	Population Dynamics Considerations	Ecosystem Considerations	Fishery-informed Stock Considerations
<b>Level 1:</b> TBD	<b>Level 1:</b> Normal	<b>Level 1:</b> Normal	<b>Level 1:</b> Normal
	Stock-specific indicators suggest no apparent population dynamics concerns.	Corrosive bottom waters and increased wind stress in Bristol Bay remain a concern for growth and survival of larval and juvenile BBRKC. While bottom waters in Bristol	Fishery-informed indicators are generally consistent with stable or mildly improving stock condition relative to recent history of low population density. No considerations



Emphasis placed on indicators that are causally linked to recruitment from DSEM indicator analysis (**BOLD** text in risk table)

## Base Mortality Models:

### Random mortality (IID):

Snow crab mortality (IID)  
+ AR1 ESP indicators

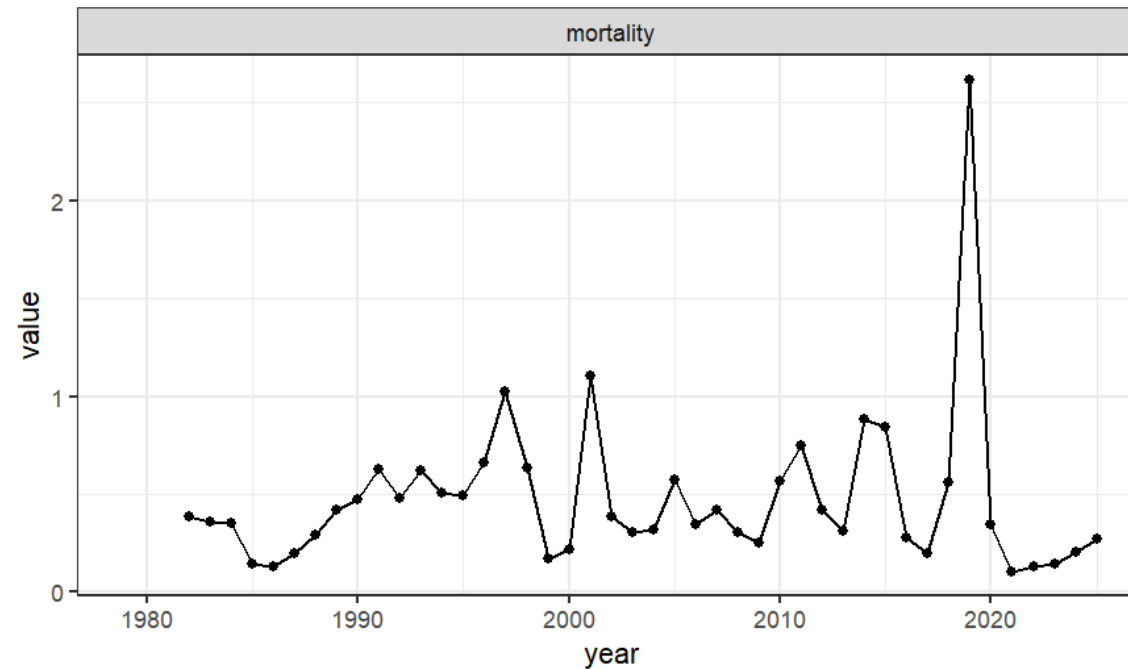


### Autocorrelated mortality (AR1):

Snow crab mortality (AR1)  
+ AR1 ESP indicators

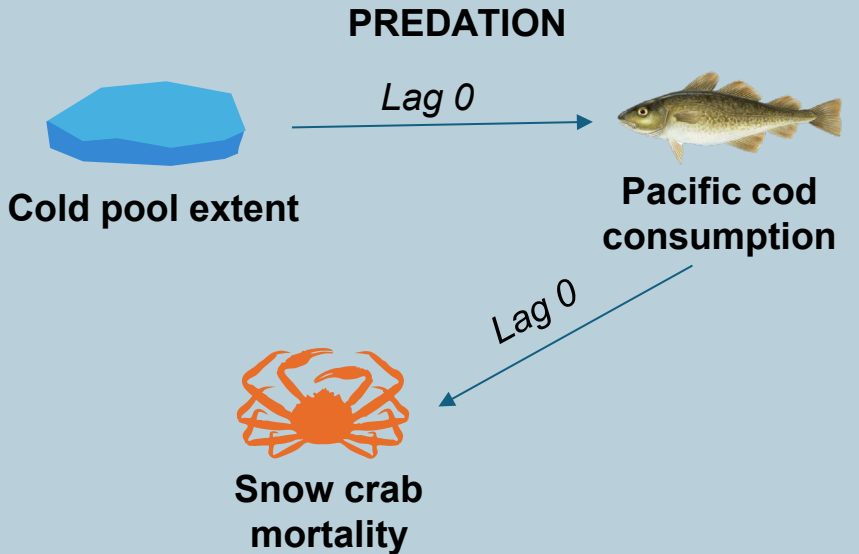
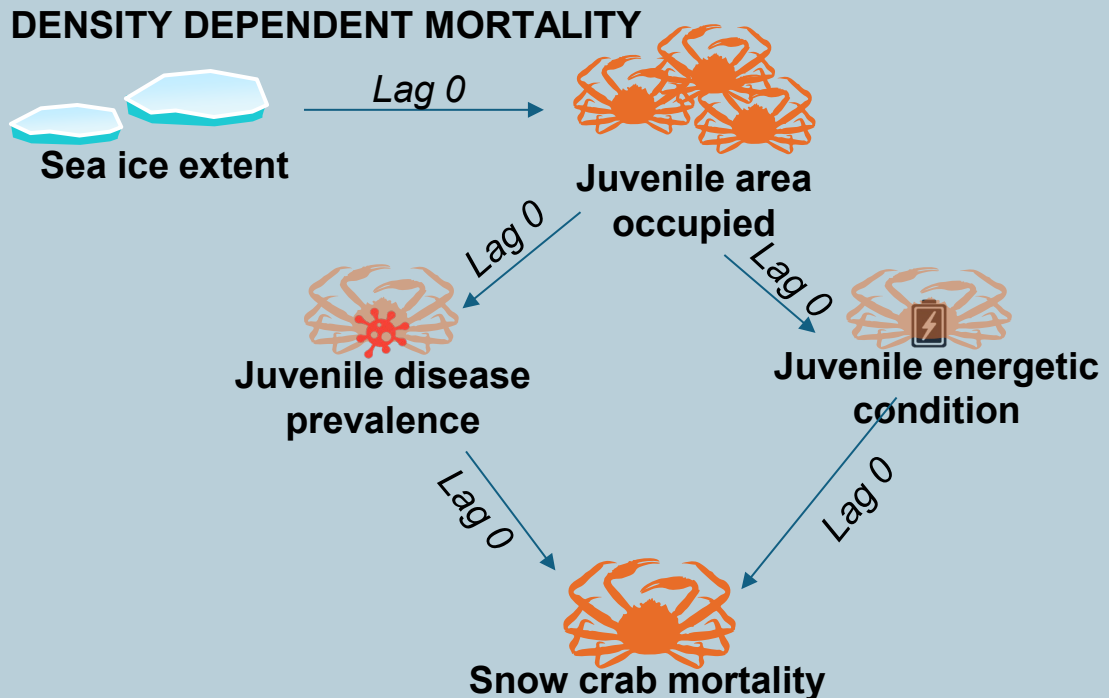
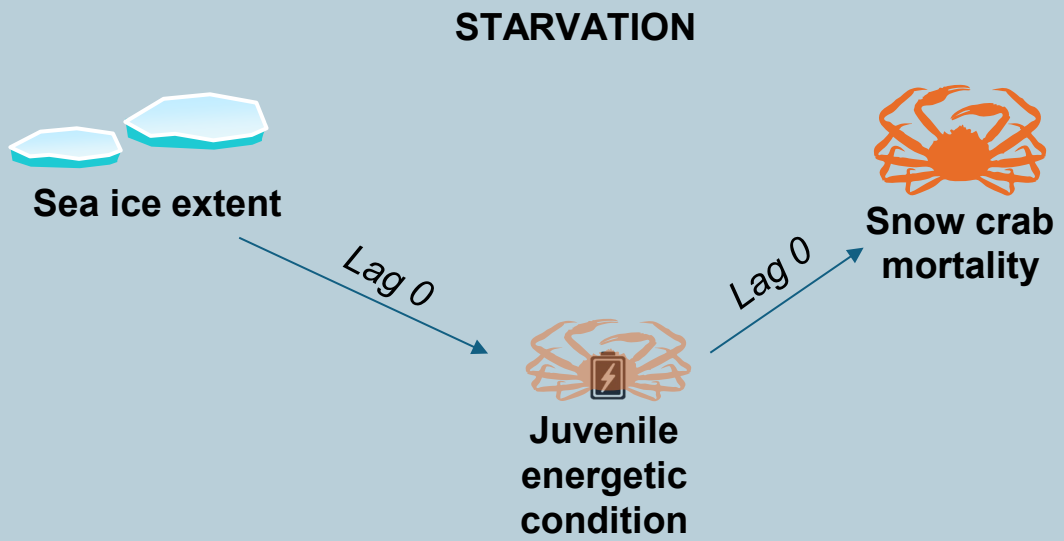
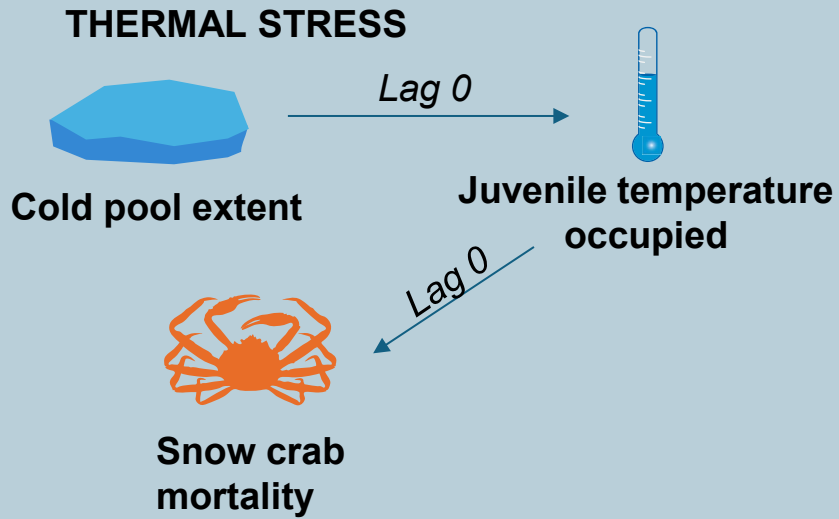


## Time-varying mortality estimates for immature snow crab (research model, Szuwalski et al.)



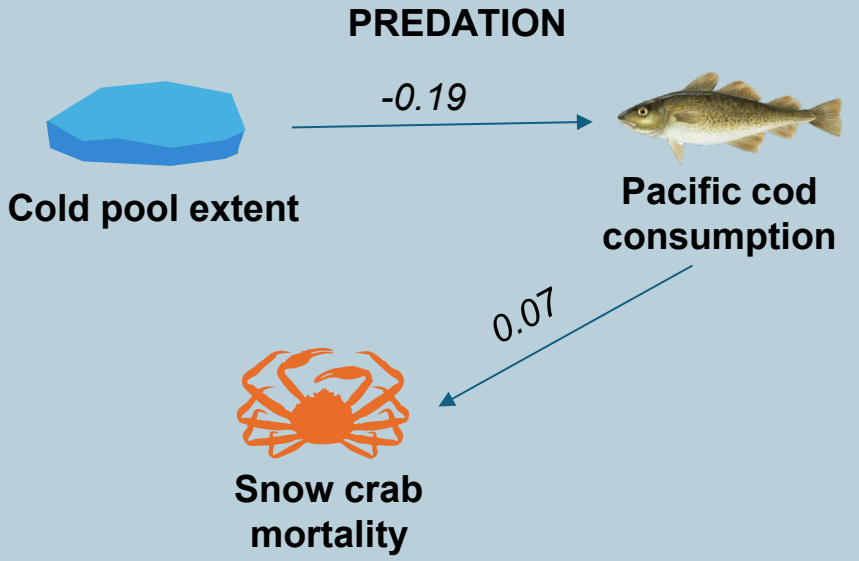
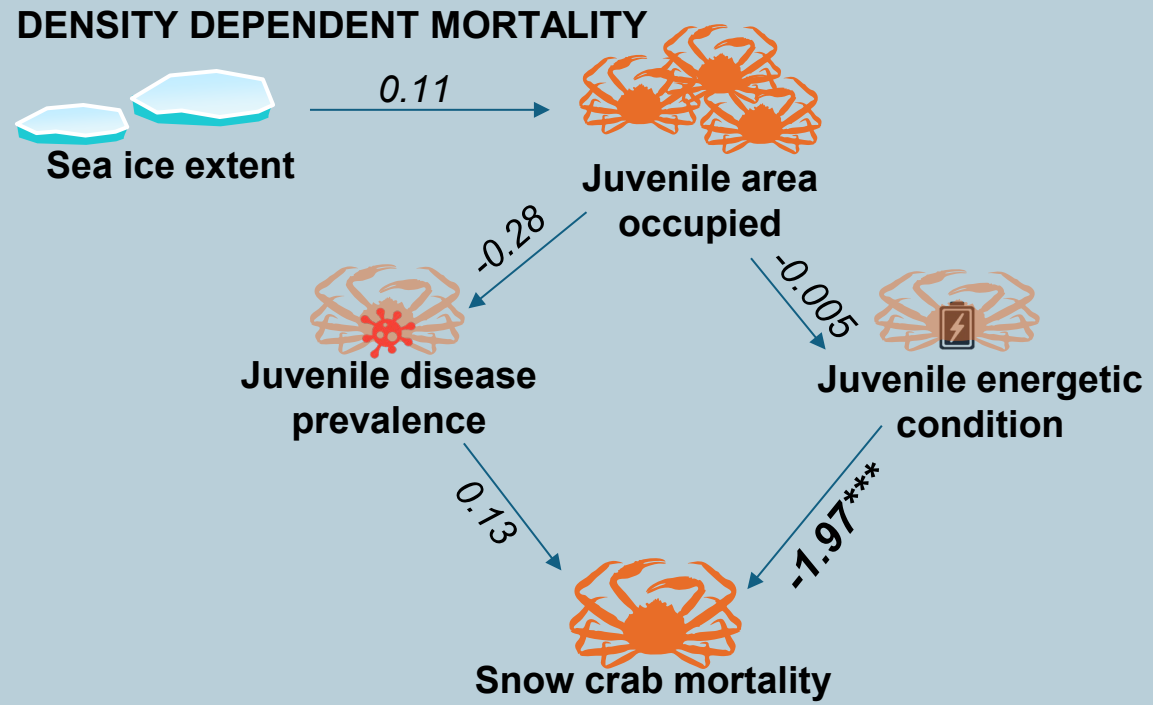
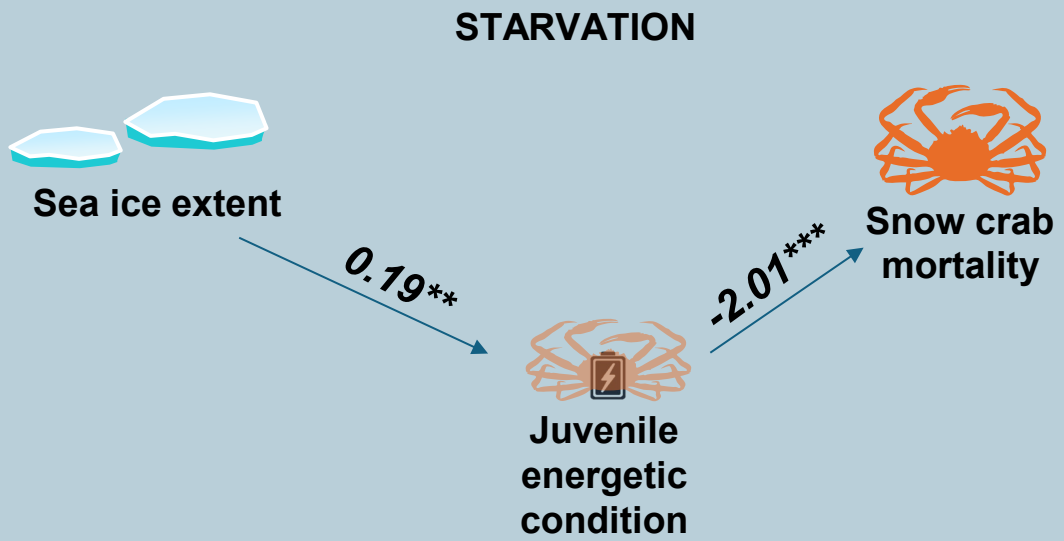
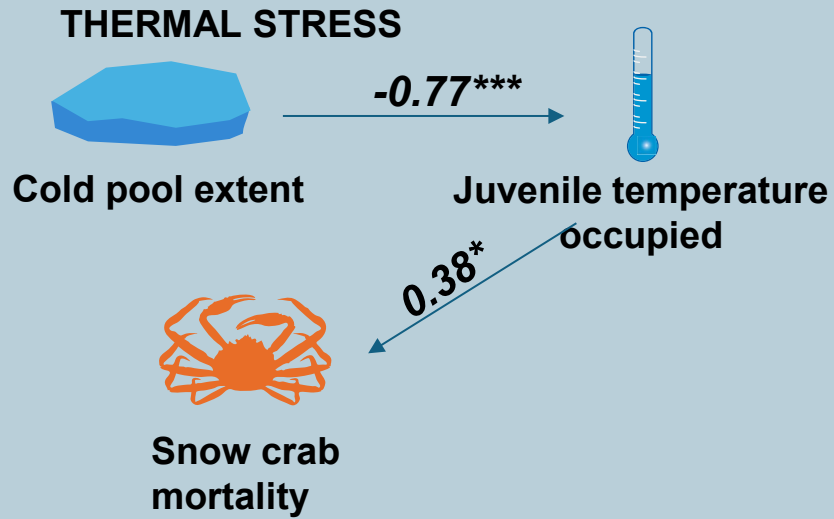
# Structural Causal Mortality Models:

Lagged causal pathways + AR1 ESP indicators



# Mechanistic Causal Mortality Models:

Lagged causal pathways + AR1 ESP indicators



# Discussion

- Operationalize DSEM for snow crab ESP in September? What about Tanner and BBRKC ESPs?
- CPT input on:
  - DAGs and models tested
  - Lag structure
  - Models and diagnostics requested for September (if operationalized)
- Proposed implementation of DSEM results into ESP report cards and risk tables
- Utility of recruitment vs. mortality models