Beyond point measurements: Modeling benthic forage response to hypoxia, temperature and nutrient conditions in Chesapeake Bay

Final Project Summary for regional management and agency stakeholders

Maryland Sea Grant-funded project
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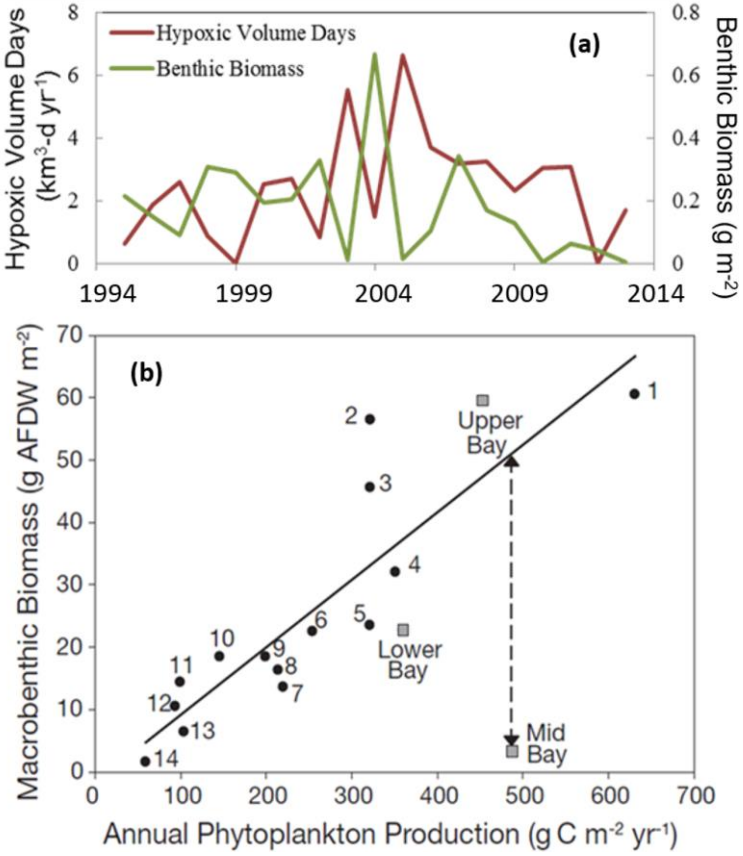
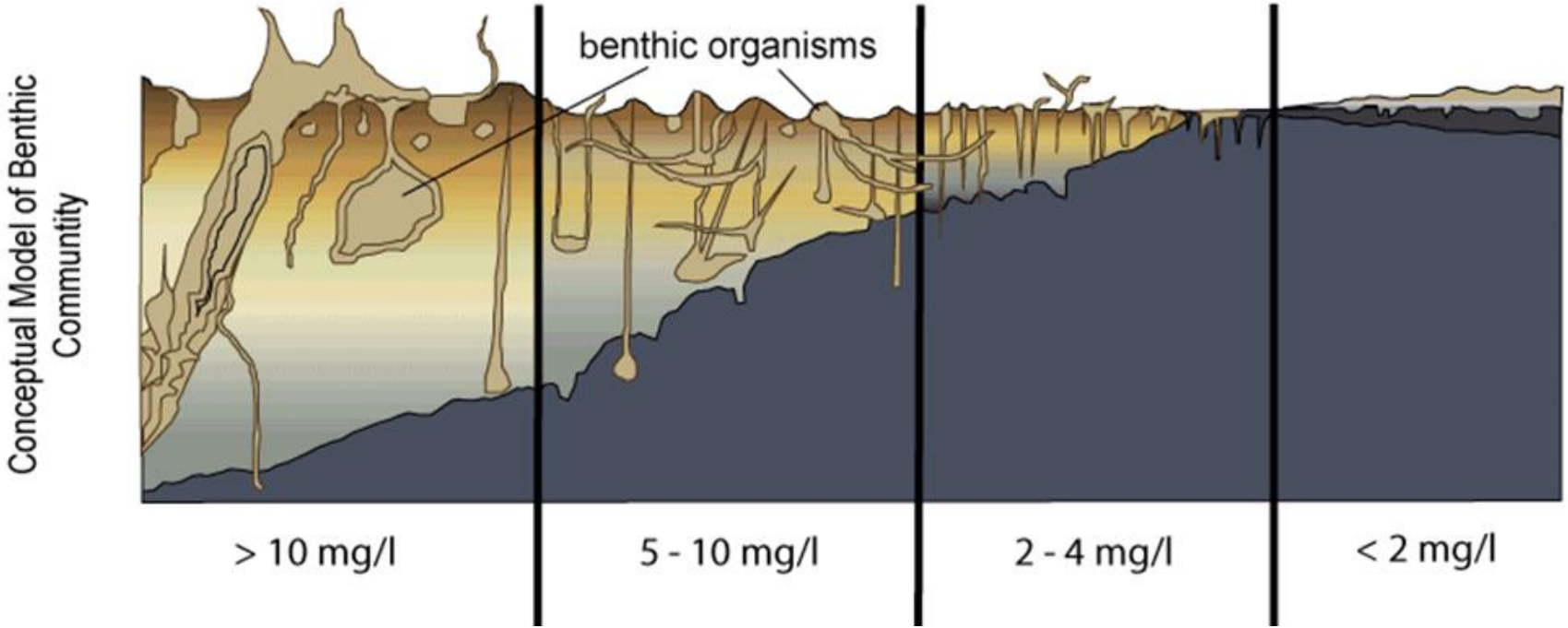
Section 1 - Introduction to the project and rationale

- Hypoxia a recurring condition in Chesapeake Bay
- Clear, negative effect of hypoxia on living resources at large scales
- Response of living resources to smaller or event-scale hypoxia difficult to predict
  - Biotic responses (In/Direct, Sub/Lethal)
  - Spatial/temporal scale of monitoring data
  - Potential for ecological trade-offs

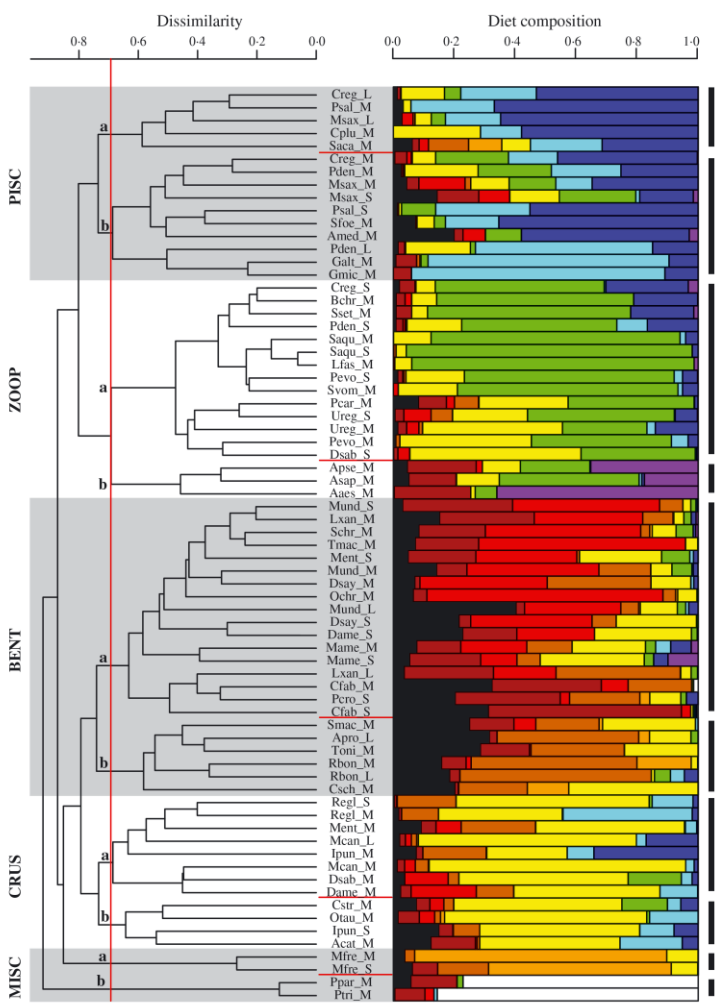


Benthos and hypoxia



Benthos in Chesapeake Bay's food web

- Benthos a key component of predatory fish
- >95% of diet of some fisheries species
- Tidal fresh to polyhaline habitats



groupings (■, miscellaneous; ■, unidentified; ■, Polychaeta; ■, Bivalvia; ■, Gastropoda; ■, Crustacea; ■, Mysida; ■, Teleost-demersal; ■, Teleost-pelagic; ■, Copepoda; □, Scyphozoa), with prey organized along a benthic to pelagic gradient.

Buchheister and Latour 2015

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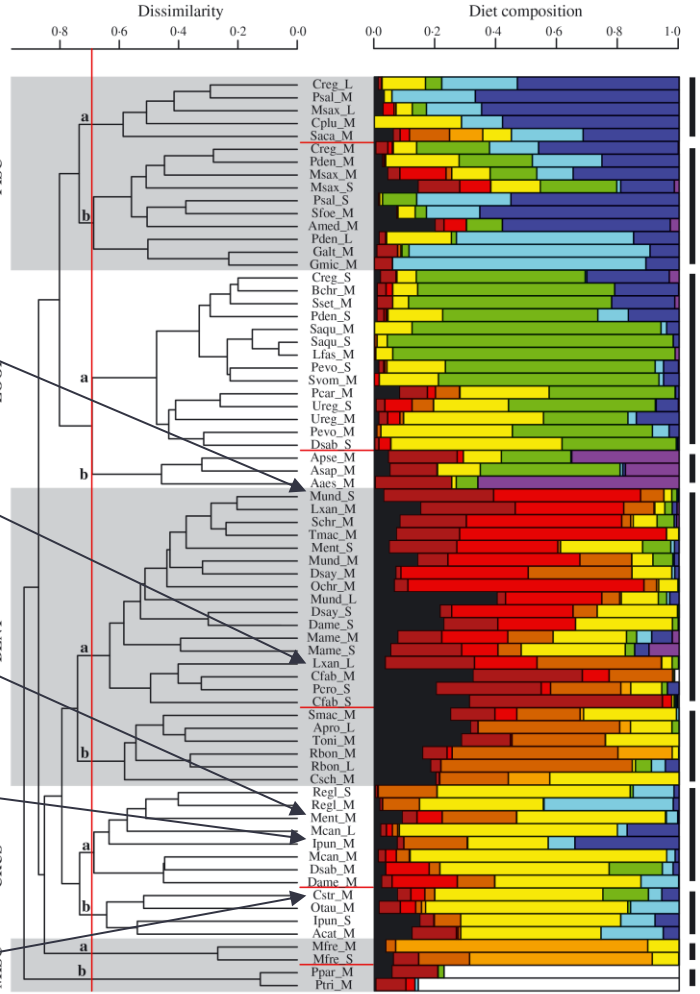

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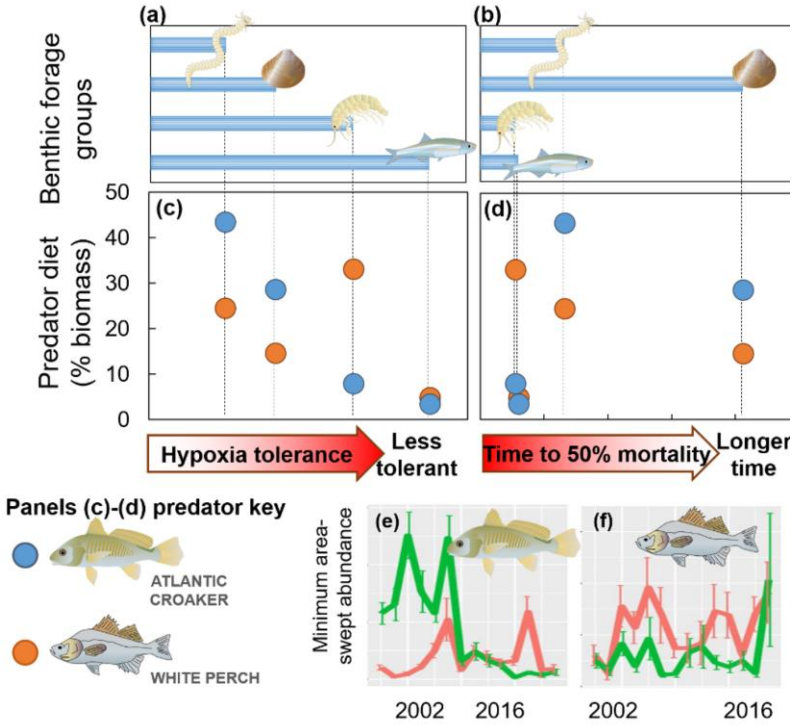
Section 1 - Introduction to the project and rationale

Project Scope

Central hypothesis: *The intensity, duration and spatial extent of hypoxia will have measurable effects on the benthic community*

Objectives

1. Construct a statistical network model to understand spatial & temporal propagation of low DO waters
2. Develop hybrid numerical-statistical model to study response of benthic groups to current & recent hypoxia, and primary production
3. Conduct scenario forecasting of different nutrient, flow and temperature conditions on benthos



Section 1 - Introduction to the project and rationale

Integrating model-based and empirical data

- Chesapeake Bay hydrodynamic water quality model (ROMS-RCA)
- Chesapeake Bay Program's Long-term Benthic Monitoring Survey

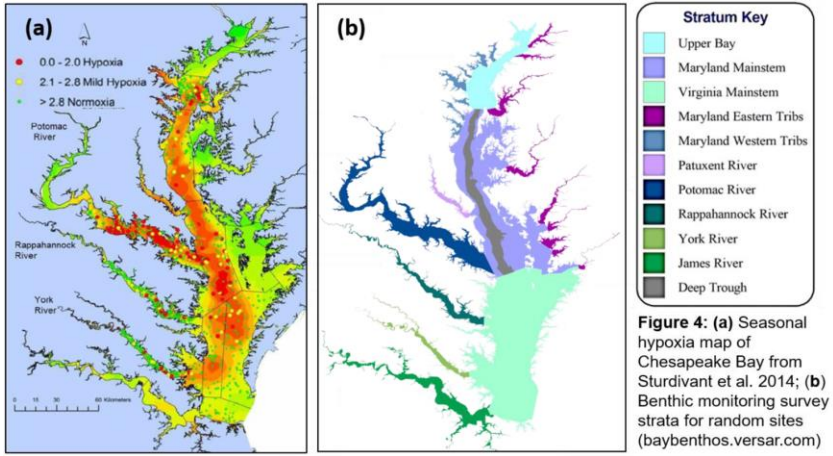


Figure 4: (a) Seasonal hypoxia map of Chesapeake Bay from Sturdivant et al. 2014; **(b)** Benthic monitoring survey strata for random sites (baybenthos.versar.com)

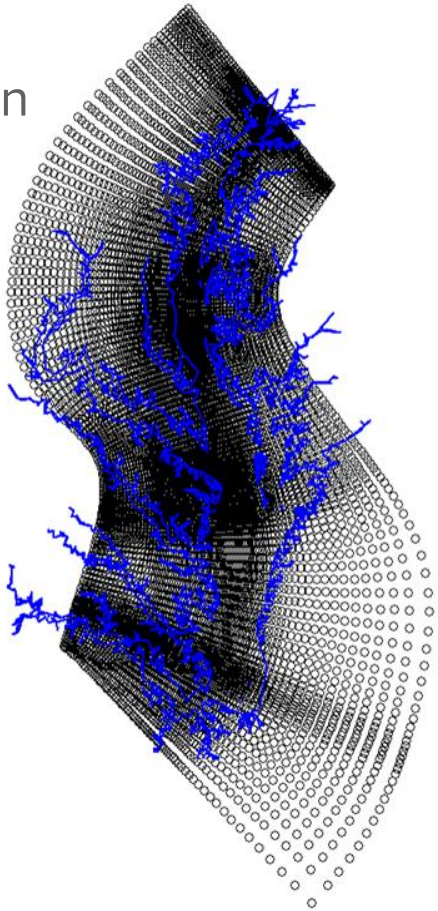
- Project provides a modeling framework for investigating hypoxia dynamics and the effects of hypoxia and primary production on benthic communities
  - Leverages established model and benthic survey dataset
  - Flexible design (e.g., taxonomic resolution, scenario testing)

Section 2

ROMS-RCA Benthos Neural Network Model

Development of spatial network of hypoxia dynamics

Step 1: Time series of oxygen concentrations for grid cells covering the bay

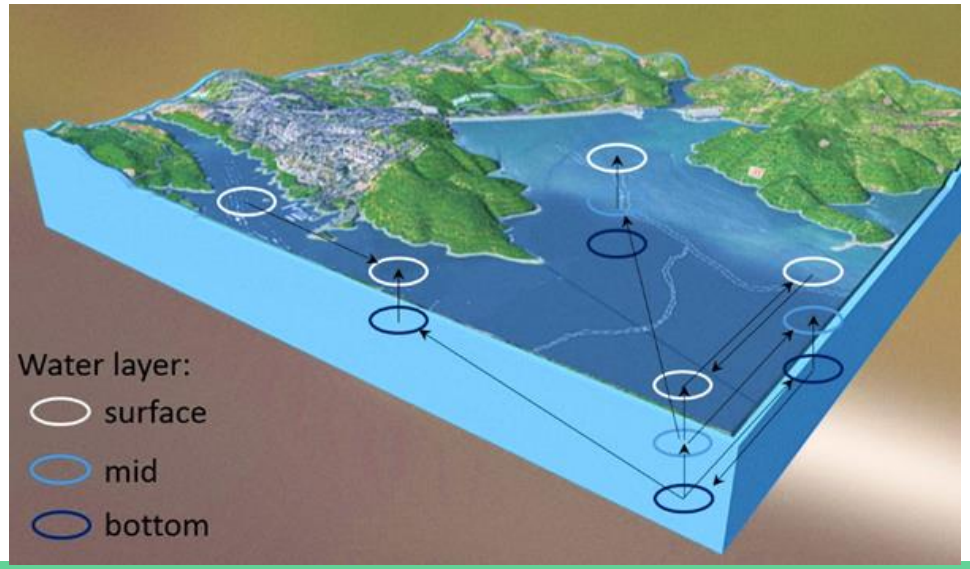


Step 2: Test pairwise predictive relationships to identify connections

$$DO[A, t] \sim DO[A, t - p] + DO[B, t - p]$$

vs.

$$DO[A, t] \sim DO[A, t - p]$$

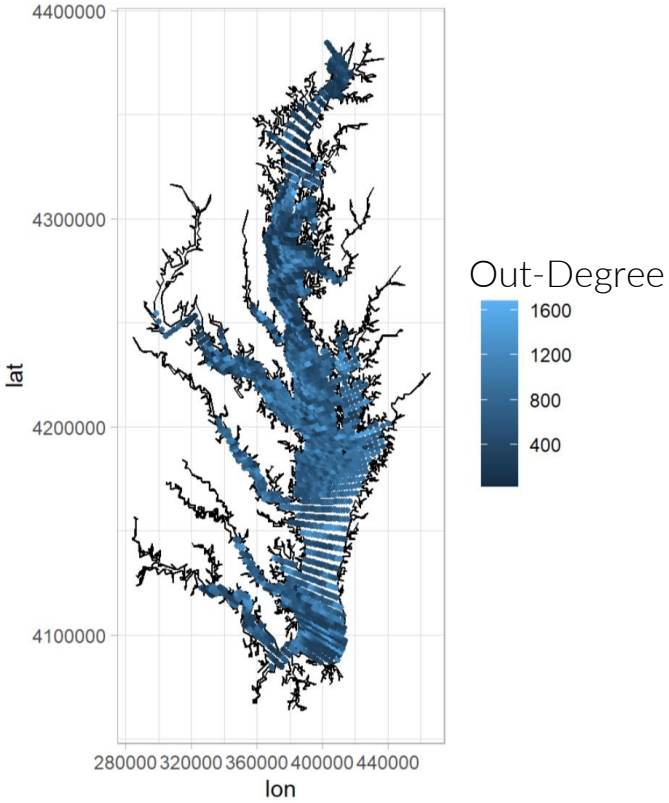


HyNet

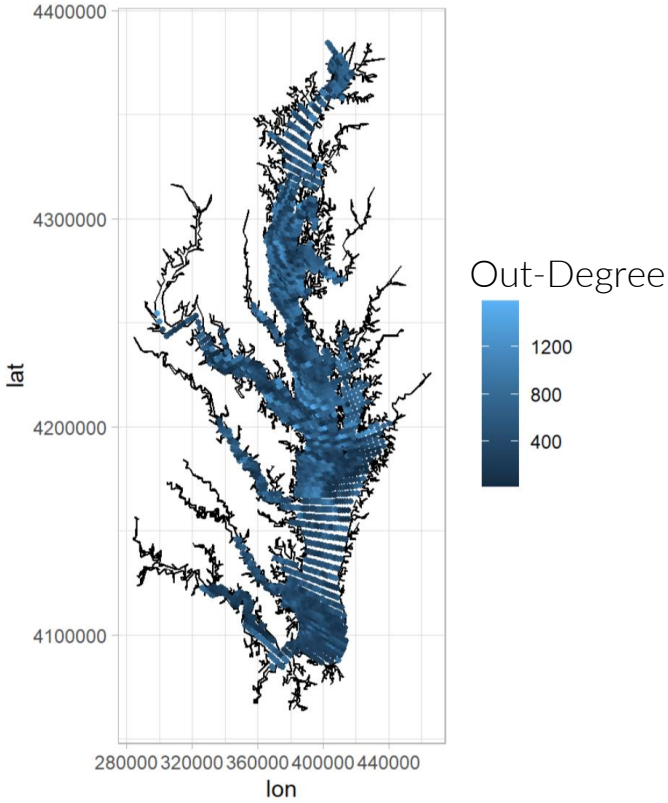
Hypoxia Network

Out-Degree = Number of other locations predicted

Good Year
2002



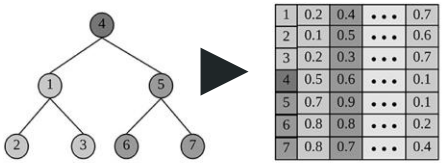
Bad Year
2011



Hybrid statistical-numerical model

Fundamentally a regression model:

Biomass of a benthic invertebrate = latitude + longitude + date + } Location



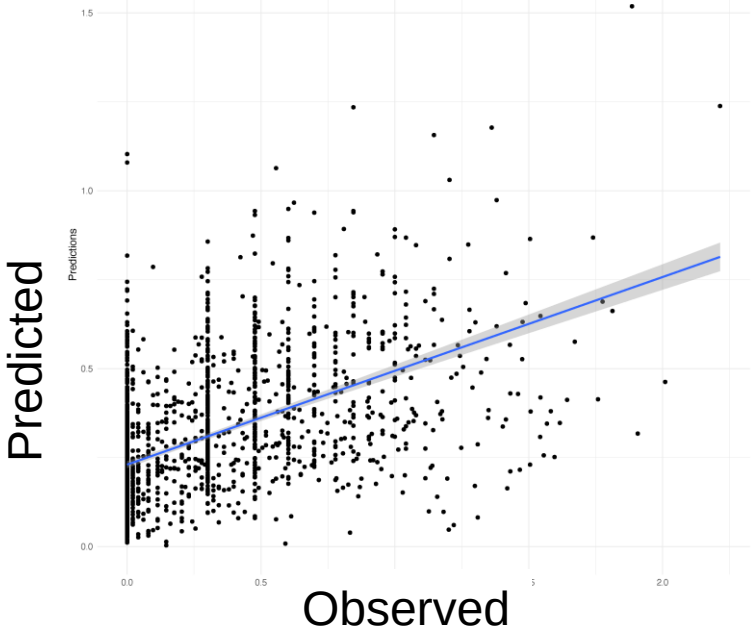
DO embedding dimension 1 +
DO embedding dimension 2 +
DO embedding dimension 3 + } HyNet

temperature +
salinity +
chlorophyll a } ROMS-RCA hydrodynamic water quality model output

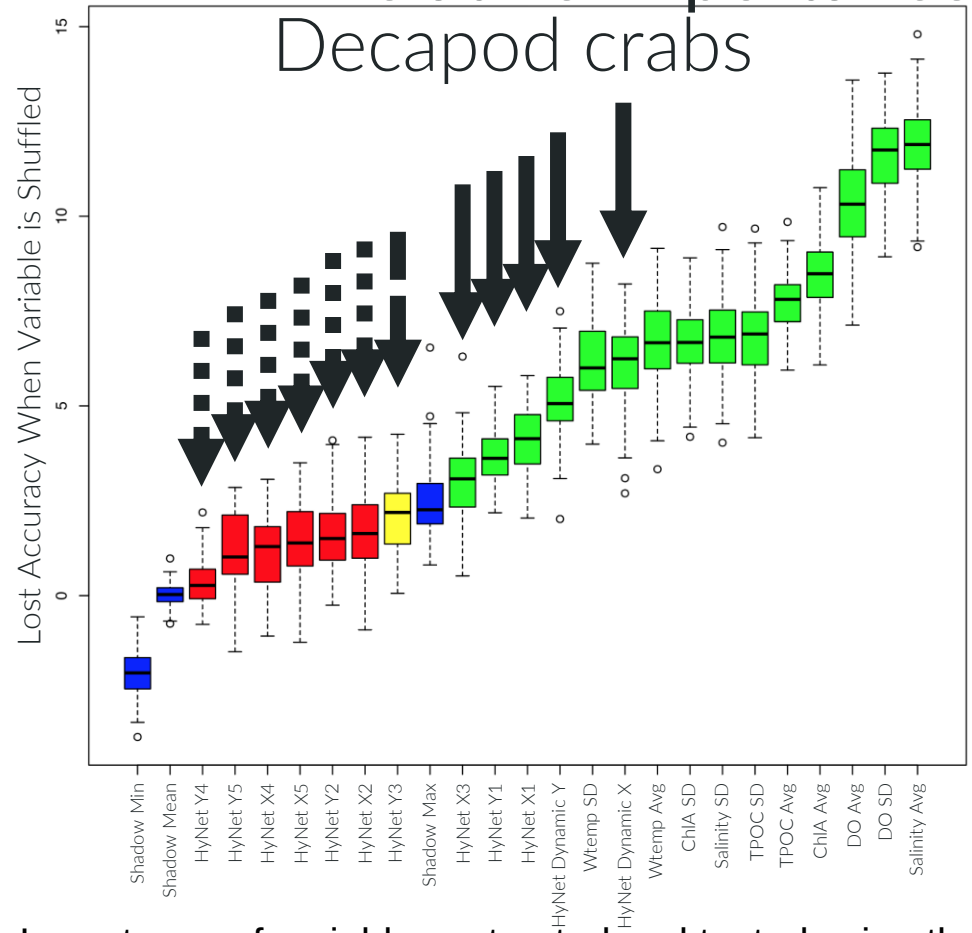
Hybrid statistical-numerical model

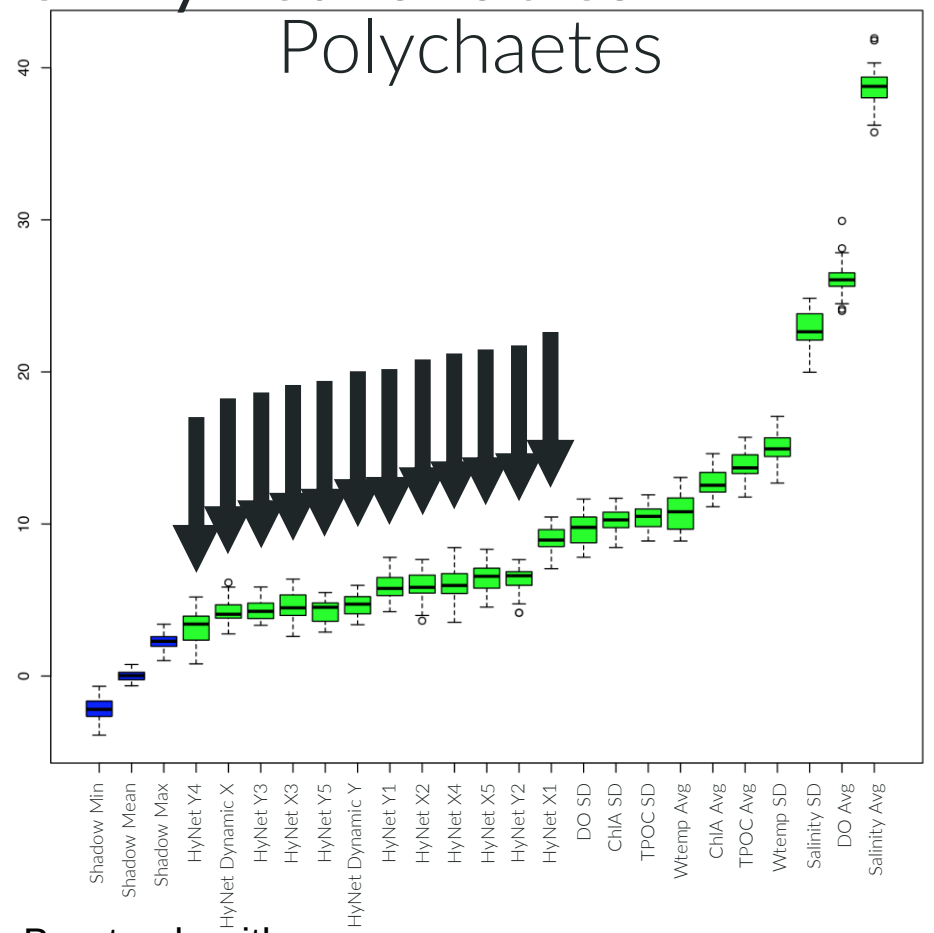
We are using: Random forest (e.g. amphipods), R^2 = 0.26 for **out-of-bag predictions**

The range of R^2 is ~ 0.1 to 0.3 for out-of-bag predictions across all the benthic groups.



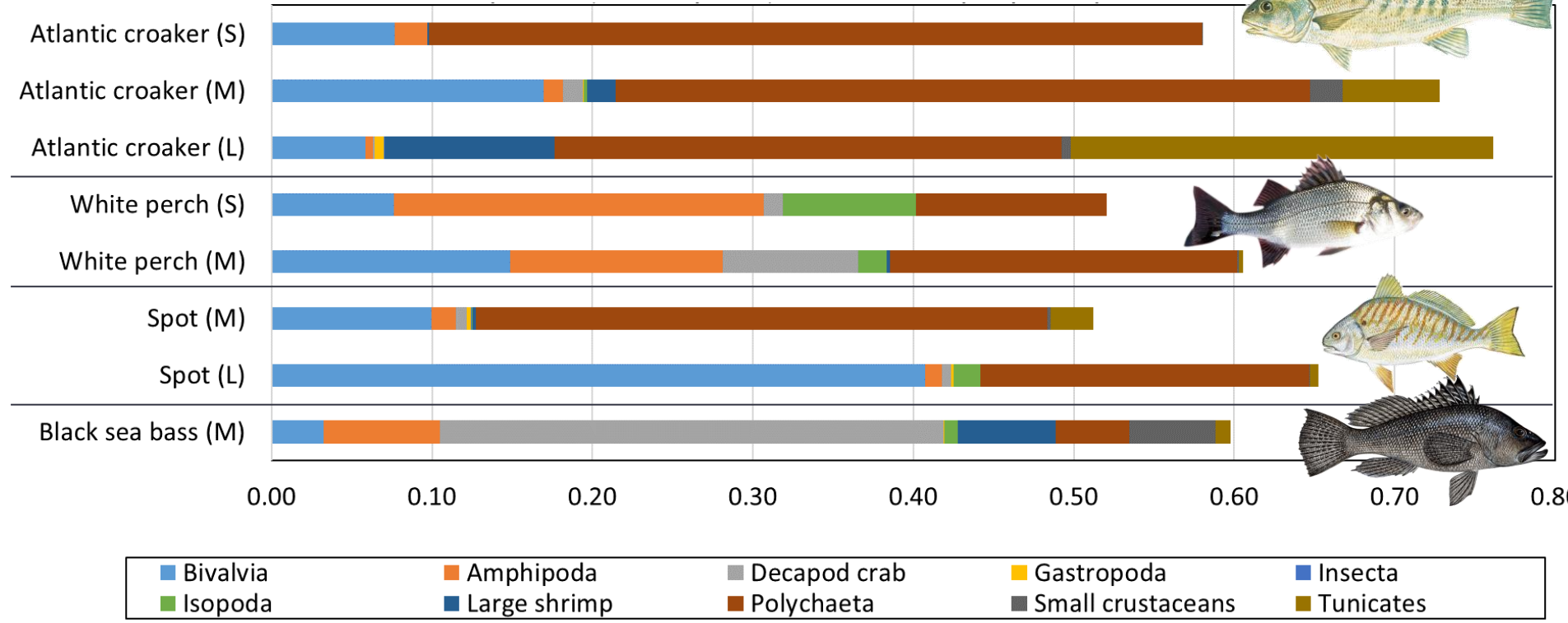
Relative importance of HyNet variables





Importance of variables extracted and tested using the Boruta algorithm

Ongoing work – Benthic forage portfolios*

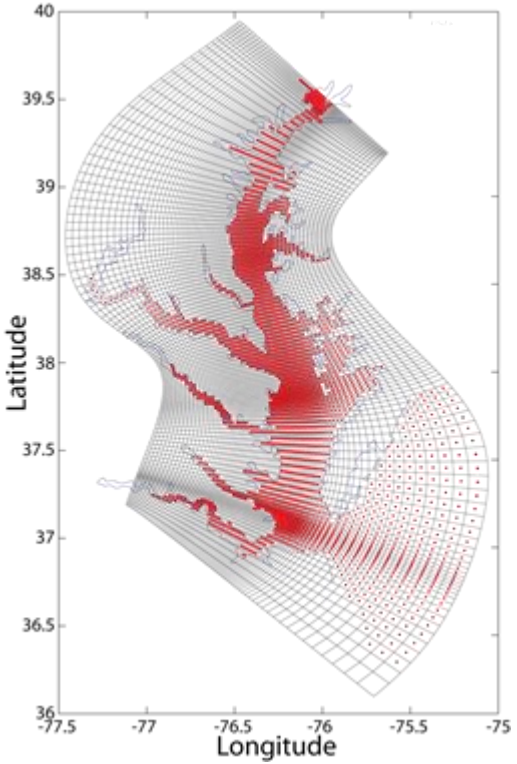


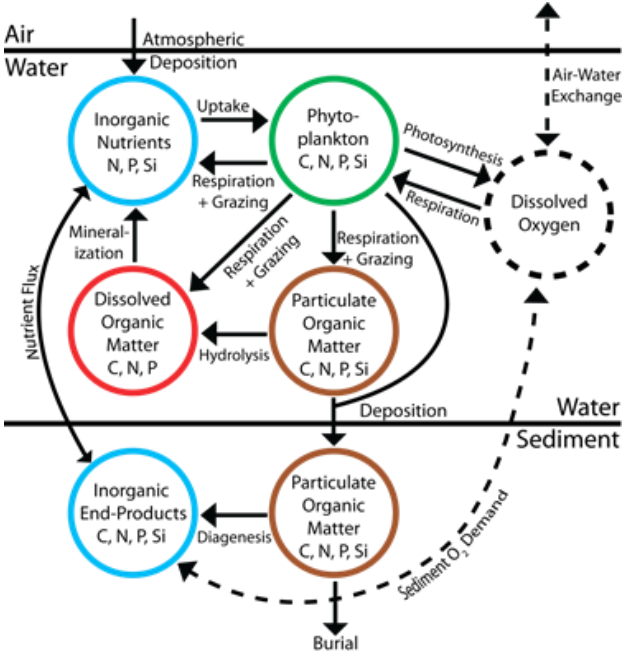
** Proportion of diet items that align with modeled groups of benthic organisms (diet comp from Buchheister and Latour, 2015)*

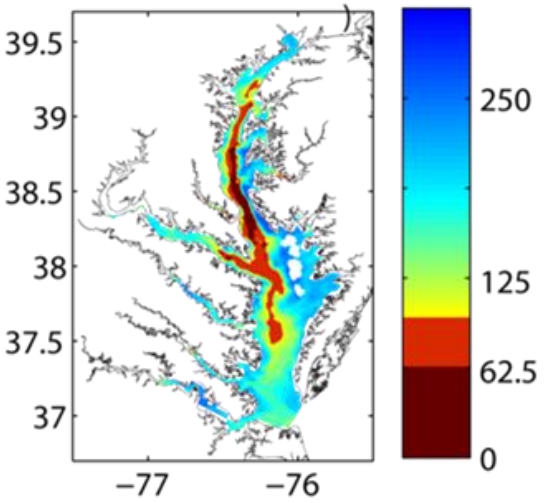
Section 4

Scenario Testing & Forecasting

Section 4 - ROMS-RCA-CC Modeling System







Model simulates organic and inorganic C, N, P, oxygen, carbonate chemistry, T/S

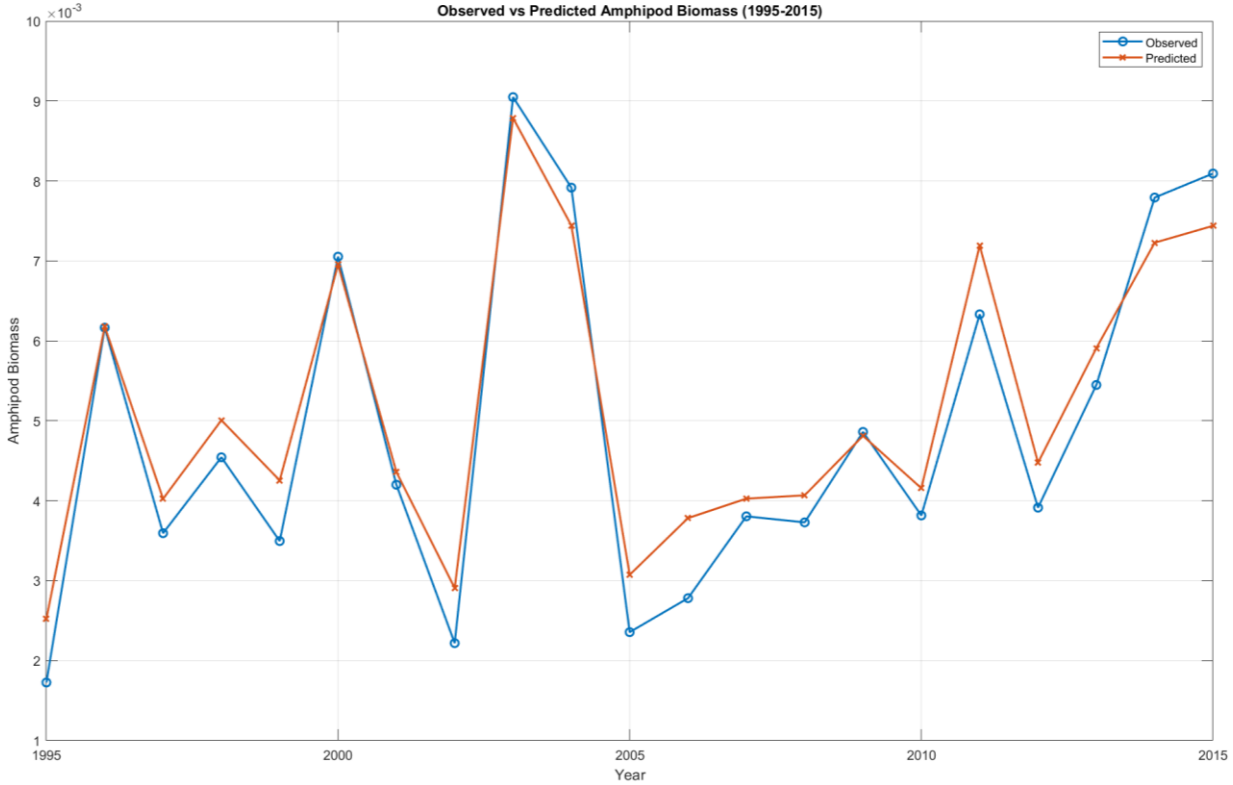
There are ~10 comparable models for the Bay, so potentially wide application of hypoxia-benthos model

Two Types of Benthic Response “Models”

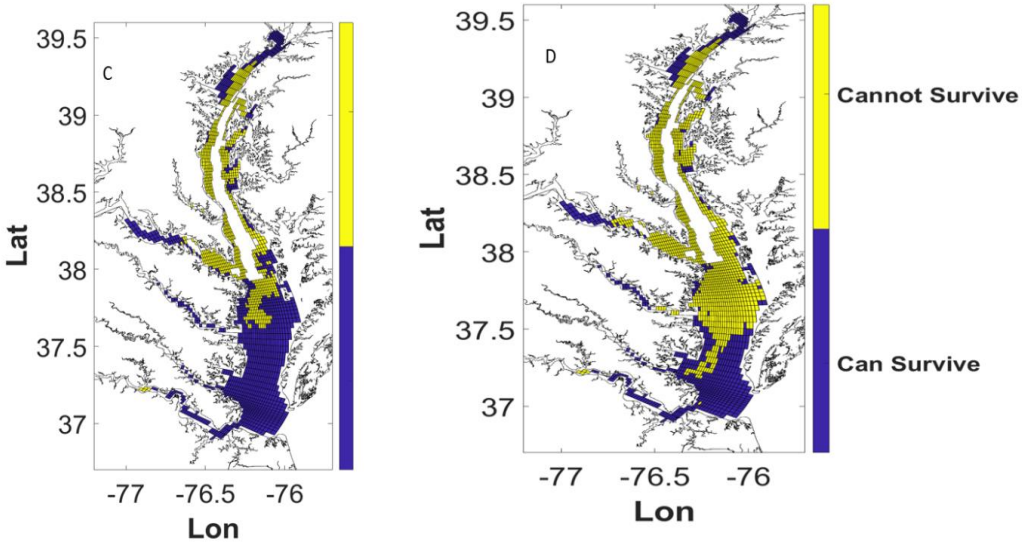
- (1) Habitat vulnerability to threshold levels of hypoxia
  - Based on literature values for survival
  - Only oxygen based

- (2) Random Forest Models
  - Based on multivariate model with network embeddings
  - Includes oxygen, salinity, temperature, food

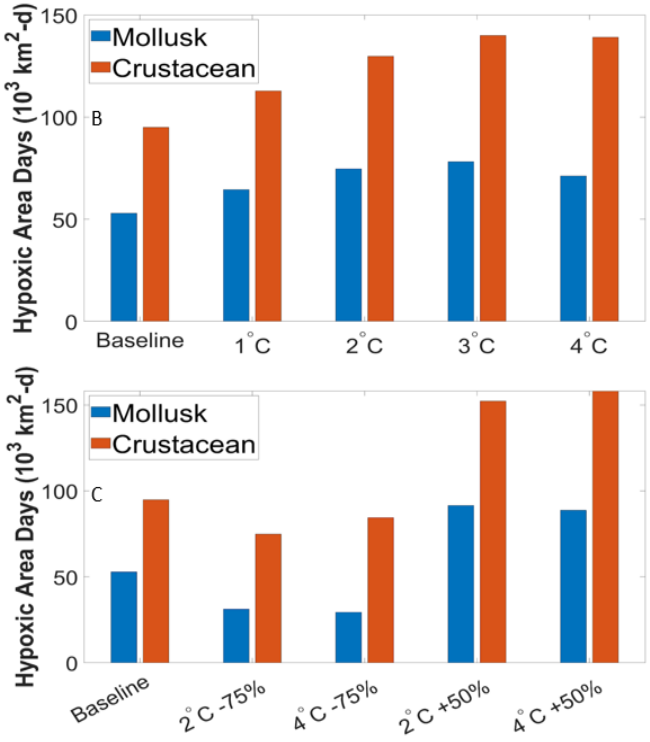
Section 4 - Hindcast Simulations



Section 4 – Sensitivity Simulations

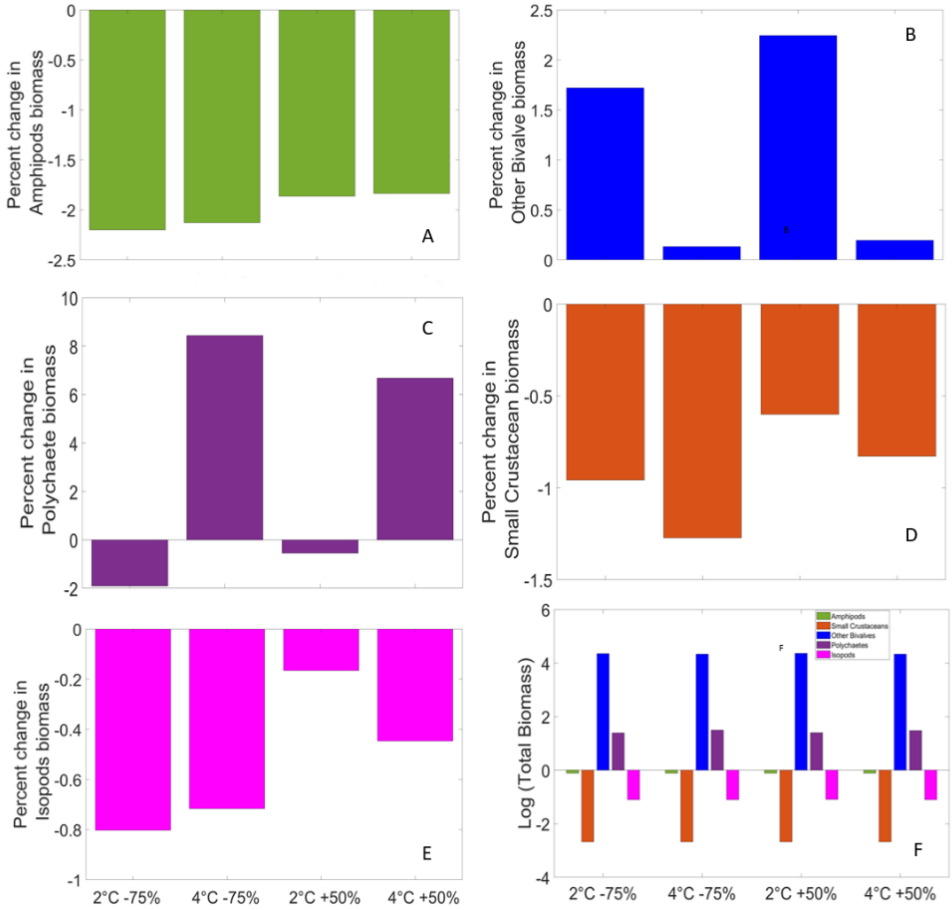


(left) Areas that crossed Crustacean's lethal threshold during Summer with a 2°C warming, 75% nutrient reduction (right) Areas that crossed Crustacean's lethal threshold during Summer with a 4°C warming, 50% nutrient increase



Changes in areas of hypoxic conditions that would cause mortality for mollusks and crustaceans across warming (top) and wamring+load change scenarios

Section 4 - Sensitivity Simulations



Conclusions

- HYNET: The strongest correlations (about -0.38) between the average annual hypoxic volume and the network density suggest that hypoxic conditions may lead to fragmentation of the bay waters
- HYNET: High out-degrees can show that a given location can be used to predict oxygen concentrations at many other locations
- Random Forest: We can model most benthic invertebrate groups, incorporate changes into feeding portfolios
- Synthesis: Nutrient load reductions outweigh 2-4 degree warming
- Synthesis: Wide range of sensitivities of key benthic organisms to load reductions and warming

Extra Slides

Hypoxia network information

1. Analyze topology of the network to identify:
   - Most influential locations with high connectivity to many other grid cells – valuable for monitoring since they give predictive capabilities
   - Clusters of cells and isolated cells – the isolated network nodes (not connected with predictive links to other nodes) might require additional water monitoring if hypoxia at those locations is possible

2. Encode the complex network information in a few abstract dimensions (via embedding) representing for each node the information from its neighborhood

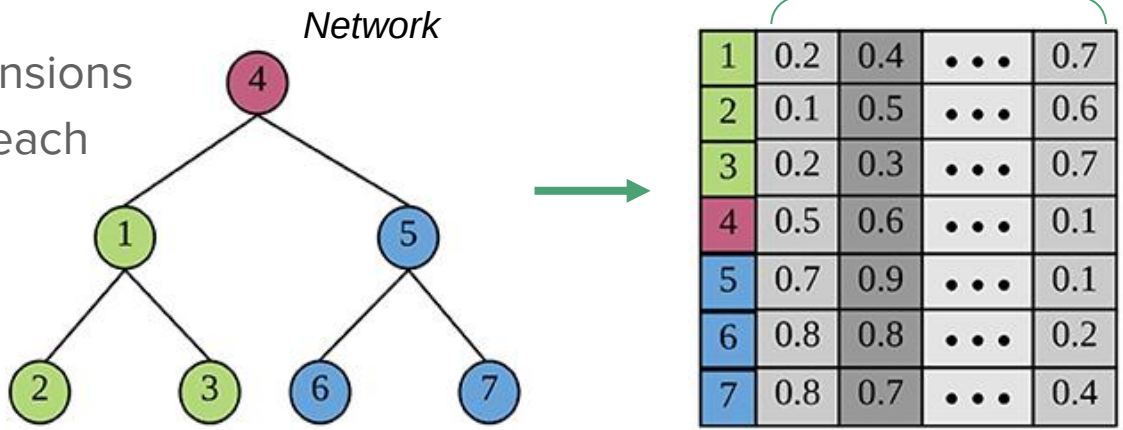
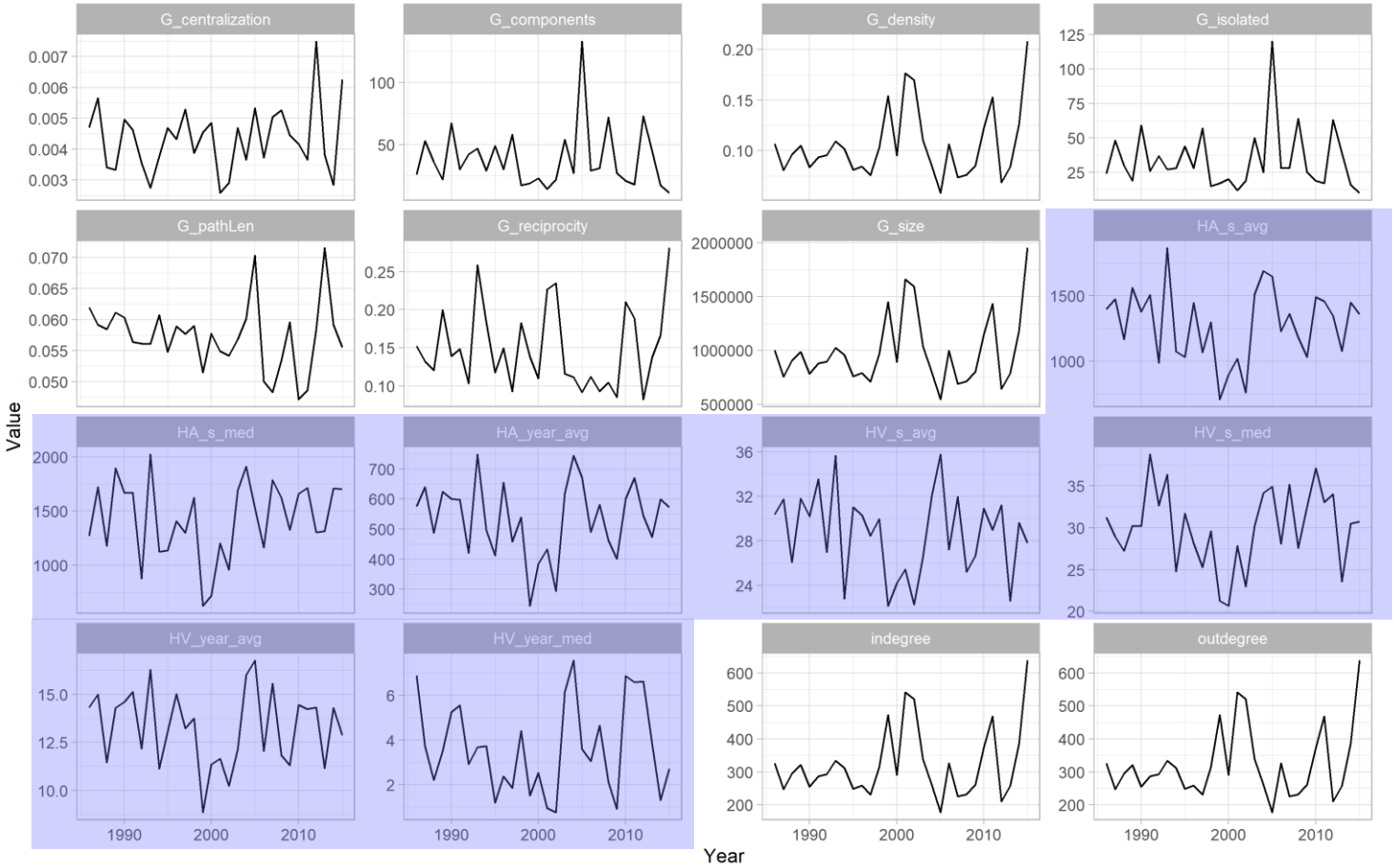
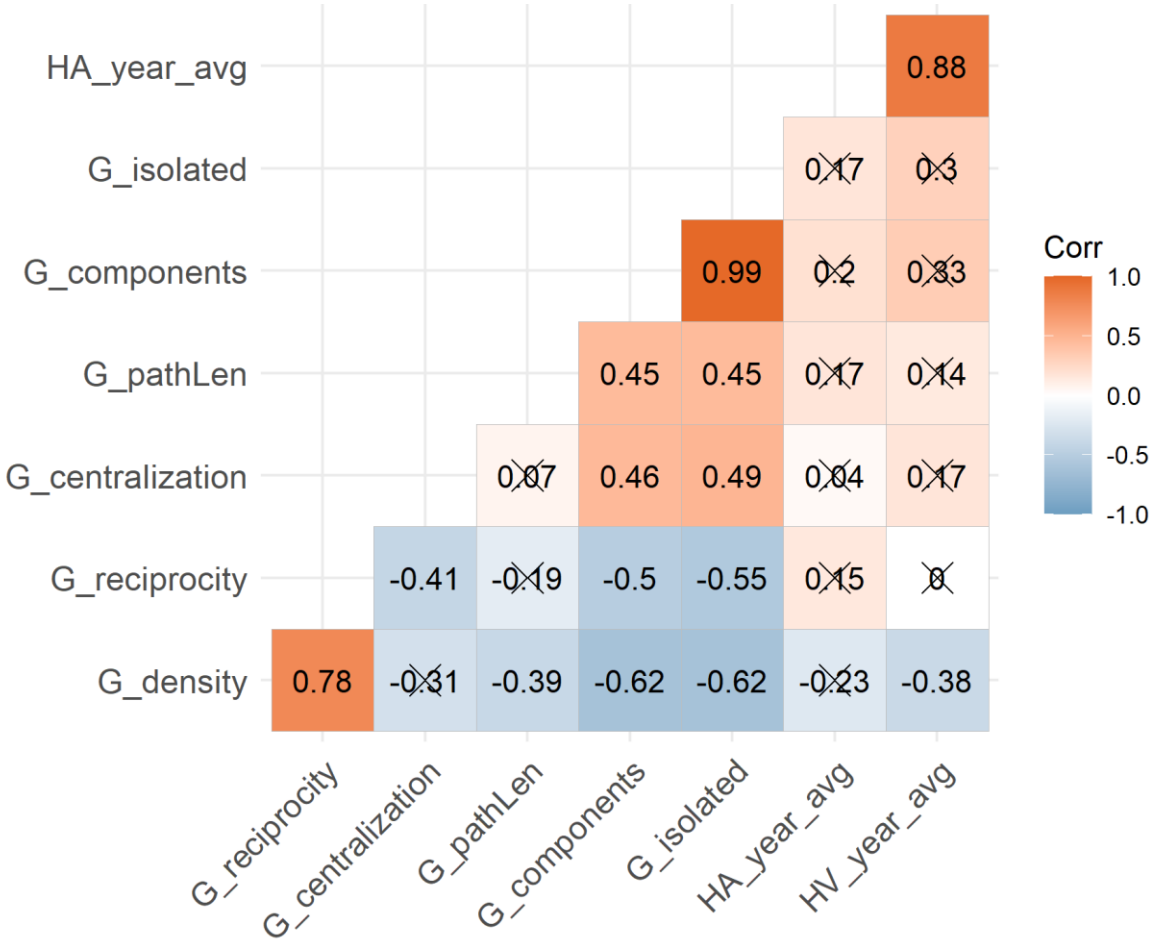


Image adapted from https://doi.org/10.3389/fdata.2019.00002

Dynamics of network statistics (white) and hypoxia (blue)



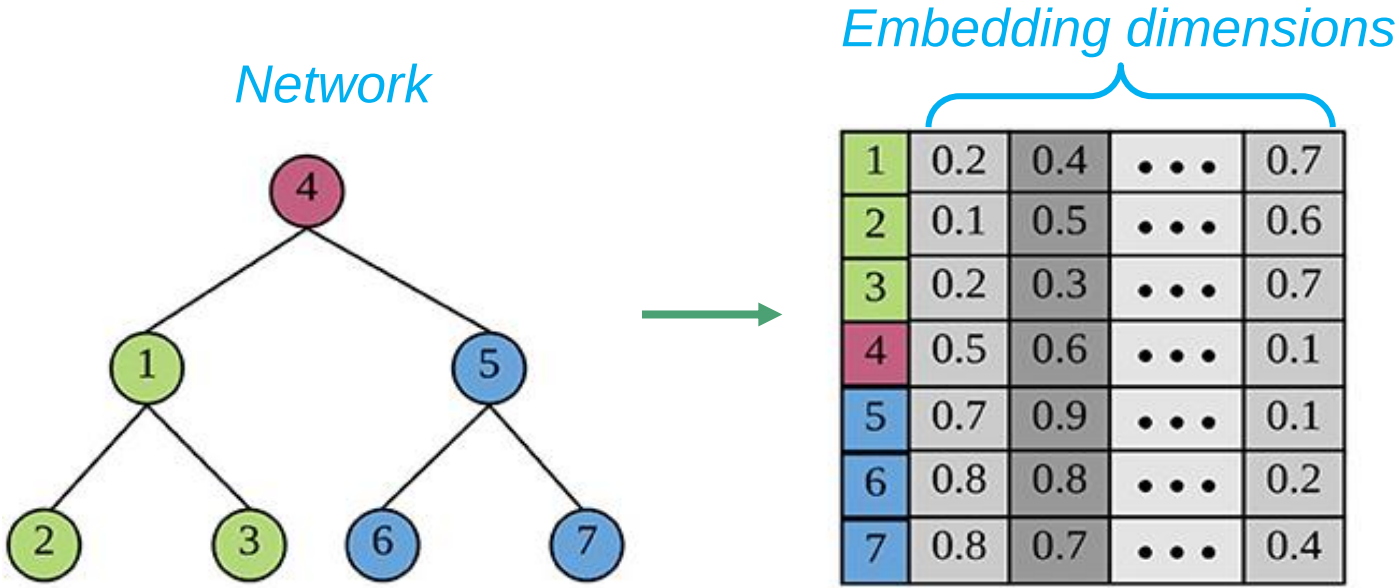
Correlations



Hypoxia network embedding

Encode the complex network information in a few abstract dimensions (via embedding) representing for each node the information from its neighborhood

- Singular value decomposition
- Back-tracing incomung edges of each node and averaging deseasonalized oxygen



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Benthic prey portfolio analysis - ongoing

- Preliminary modeling suggests % increases in benthic prey portfolio under 2 °C warming conditions