Gulf of Mexico Shrimp
Empirical Dynamic Modeling Workgroup Summary

NOAA Fisheries
Southeast Fisheries Science Center
Gulf Branch - Sustainable Fisheries Division

March 7, 2023

Workgroup Purpose

- This workgroup is convened following a request to the Southeast Fishery Science Center from the Gulf Council following their April 2022 Meeting.
- *"… the Council thinks that the continued engagement of the aforementioned groups* [SSC members, Council staff, and shrimp industry representatives] *during the development of the shrimp EDMs is preferable, as there were numerous logistical and ground truthing questions regarding operations of the shrimp industry and data utilization that could assist in a more robust result that can be employed by management, versus waiting to the end to be engaged. Specifically, the various AP and SSC members can provide technical insight, historical institutional knowledge, management expertise, and on-the-water perspectives that will improve the quality and the buy-in of the resulting analytical tools."*

Meeting Summary

- Met 3 times August-October 2022
- Participants

Jim Nance
Leann Bosarge
Steve Bosarge
Glen Delaney
Nathan Putman
Benny Gallaway
John Froeschke
Matt Freeman
Dave Chagaris
Corky Perret
Lew Bullock

Workshop Briefing

- Provided an overview of EDM theory and examples in fisheries applications.

- Provided an overview of current Gulf of Mexico Shrimp EDM methods, results, and proposed next steps for Gulf of Mexico Shrimp EDM work.

Workshop Meeting Objectives

- Brief workgroup members on Empirical Dynamic Models (EDM) and Gulf of Mexico Shrimp EDM results.
- Receive input from workgroup members and discuss future model development.
- Receive input from workgroup participants and discuss utility of Shrimp EDM to inform management.

Environmental drivers and other species have their own dynamics – not really ‘noise’

Feedbacks between the focal stock and other parts of ecosystem may be important

But we don’t have data for everything - Need a method that will allow us to implicitly account for these!

Empirical Dynamic Modeling: an example

Three-species model with type-2 functional response

Z – pr
Y – gr
X – pr

EDM:

1. Don’t need data on all variables to make accurate predictions
2. Don’t need equations, if we have enough data

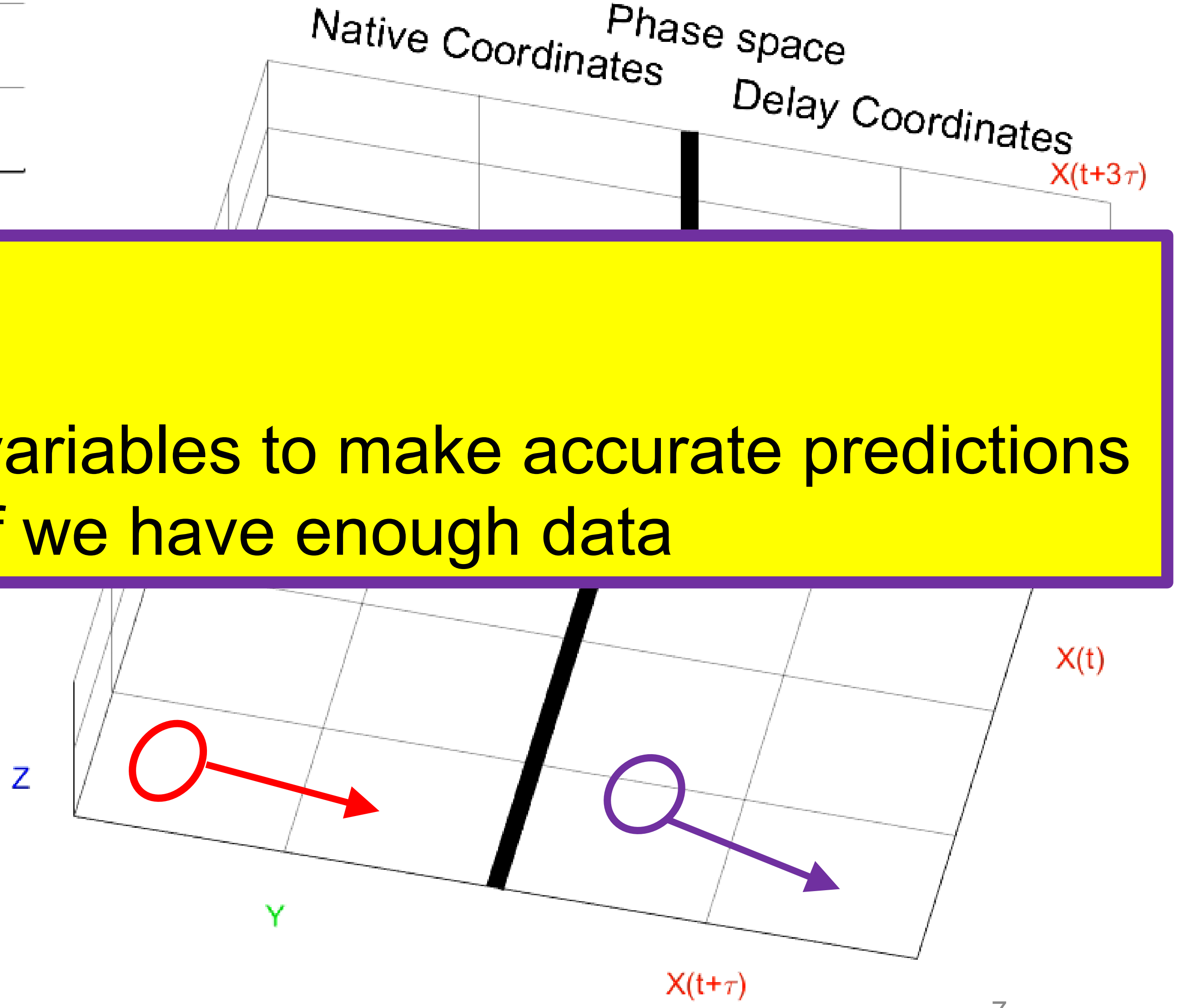
Trace nearby
obtain discre

$$x_{t+1} = F[x_t, y_t, z_t]$$

Analogous model in ‘delay coordinates’

$$x_{t+1} = \tilde{F}\,[x_t, \ldots, x_{t-E}]$$

Dynamics equivalent to full state space, based only on observed time series



Takens *without* Topology

Observed variables

$$x_{t+1} = F(x_t, y_t)$$

Unobserved variables

$$y_{t+1} = G(x_t, y_t)$$

Given enough data
we can approximate ***past*** value of
y (aka solve for y in terms of x)
Leading to a model in delay
coordinates

$$x_{t+1} = E_{y|x_t, \ldots x_{t\_E}}\{F(x_t, y)\} = \tilde{F}\,[x_t, x_{t-1}, \ldots, x_{t-E}]$$

Takens guarantees that, in theory,
this can be made ***exact***

In both the deterministic and stochastic case, we need to approximate
$\tilde{F}$ (the map from past states to future)
-use Bayesian GP regression, with automatic relevance
determination prior

Bhat and Munch (2021) Phys. Rev. E

Why ‘delay coordinates’? An example using the standard age-structured model

$$n_{a+1,t+1} = s_a n_{a,t}$$

$$B_t = \sum_{a=A_m}^{\infty} m_a n_{a,t}$$

$$n_{0,t+1} = f(B_t)$$

$n_{a,t}$ numbers at age a in year t

s_a survival from age a to a+1

m_a mass at age a (proportional to fecundity)

B_t spawning biomass

f density dependent recruitment

So, we’ve used lags in fisheries for a long time, as approximations to an age-structured model. Takens just makes this idea more general.

$$S_a = \prod_{j=0}^{a-1} s_j$$

Can re-write age structured model several ways in terms of lags of a single ‘observable’

1. Using a single age class, e.g. age 0, (Renewal Equation)

$$n_{0,t+1} = f\left(\sum_{a=A_m}^{\infty} m_a S_a n_{0,t-a}\right)$$

2. Production model
   a) survival is constant across ages
   b) growth is ~linear so that $m_{a+1} = g m_a$

$$B_{t+1} = gsB_t + bm_{A_m} S_{A_m} f\left(B_{t-A_m}\right)$$

Finding reference points and control rules from EDM

1. MSY
2. Optimal control rules
    - -numerically intensive,
    - -statistically challenging

2a. Harvest control rules

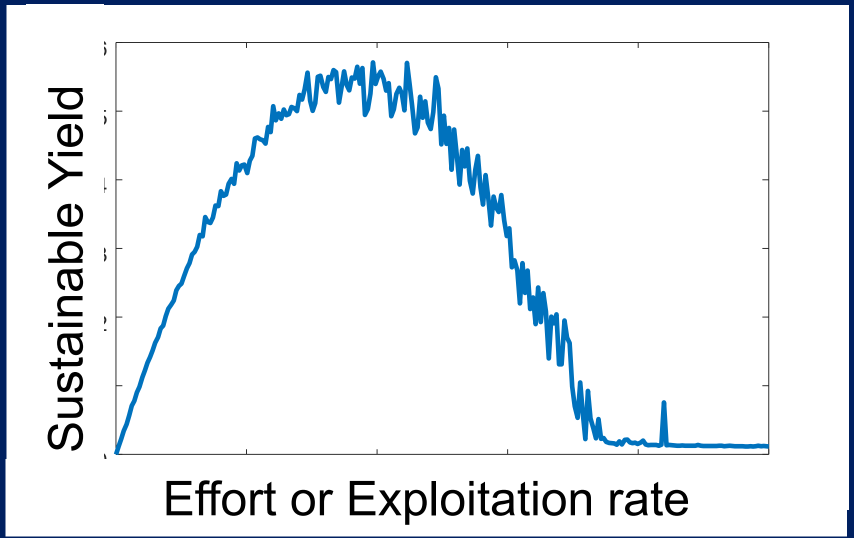
Steady state yield and MSY

Standard approach

Fit assessment model

Fix harvest rate, run to equilibrium, find sustainable yield

Vary harvest rate to find maximum sustainable yield



EDM approach

Fit EDM model with abundance and landings
(or landings and effort)

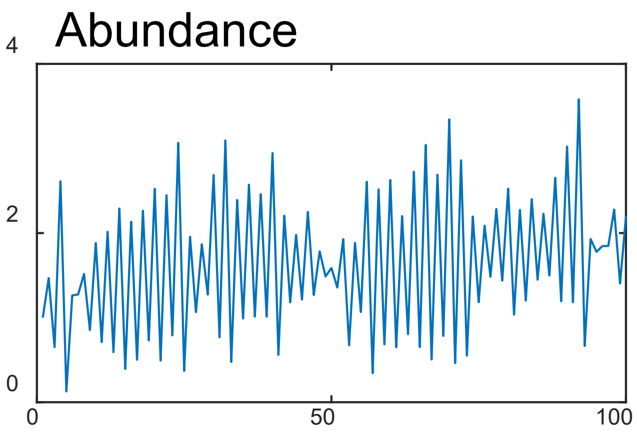
Fix harvest rate, run to equilibrium, find sustainable yield

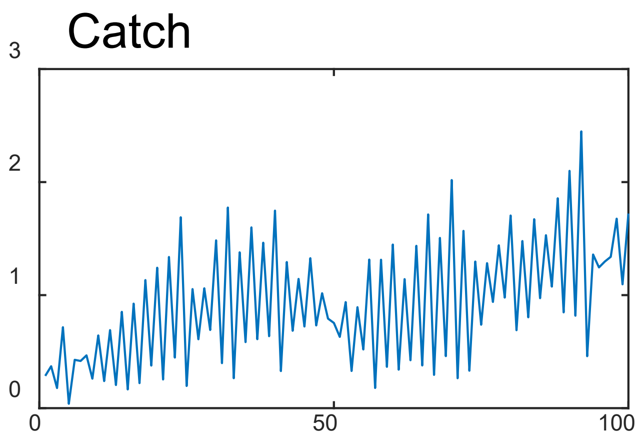
Vary harvest rate to find maximum sustainable yield

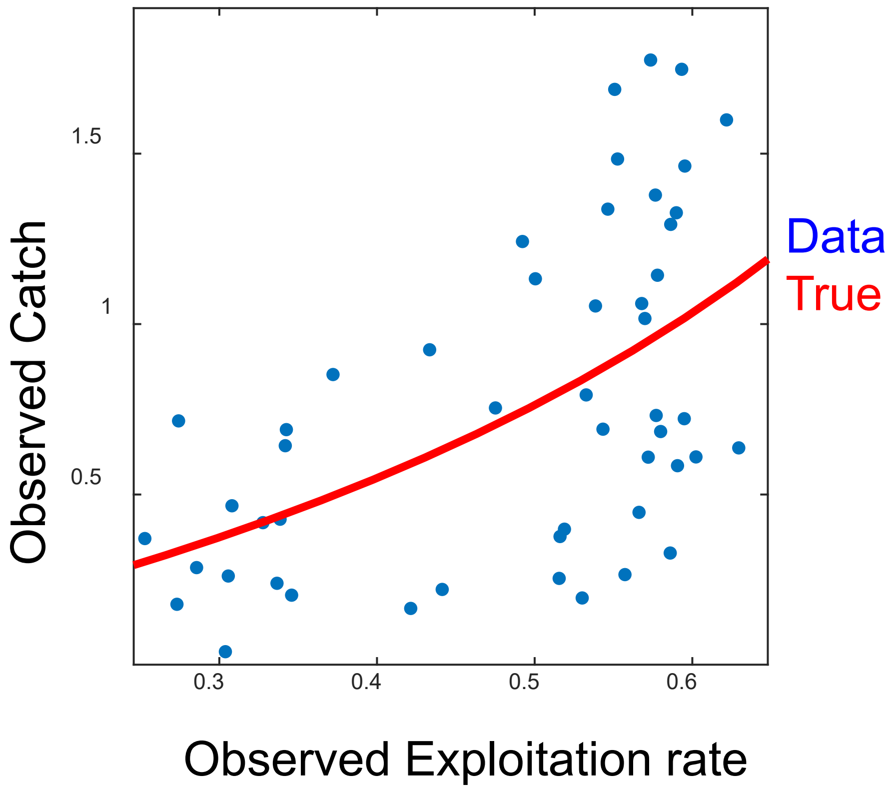
Using GP-EDM to estimate MSY: an example

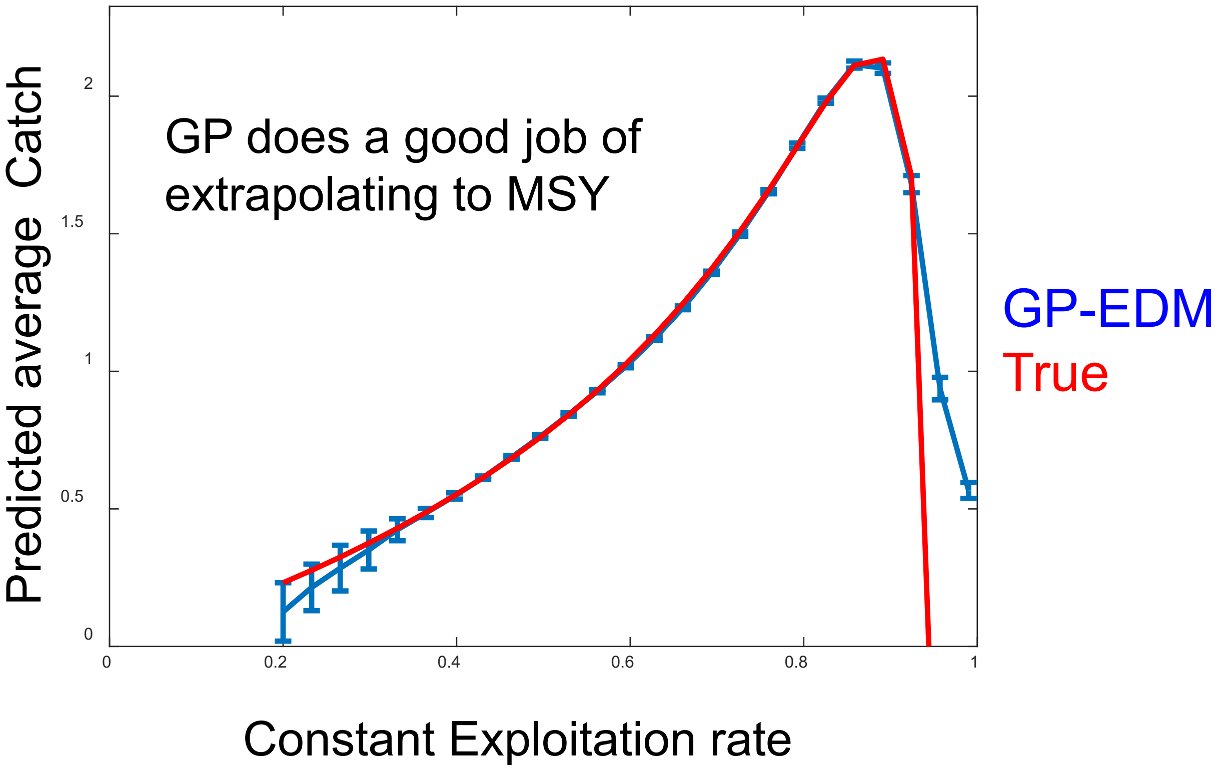
Simulate Ricker model
with fishing

Use GP to estimate MSY





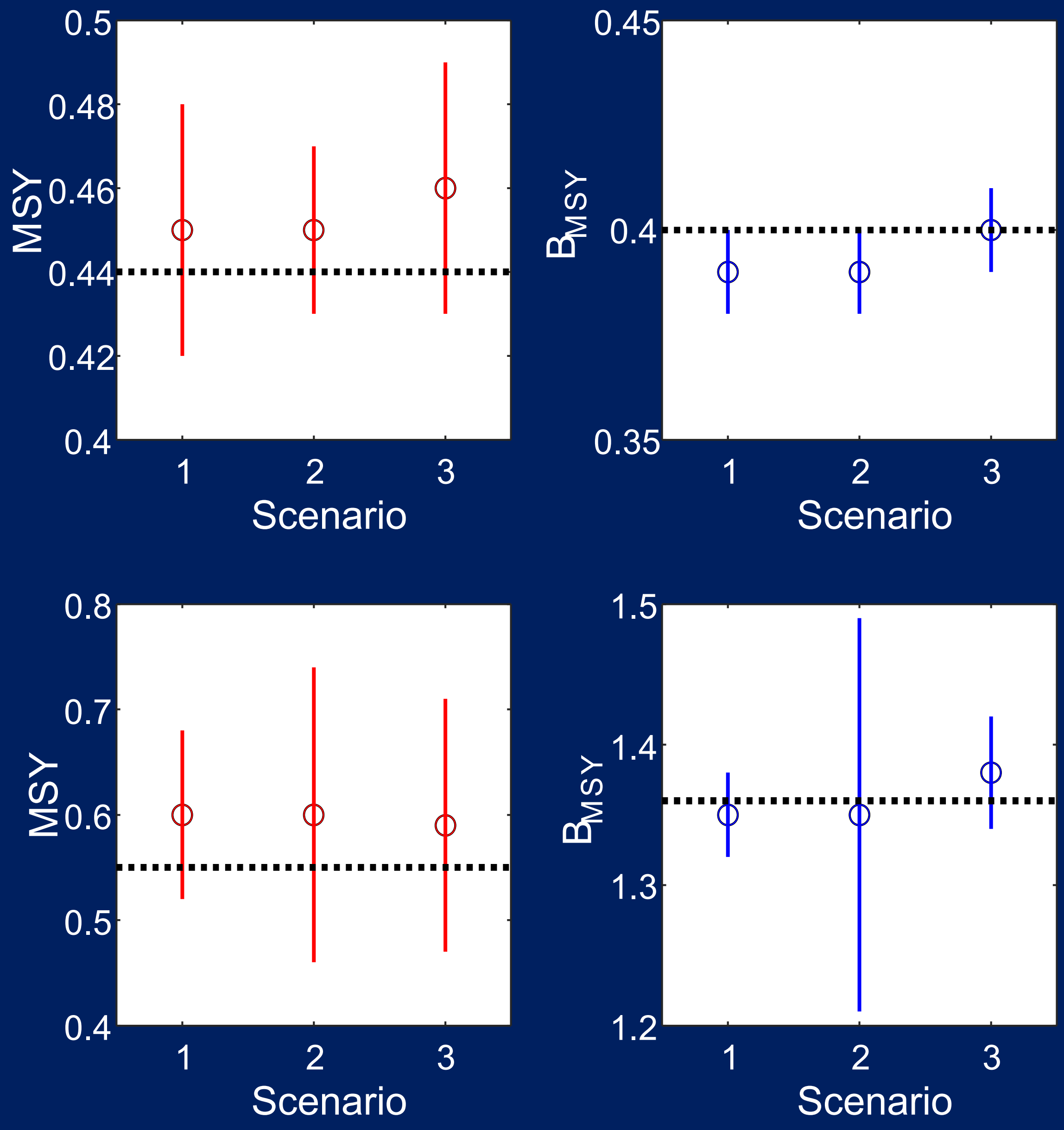




Testing EDM-> MSY

Pella-Thomlinson

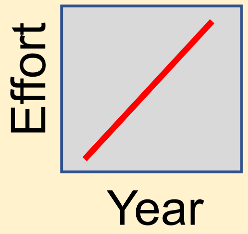
Two-species (predator harvested)



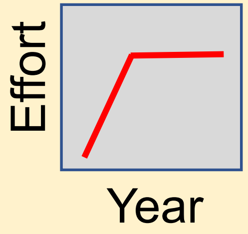
Cheng-han Tsai

Exploitation Scenarios:

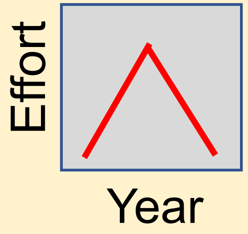
1. One way trip



2. Effort levels out



3. Effort rises and falls



Applications to brown and white shrimp

Background of EDM development for Gulf shrimp

- Previously we developed spatial hierarchical models using only SEAMAP and in situ environmental data (manuscript in publication)
- Previously we concluded using SEAMAP summer index as the first version model potentially used for index-based management
- To facilitate the interpretation and exploring harvest policies using simpler models, we investigate the aggregated gulf-mean SEAMAP and fishery catch data for EDM forecasts
- Additionally, environmental variables (temperature, oxygen, salinity) and Louisiana recruitment indices (statewide, westside, eastside) are investigated at the aggregated gulf-mean scale, together with catch data

Current models

GP-EDM used to predict average annual CPUE in SEAMAP survey.

Models include lags of CPUE and catch

Prediction accuracy assessed with leave-one-out forecasts

Also tested temperature, salinity, and dissolved oxygen and Louisiana recruitment index as inputs

x_t log(SEAMAP CPUE)

y_t log(catch)

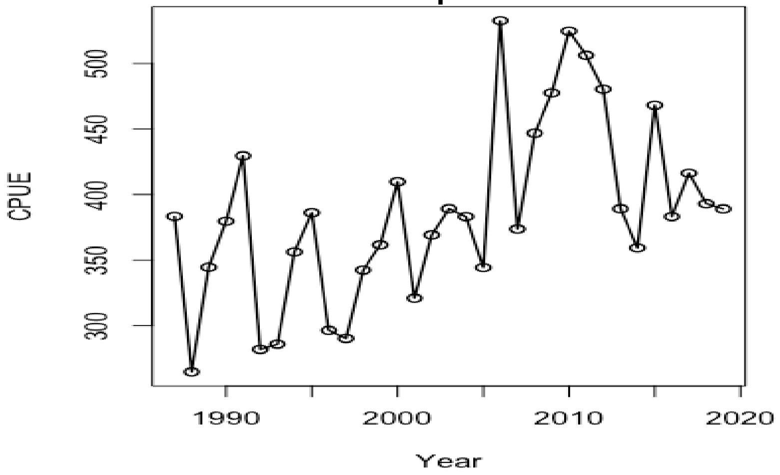
Delay embedding map

$$x_t = f(x_{t-1} - b y_{t-1}, \ldots, x_{t-E} - b y_{t-E}) + \varepsilon_t$$

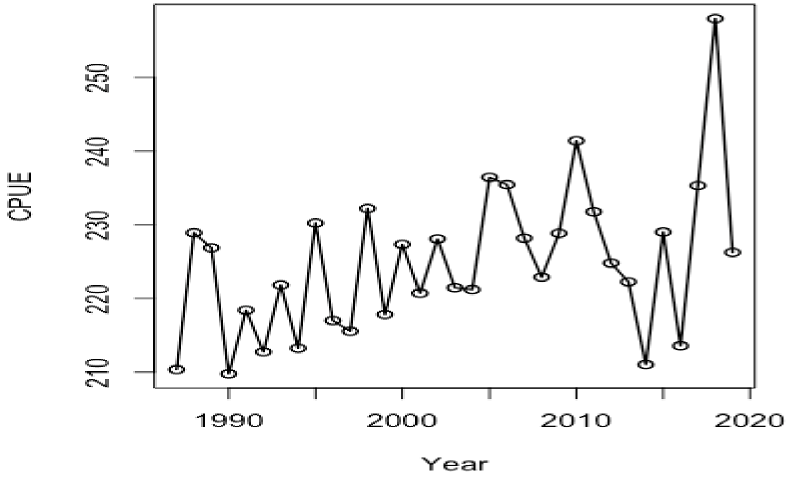
$^{**}\, b\ -$ *additional scaling factor to convert SEAMAP and Catch into same units*

SEAMAP data (annual average)

Brown shrimp

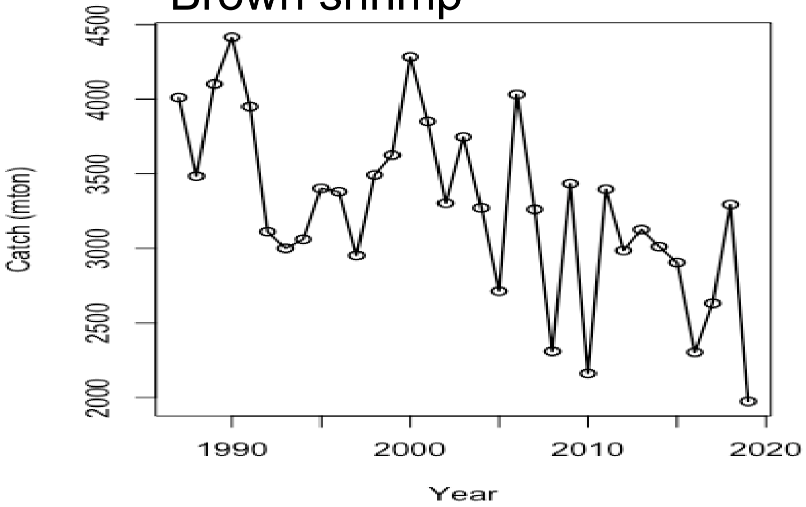


White shrimp

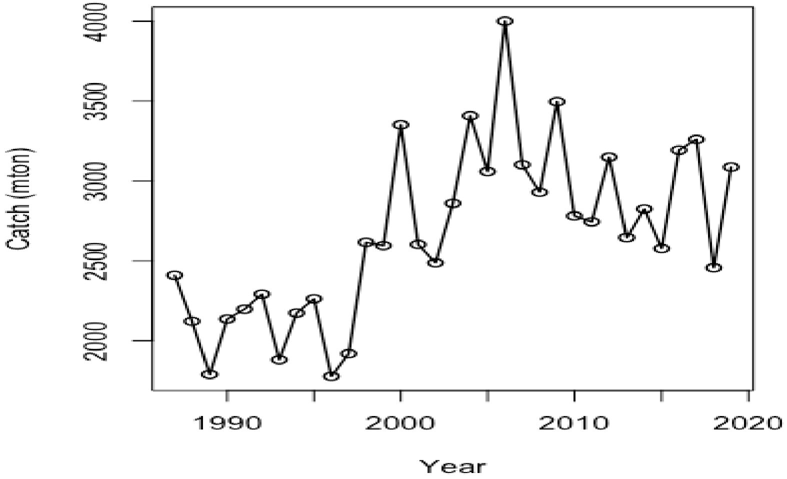


Catch data (annual average)

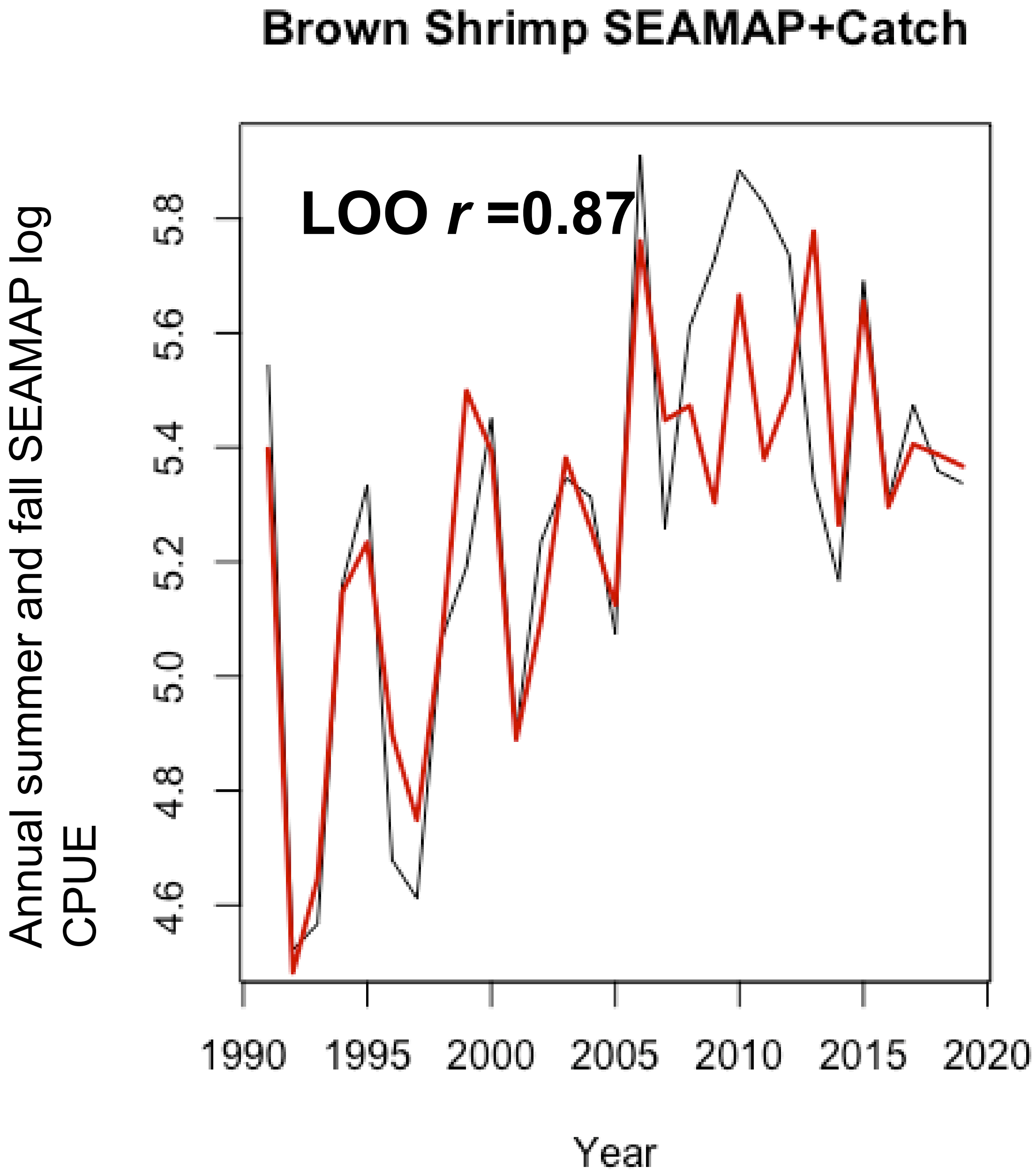
Brown shrimp

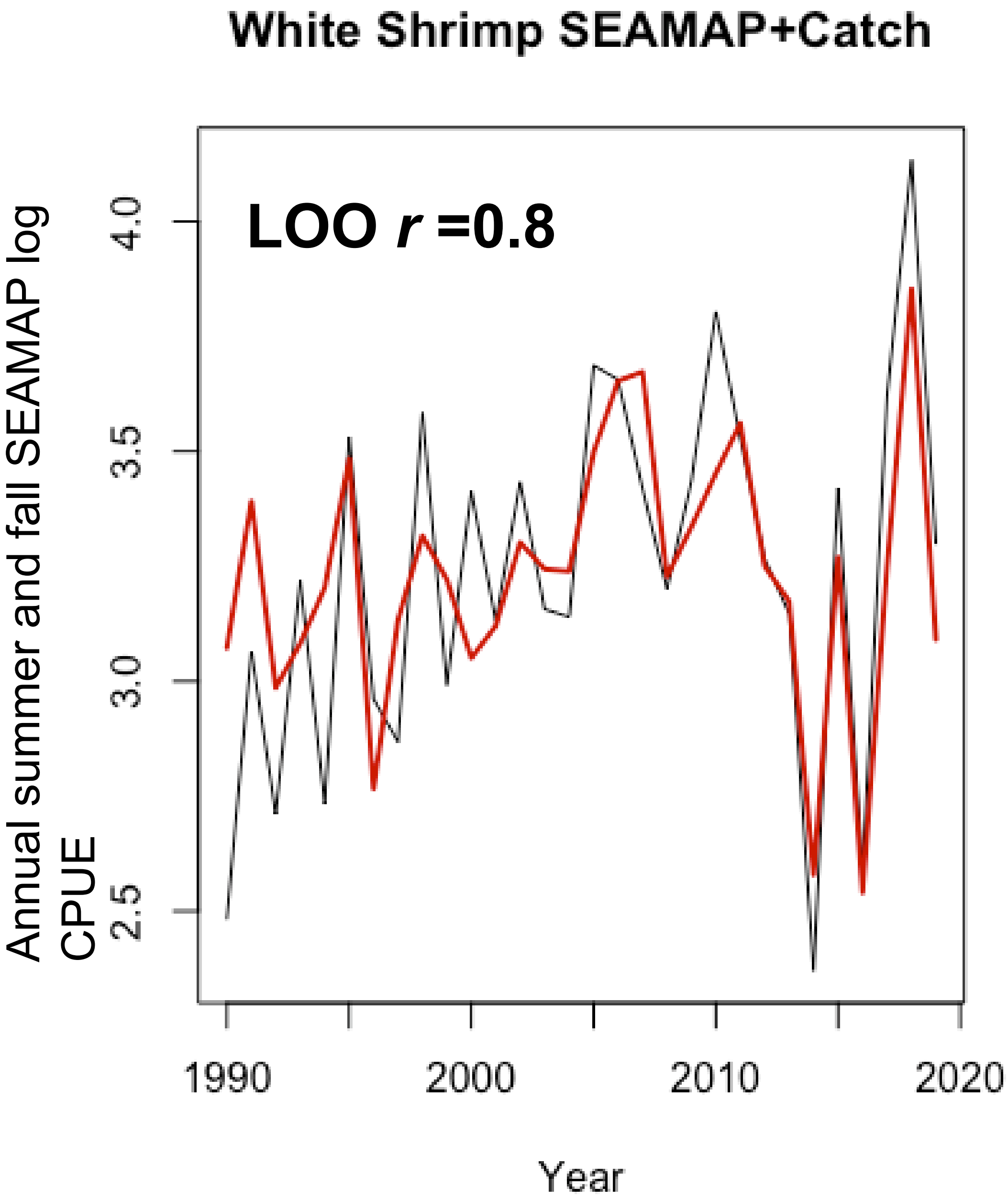


White shrimp



EDM out-of-sample forecasting

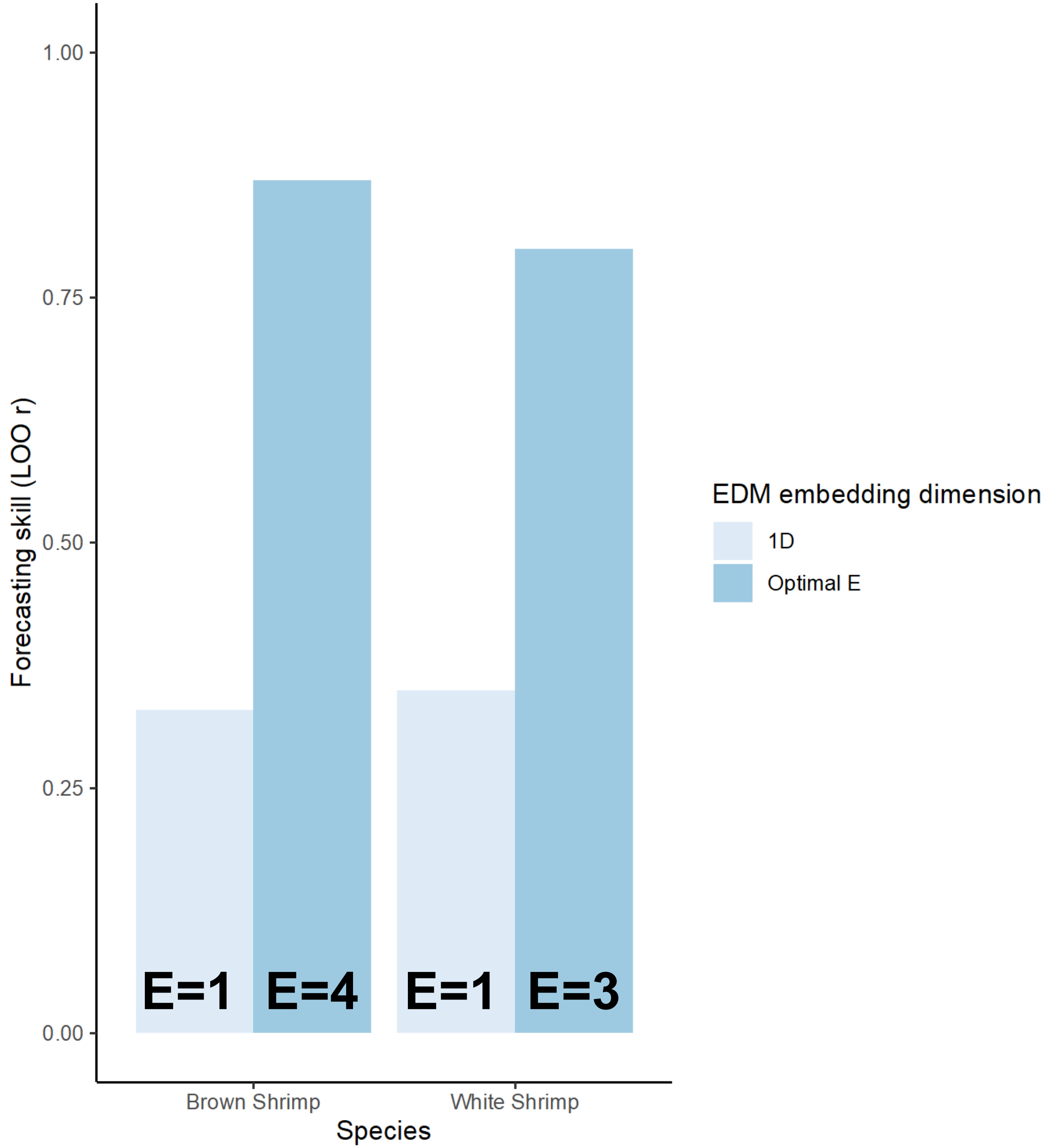




Comparison of EDM forecasting between optimal embedding dimension vs. 1-d model (i.e. a non-parametric production model)

1-d model r ~ 0.3

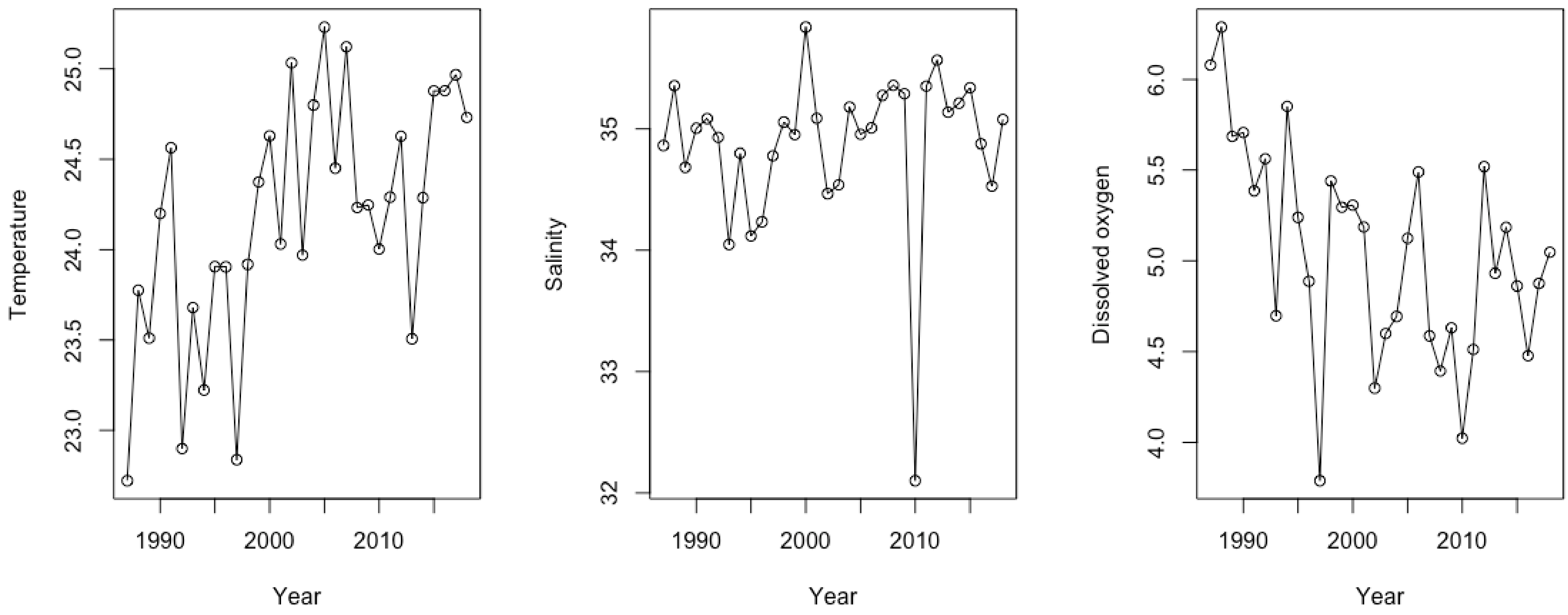
EDM produces 2-3x more accurate forecasts than just using current stock



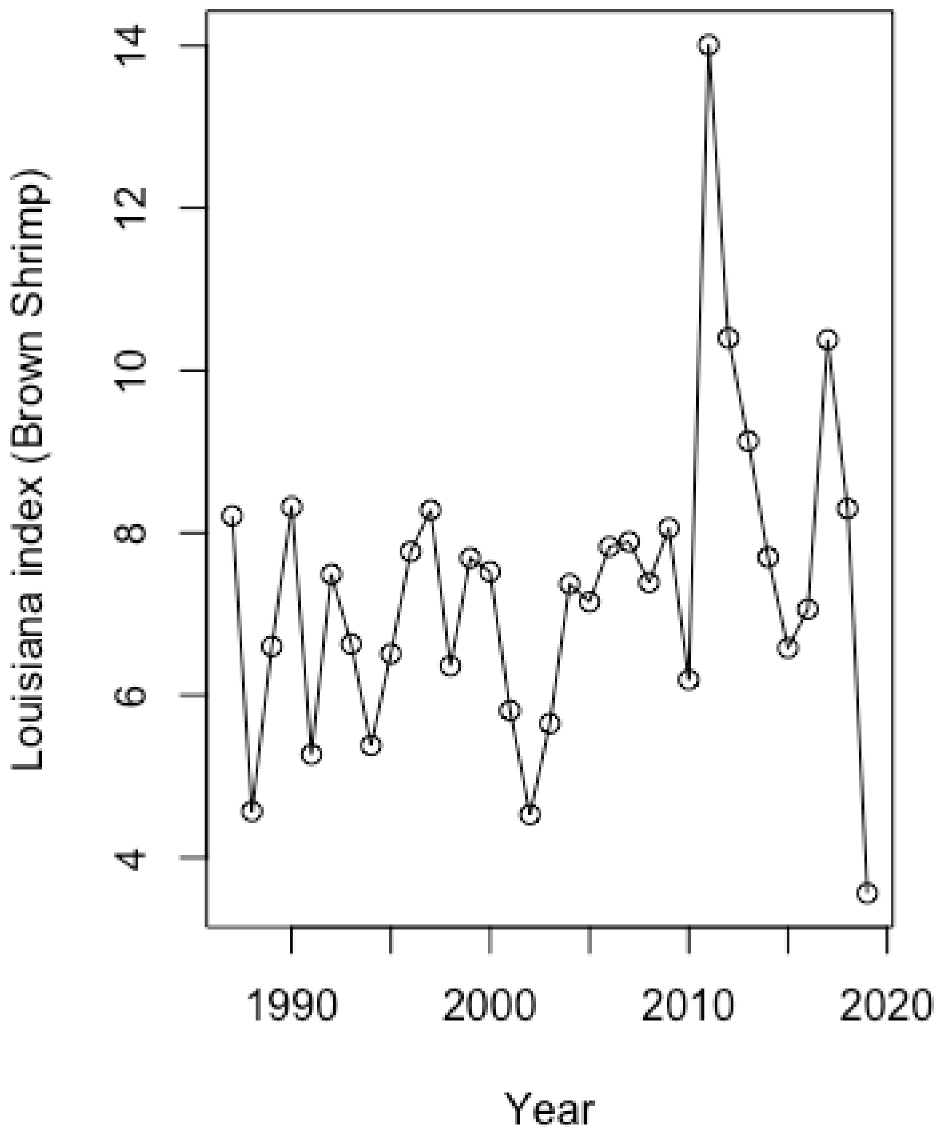
Exploration of predictors other than SEAMAP and catch data

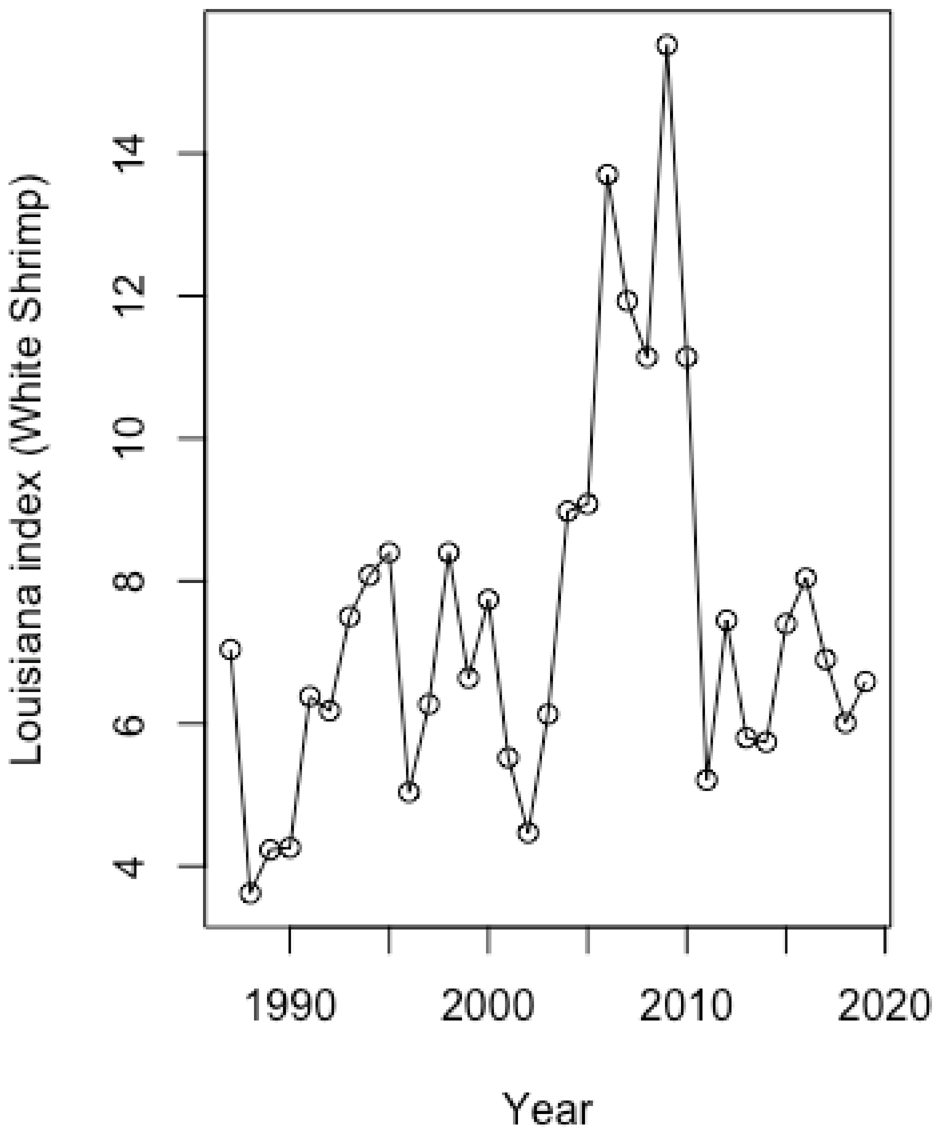
- Environmental variables (bottom temperature, oxygen, salinity)
- Louisiana recruitment indices.

Gulf-mean environmental data

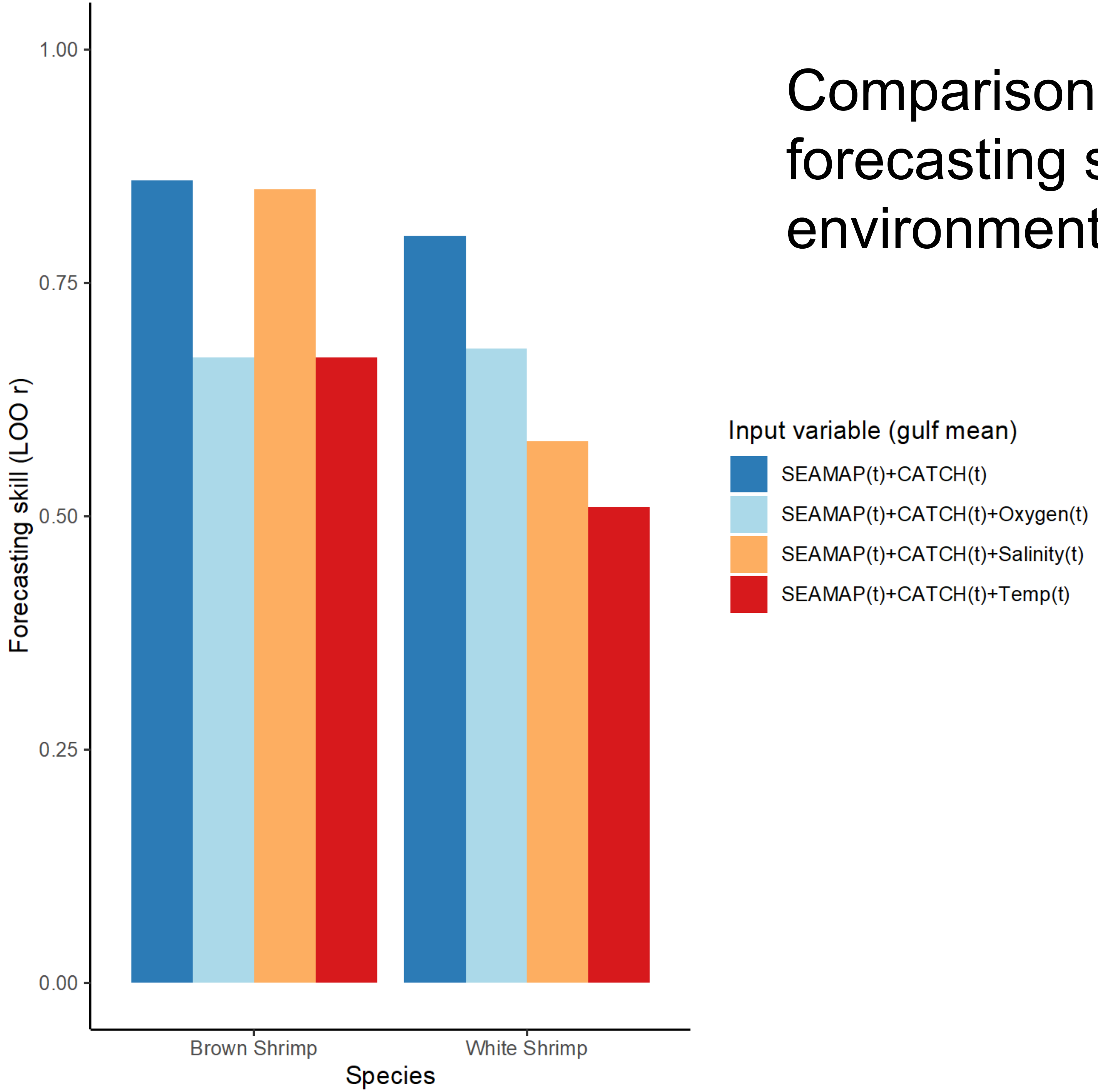


Louisiana survey indices

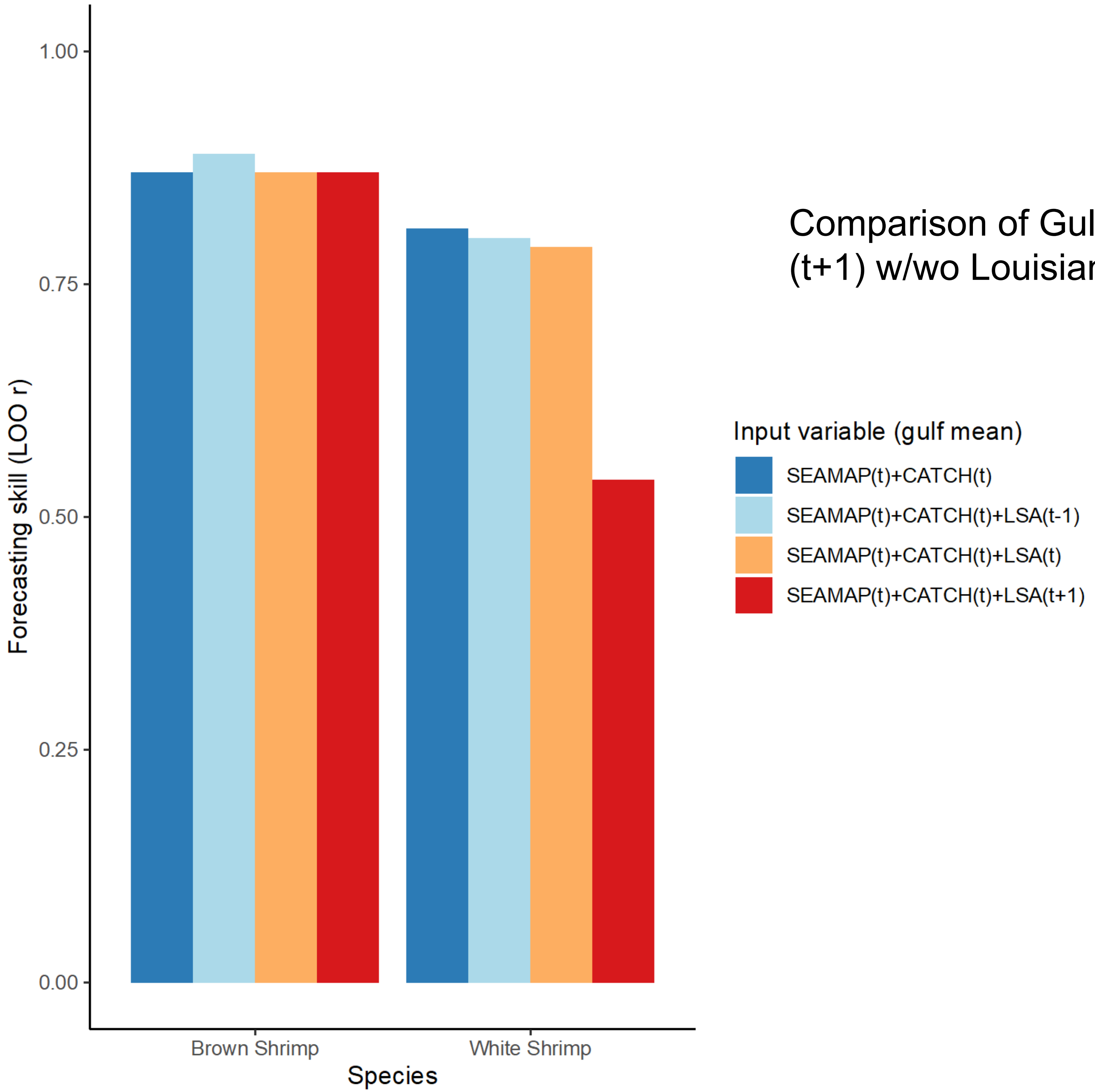




Comparison of Gulf-mean EDM forecasting skill w/wo environmental variables



Comparison of Gulf-mean EDM forecasting skill at (t+1) w/wo Louisiana indices at (t+1, t, and t-1)



Comparing production model and EDM

(data, parameters, biomass)

Biomass dynamics

B: Biomass (lbs)
C: Catch (lbs)
P: production (lbs)

$$B_{t+1} = B_t - C_t + P(B_t - C_t)$$

$P(x) = rx(1 - \frac{x}{k})$ production function

I: abundance index (#/tow)
q: #/lbs/tow

$$I_t = qB_t$$

u: exploitation rate (lbs/lbs)

$$u_t = \frac{C_t}{B_t}$$

Regression to estimate parameters q, r, k
AND biomass through time, $B_1, B_2, \ldots$

ASSUMES ALL PARAMETERS ARE CONSTANT

Model if fishing comes after reproduction

$$B_{t+1} = B_t + P(B_t) - C_t$$

Re-write model just in terms of observables:
(multiply by q)

$$qB_{t+1} = qB_t - qC_t + qP(B_t - C_t)$$

$$I_{t+1} = I_t - qC_t + qP\left[\frac{(I_t - qC_t)}{q}\right]$$

Now we have model in terms of Index and Catch

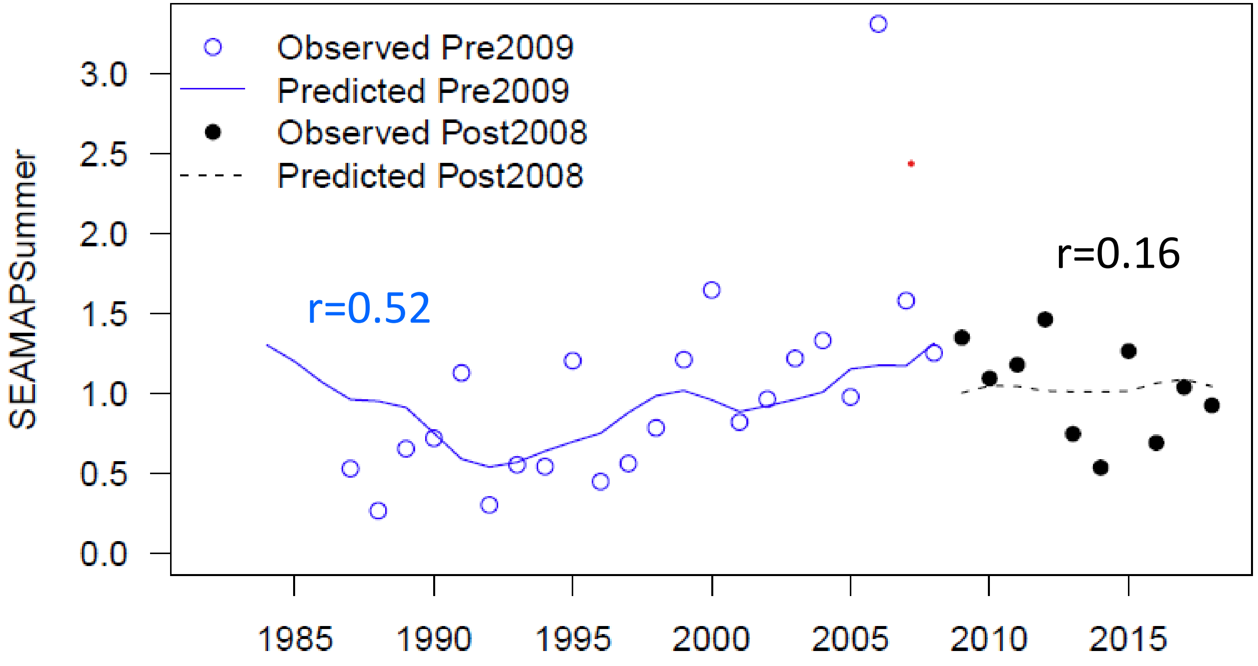
Note that $(I_t - qC_t)$ is proportional to surviving biomass $(B_t - C_t)$

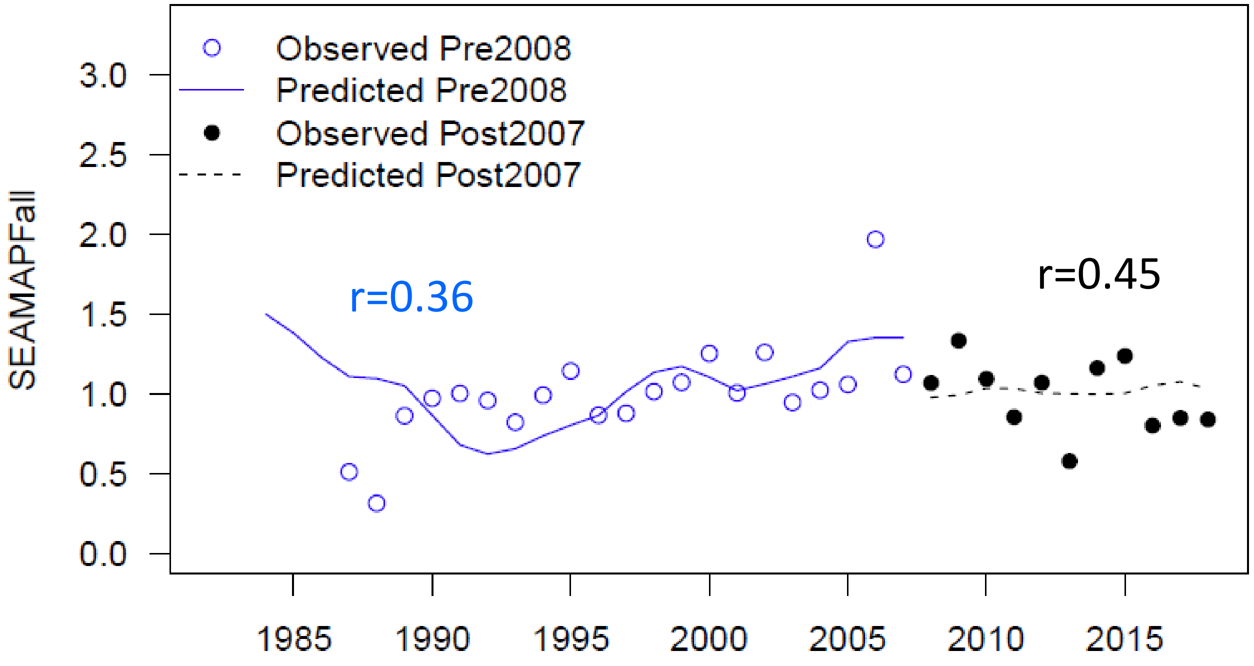
EDM MODEL:

$$I_{t+1} = f(I_t - qC_t, I_{t-1} - qC_{t-1}, ..)$$

Uses $I_t - qC_t$ as proxy for surviving biomass
Estimates q
But does not assume a known production function
Lags allow for unobserved state variables

Production model fit (courtesy of Lew Coggins)





Overall correlation with index ~ 0.4 (in sample)

1-lag EDM model (production model analogue): r ~ 0.3 (out of sample)
4-lag EDM model: r ~0.8

Predicting abundance

Models using SEAMAP and fishery catch data, in general, **outperform** the models including environmental variables (bottom temperature, oxygen, salinity)

Models using SEAMAP and fishery catch data, in general, **perform equally well** with the models including Louisiana recruitment indices.

This **DOES NOT** mean that these other variables are irrelevant! Just means that the information they provide is already contained in the lags of shrimp.

EDM predictions are 2-3x more accurate than production model- because of lags (1-d EDM is about same as production model).

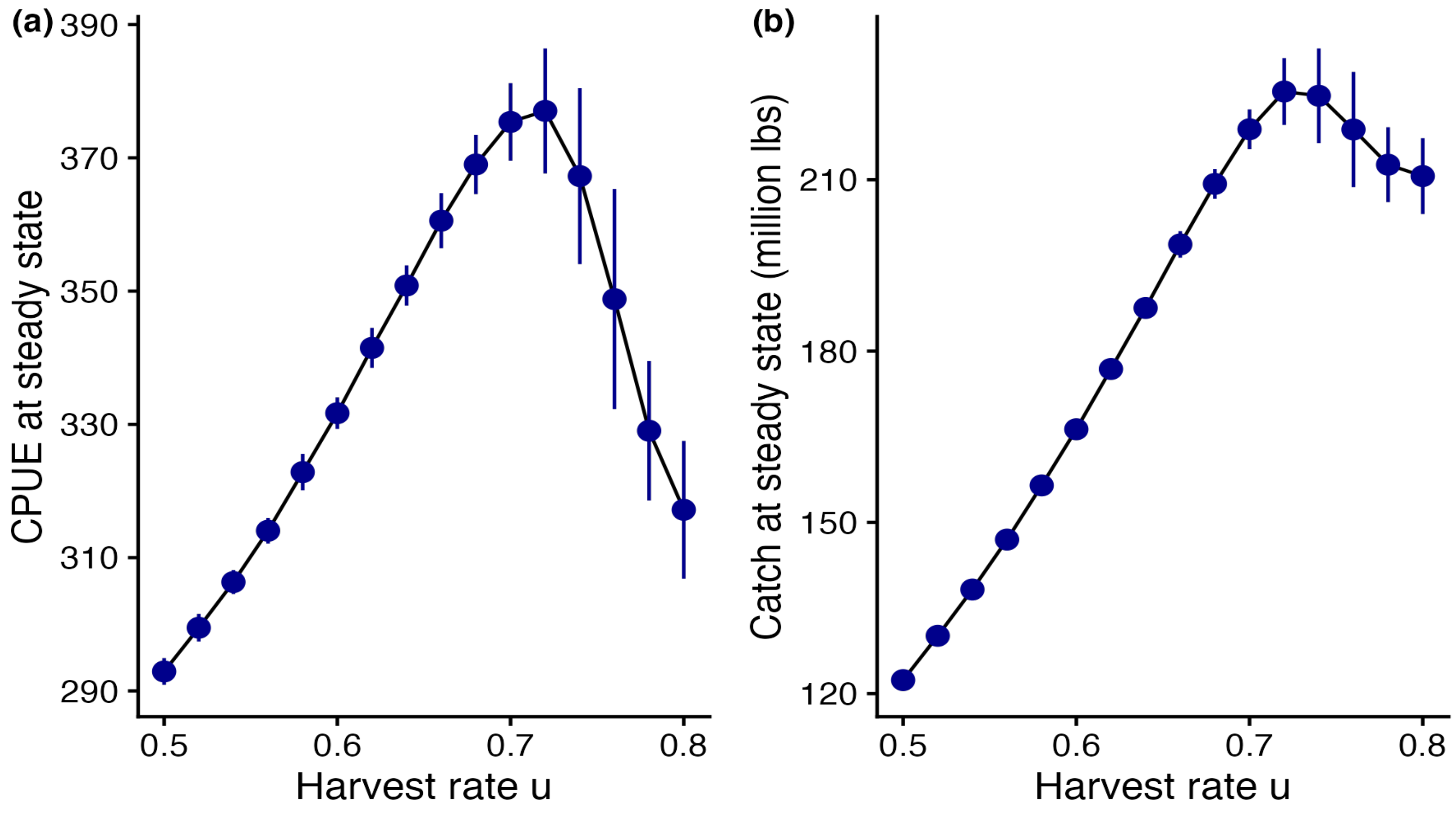
Can do same post-hoc calculations we'd do with a production model (e.g. stock status, etc)-- Use best-fitted EDM to produce benchmarks for constant catch/effort policy.

Exploration of management policies for brown shrimp

Use posterior simulation to explore the performance of different constant catch levels:

1. We use the best-fitted EDM and the same initial condition of the first year of CPUE data to predict forward in time with varied constant catch level.
2. The year-ahead prediction was randomly generated from posterior probability density of best-fitted EDM and iterated for 30 years.
3. Overall N=500 simulations were conducted for each run.

EDM-MSY for brown shrimp



EDM
Umsy ~0.72
MSY ~ 225 million lbs

Production model
Umsy~ 0.9
MSY ~95 million lbs

U: FRACTION of BIOMASS REMOVED (CATCH/BIOMASS)

Summary

Using EDM:

Estimate model of changes in abundance index using catch, SEAMAP

-Prediction accuracy is pretty good (r>0.8)

EDM more closely describes what we see in the data, because of the **lags**

(1-d model & production model are about the same)

Use fitted function to determine MSY / BMSY / UMSY

…Could also estimate current biomass (and stock status)

$I_t = qB_t$ -> $B_t = I_t/q$

Can also evaluate other harvest control rules (e.g. hockey stick, etc)

Summary Workshop Meeting Objectives

- Brief meeting participants on Shrimp Fishery Management Plan and stock assessment requirements.

- Brief meeting participants on Gulf of Mexico Shrimp SEDAR research track assessment planning.

Shrimp SEDAR Research Track Assessment Planning

- Two meetings including SEFSC, SEDAR, SERO and SSC Chair
  - Identify Data Providers – *done*
  - Potential SEDAR Participants by Stage – *in progress*
    - Work with Council and SERO to appoint – *in progress*
  - Construct a conceptual model along with the data provision and review
  - Data Scoping, Beginning July 2023
  - Stage 2- Data Workshop, September 2023
    - Format and content of data workshops (multiple species considerations)

Questions?

NOAA FISHERIES