Hypoxia effects on fish populations: model predictions under fixed vs. dynamic oxygen environments

Sean Creekmore, Kenneth Rose, Lixia Wang, Dubravko Justic
Department of Oceanography and Coastal Sciences
Louisiana State University

Peter Thomas and Md. Saydur Rahman
Marine Science Institute
University of Texas

J. Kevin Craig
Southeast Fisheries Science Center
National Marine Fisheries Service

Rachael Miller-Neilan
Department of Mathematics and Computer Science
Duquesne University

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NCCOS
NOAA's NCCOS, Center for Sponsored Coastal Ocean Research

Does hypoxia have population level effects on coastal fish?

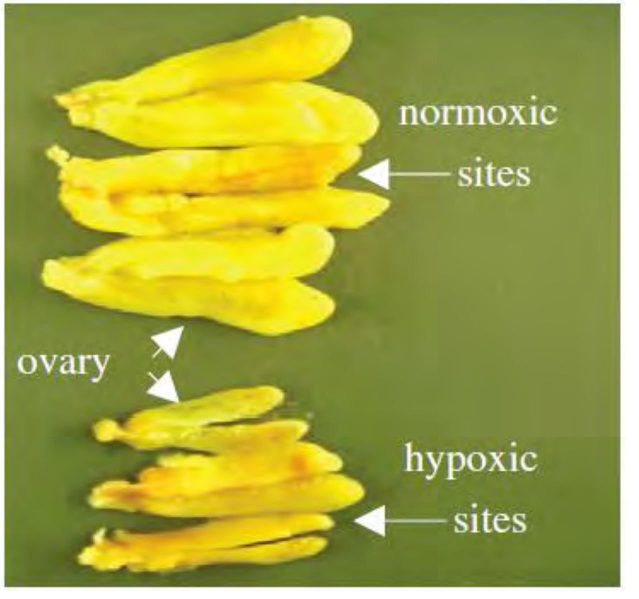
- Surprisingly little conclusive evidence for population level effects

- Multiple stressors, high variability, and compensatory mechanisms make detecting the effects of hypoxia difficult

- Need for population studies that quantify exposure and separate hypoxia effects from other stressors

What are the long-term effects of hypoxia on Atlantic croaker in the NWGOM?

- Croaker good test case
  - Well studied
  - Mobile, demersal
  - Tolerant to hypoxia
  - Fecundity affected by hypoxia



Thomas & Rahman 2012

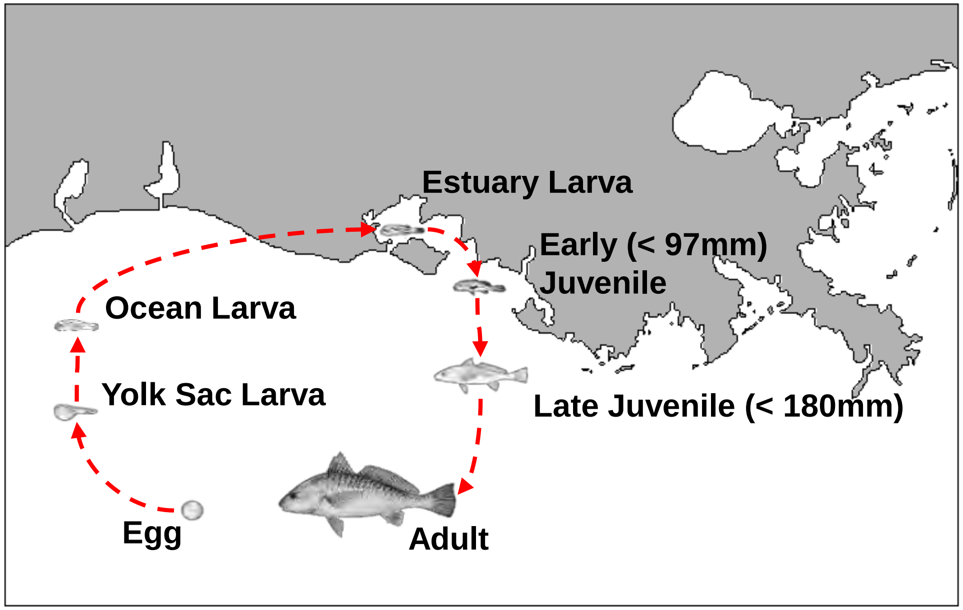
Quantifying Exposure and Determining Effects

- Approach: Individual-based population model
  - Exposure determined by movement
  - Effects determined by exposure and applied to growth, mortality, and reproduction

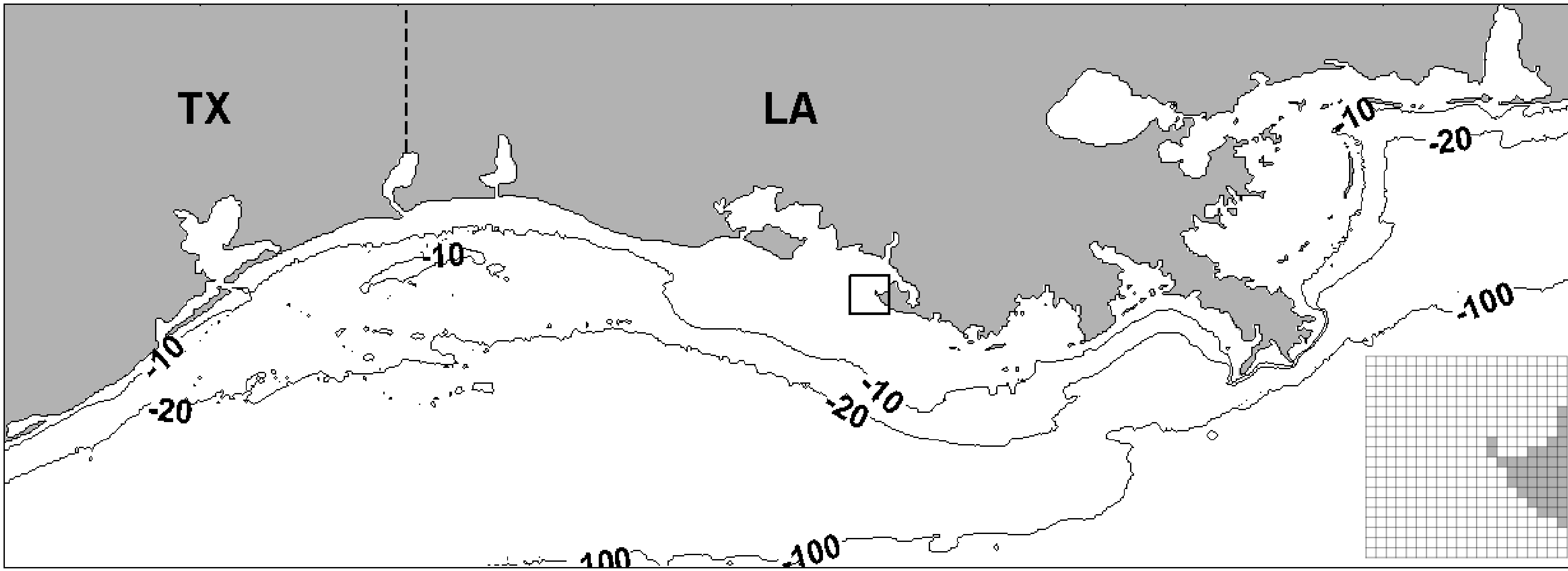
- Strategy:
  - Keep most things constant
  - No food web interactions

Model Overview

- Spatially explicit, IBM
  - Follows 7 stages to age 8
  - September 1 birthday
  - Model year begins Sept. 1
  - Each year 365 days long
- Hourly processes
  - Growth
  - Mortality
  - Reproduction
  - Movement
- Environmental conditions simulated on a 2-D spatial grid
  - Climatological temperature
  - Climatological surface Chl-a
  - Dissolved oxygen

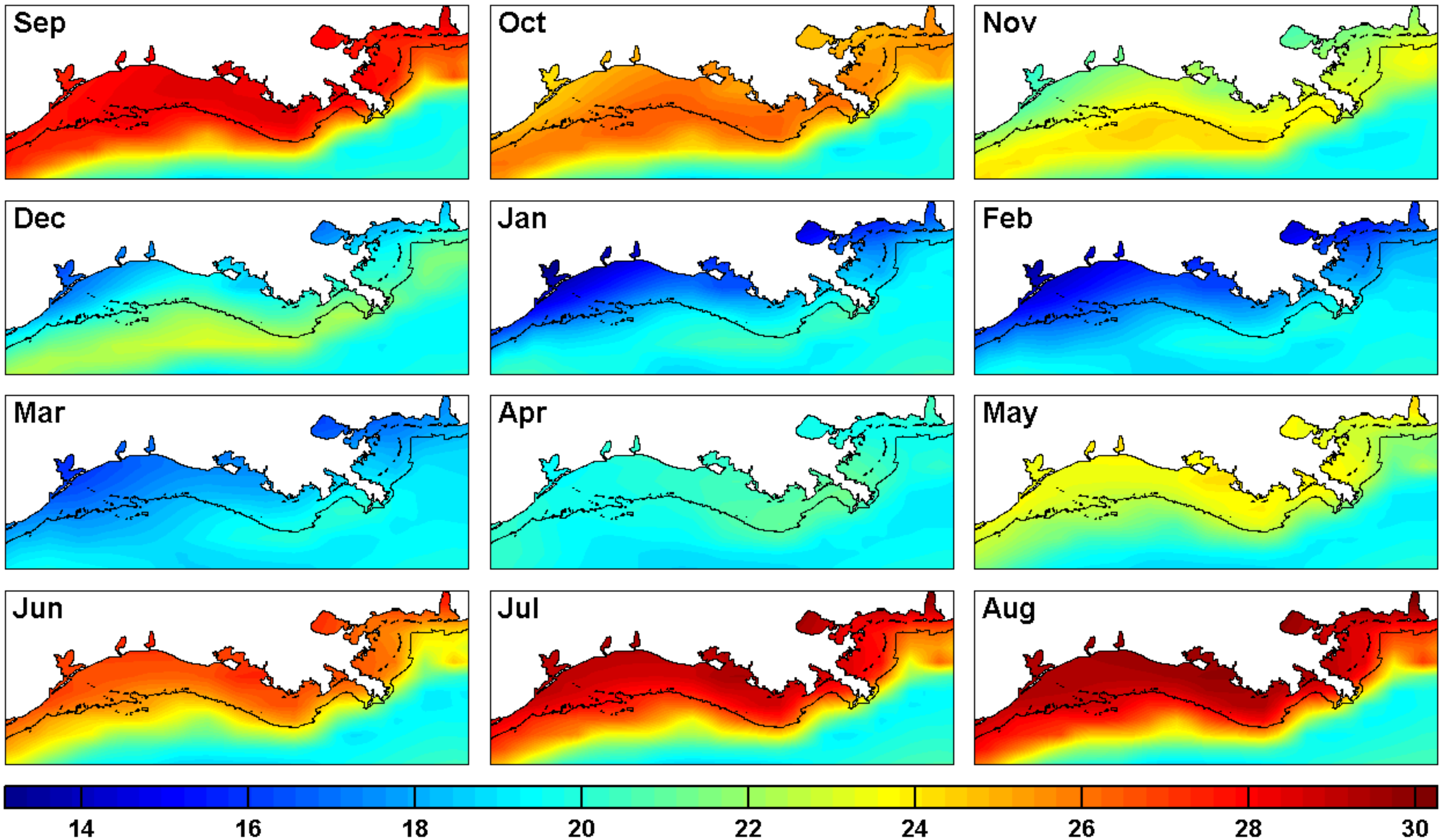


Model Grid



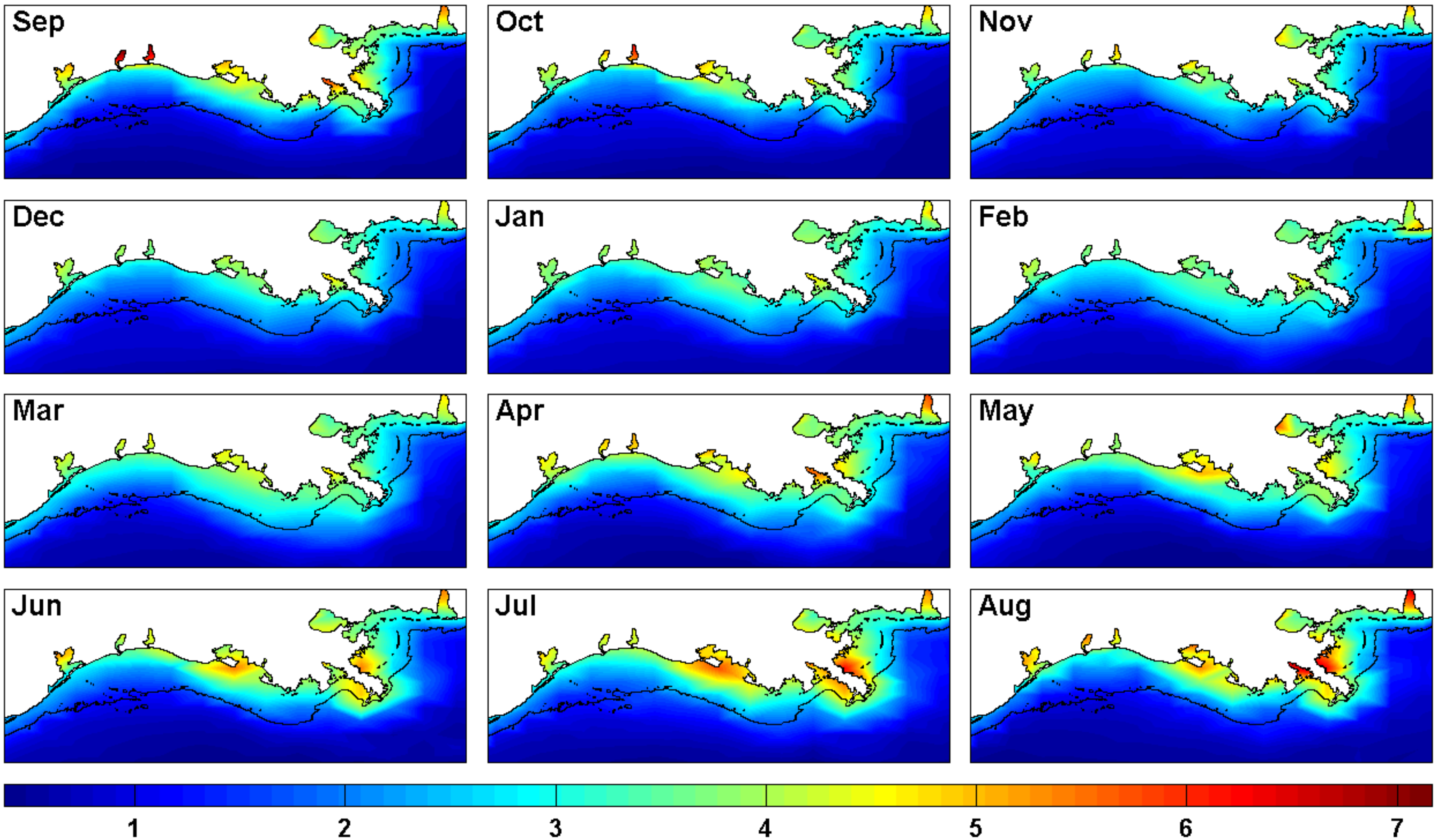
- Idealized 300 x 800 cell grid (1 km resolution)
- Bottom elevation for each cell is truncated beyond 100 m

Environmental Variables: Temperature



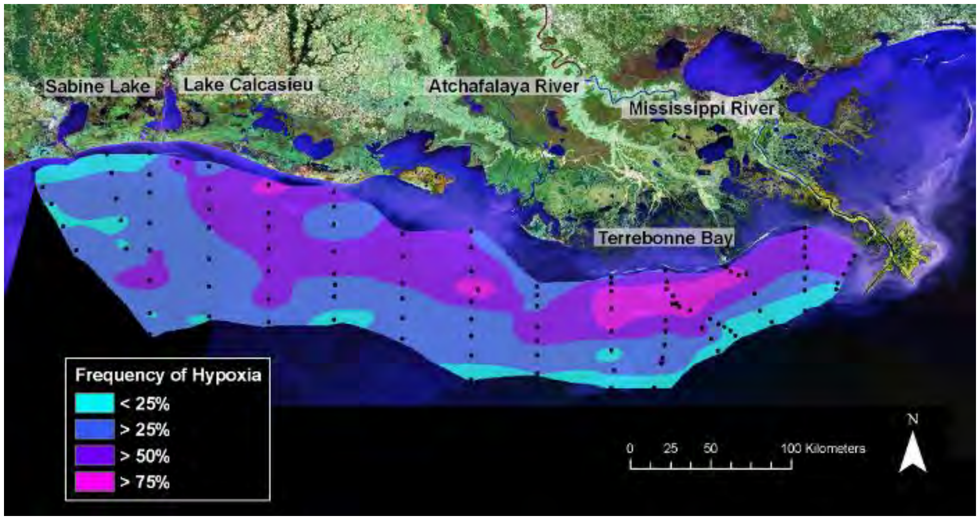
Environmental Variables: Chlorophyll-a

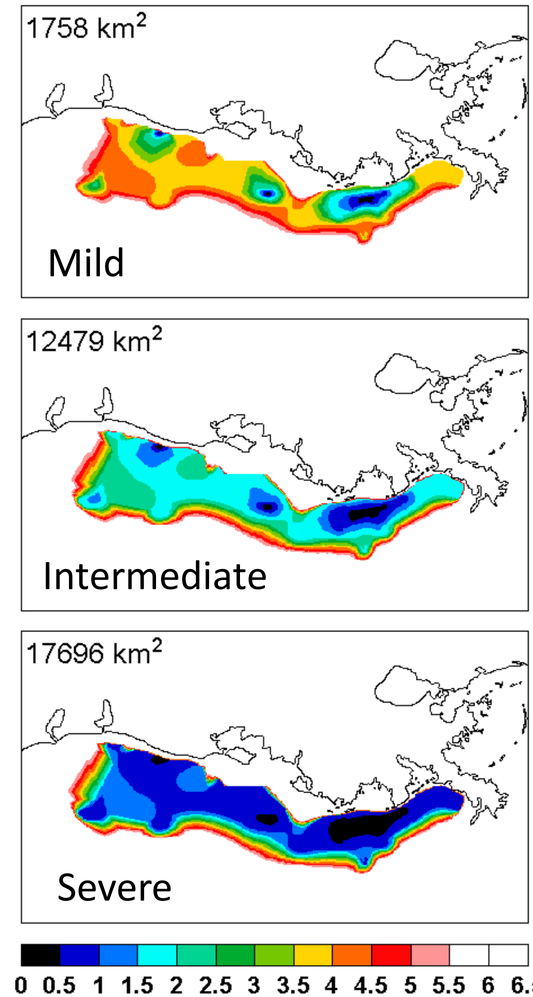
(mg/m^3, sqr-transformed)



Environmental Variables: Oxygen (Source 1)

www.gulfhypoxia.net

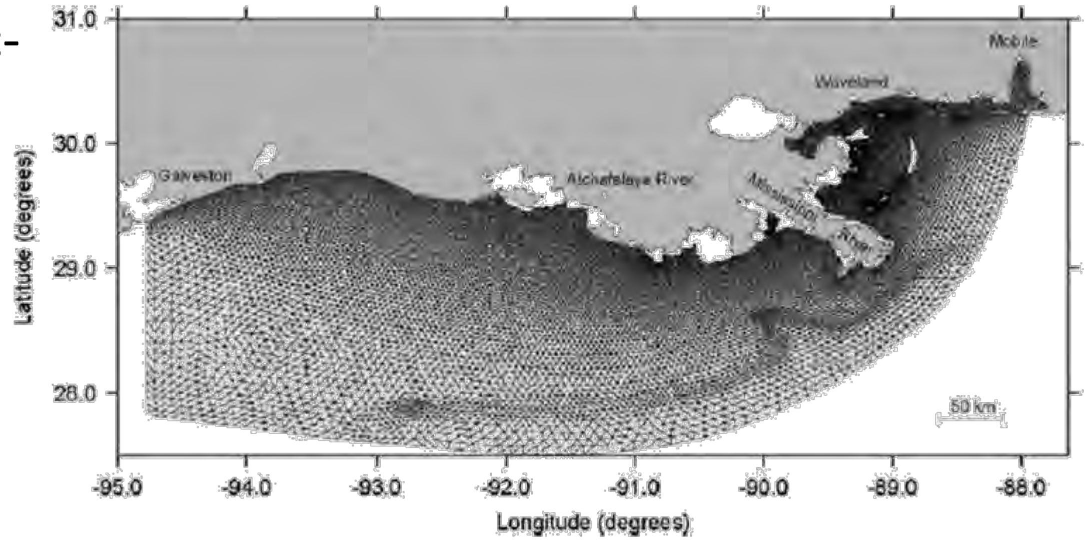




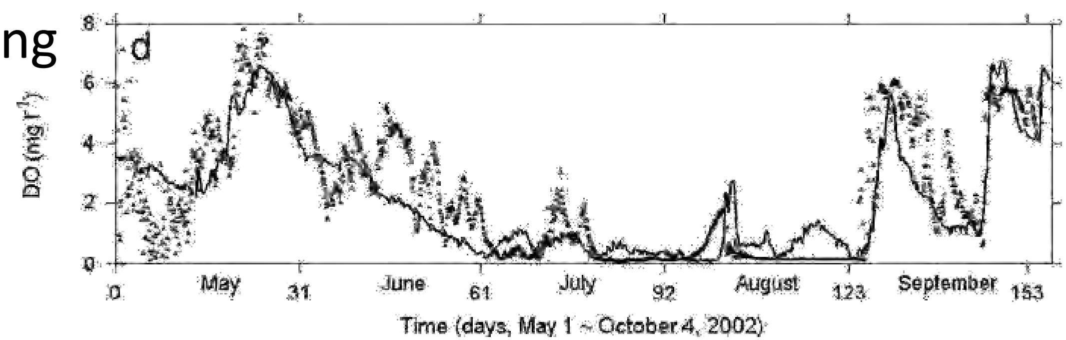
- Hypoxia
  - June1-7, DO in hypoxic zone declines from 8 mg/L to specified local minimum
  - low DO from June to August
- Scenarios: mild, intermediate, & severe

Environmental Variables: Oxygen
(Source 2)

- 3-D coupled hydrodynamic-water quality model
  - FVCOM + WASP
  - 1-10 km horizontal
  - 0.2-2.0 m vertical



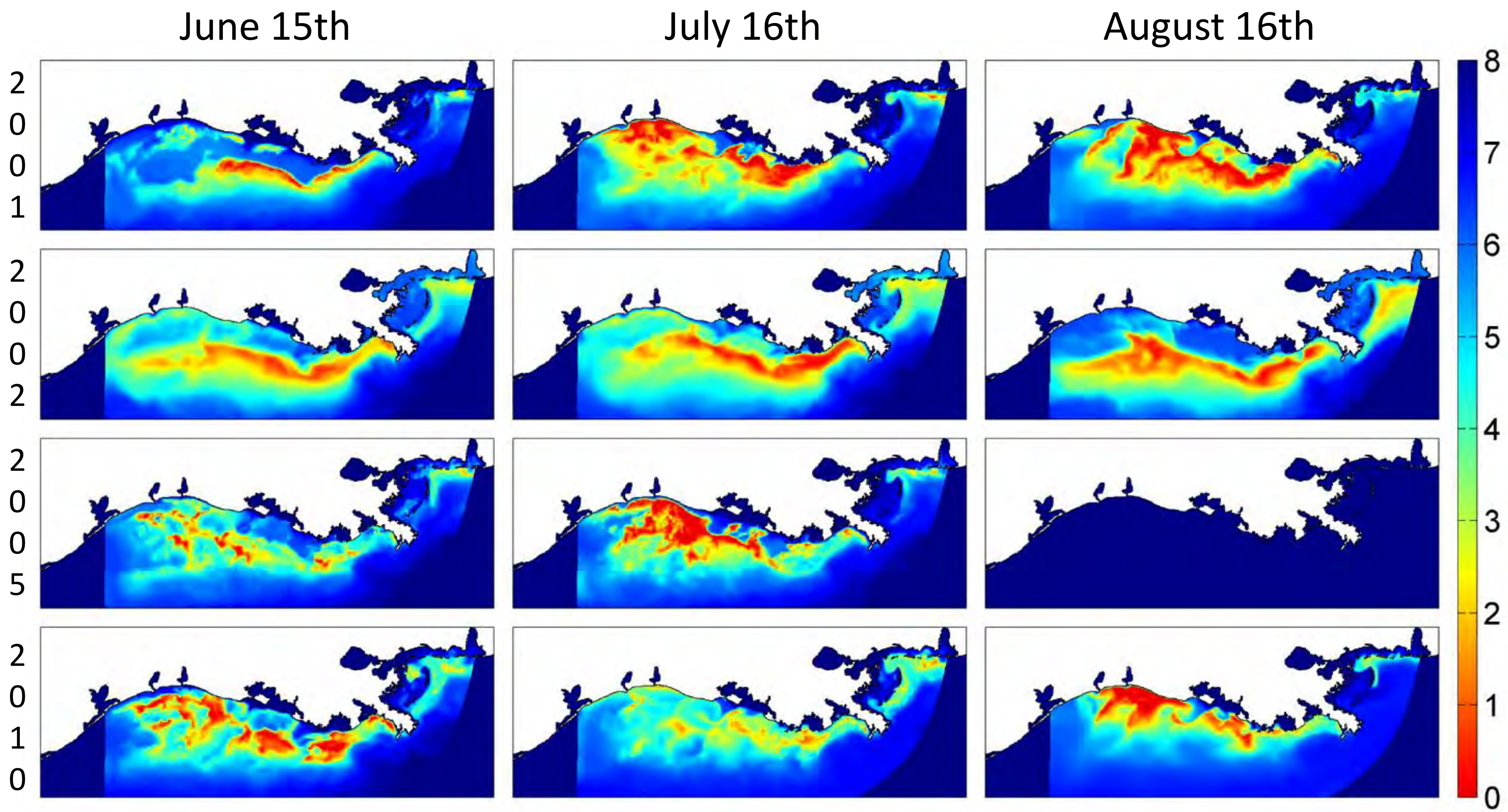
- Calibrated and assessed using multiple independent data sources for the 2002 year.
  - *see Justić & Wang 2013*



Environmental Variables: Oxygen (Source 2)

- June 1 through August 31
- Hourly bottom layer DO for FVCOM grid
- Years:
  - 2001 (20,100 km^2) – severe
  - 2002 (21,700 km^2) – severe
  - 2005 (10,200 km^2) – intermediate
  - 2010 (15,600 km^2) – intermediate
  - Normoxic – mild
- Interpolated to IBM grid

Environmental Variables: Oxygen
(Source 2)



Growth

- Duration in the egg and yolk sac, ocean larva, and estuary larva stages determined off-grid, and was a function of daily average grid temperature

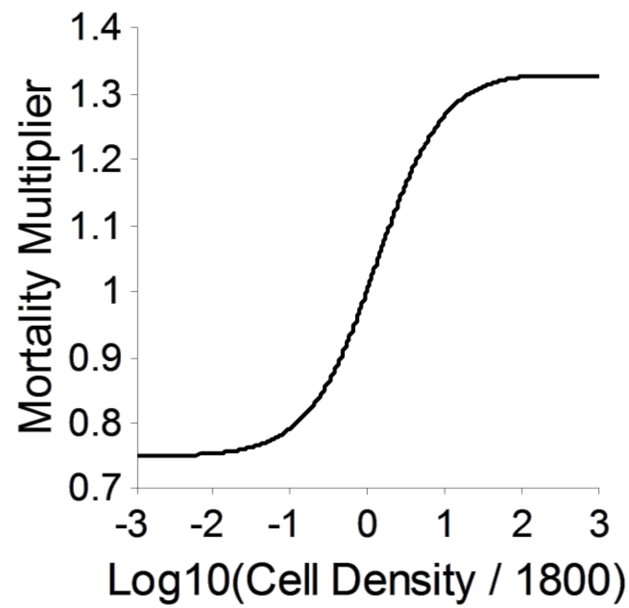
- Bioenergetics models were developed for juvenile and adult croaker following the Wisconsin formulation:

$$W_t = W_{t-1} + [C - (R + SDA + Eg + Ex)] \cdot W_{t-1} \cdot \frac{\rho_p}{\rho_f} \cdot \Delta t$$

- Local temperature and Chl-a values were used as inputs to compute hourly growth rates for juveniles and adults

Mortality

- Stage-specific mortality rates (Murphy 2006)
- Different mortality rates between for early life stages based on estuaries east or west of TX/LA border
- Late juvenile mortality is density dependent

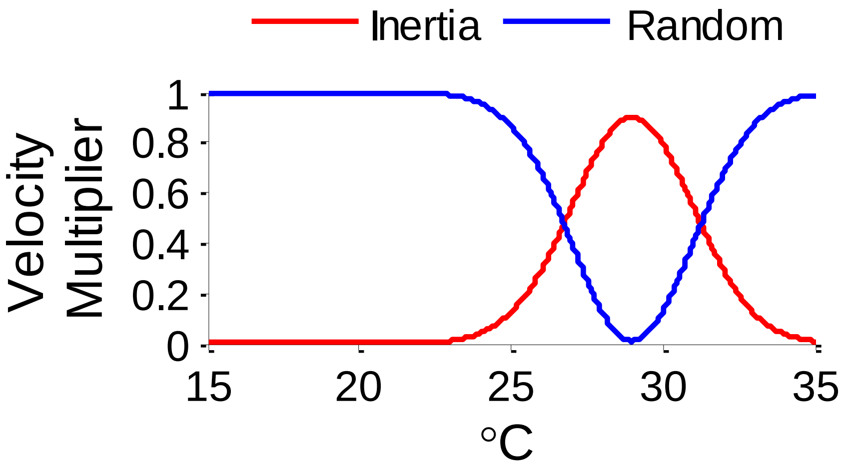


Reproduction

- 1:1 sex ratio
- Maturity and annual fecundity for each individual is size-based
- Batch spawning (12 clutches per year)
- Protracted spawning (September-March)
  - Start based on degree days
  - 4 days between clutches
- Eggs are pooled daily and allocated to either TX or LA

Movement: Routine

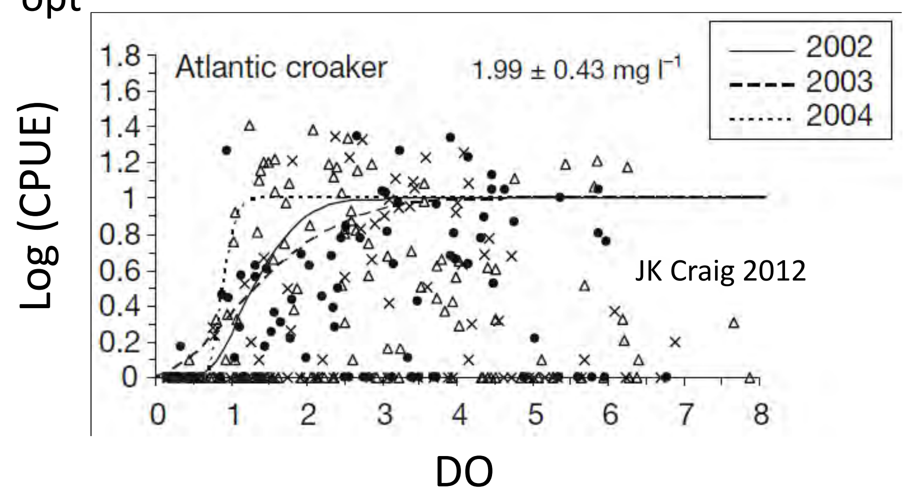
- Each individual is followed in continuous and cell space once they reached the early juvenile stage
- X and Y velocities are computed hourly based on response to temperature



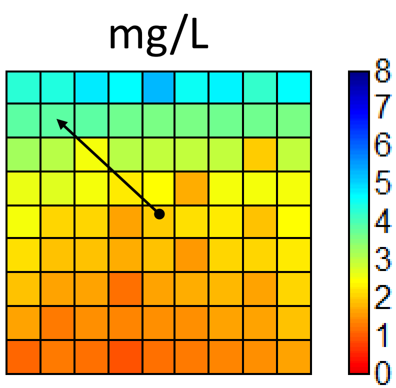
Movement: Avoidance

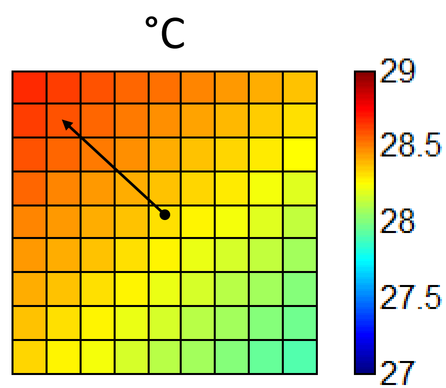
- If DO < 2.0 mg/L, search *80 cells* that has:
  1. Temperature closest to T_{opt}

     and
  2. DO > 2.0 mg/L



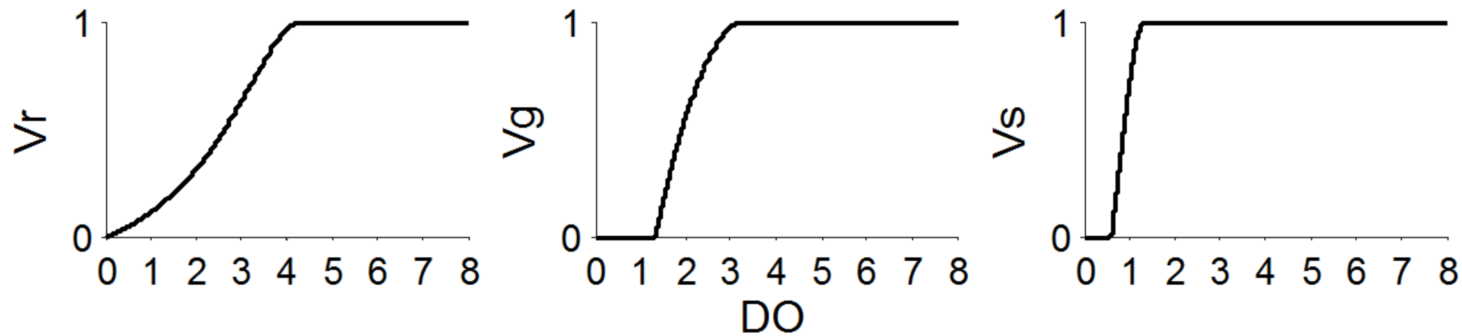
- Illustrations:





Direct Effects of Low DO

- Exposure-effects sub-models (Neilan and Rose 2014) are used to follow growth, reproductive, and survival vitalities:



- Vr only affected by the *last 10 weeks* of exposure

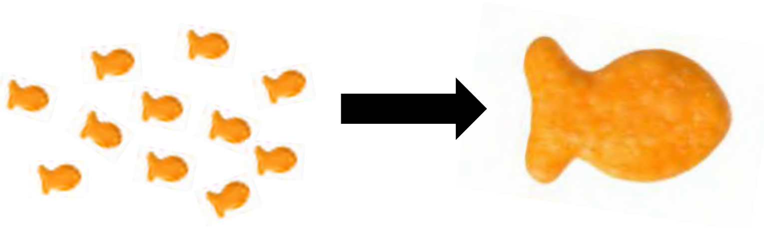
- Vg and Vs are reset to 1.0 on September 1; Vr not reset until June 1

- Assembled from exposure experiments on survival and growth in spot (existing lab experiments) and on fecundity in croaker (Thomas and Rahman 2012, Rahman and Thomas 2012)

- Only imposed on late juveniles, age-1 adults, and age-2 adults

Design of Simulations

- Initial population
  - 6 million age 1, 10 million age 2+
  - Randomly on grid, per area basis LA versus TX
- Super-individuals
  - 20,000 per age class
  - Maximum age of 8

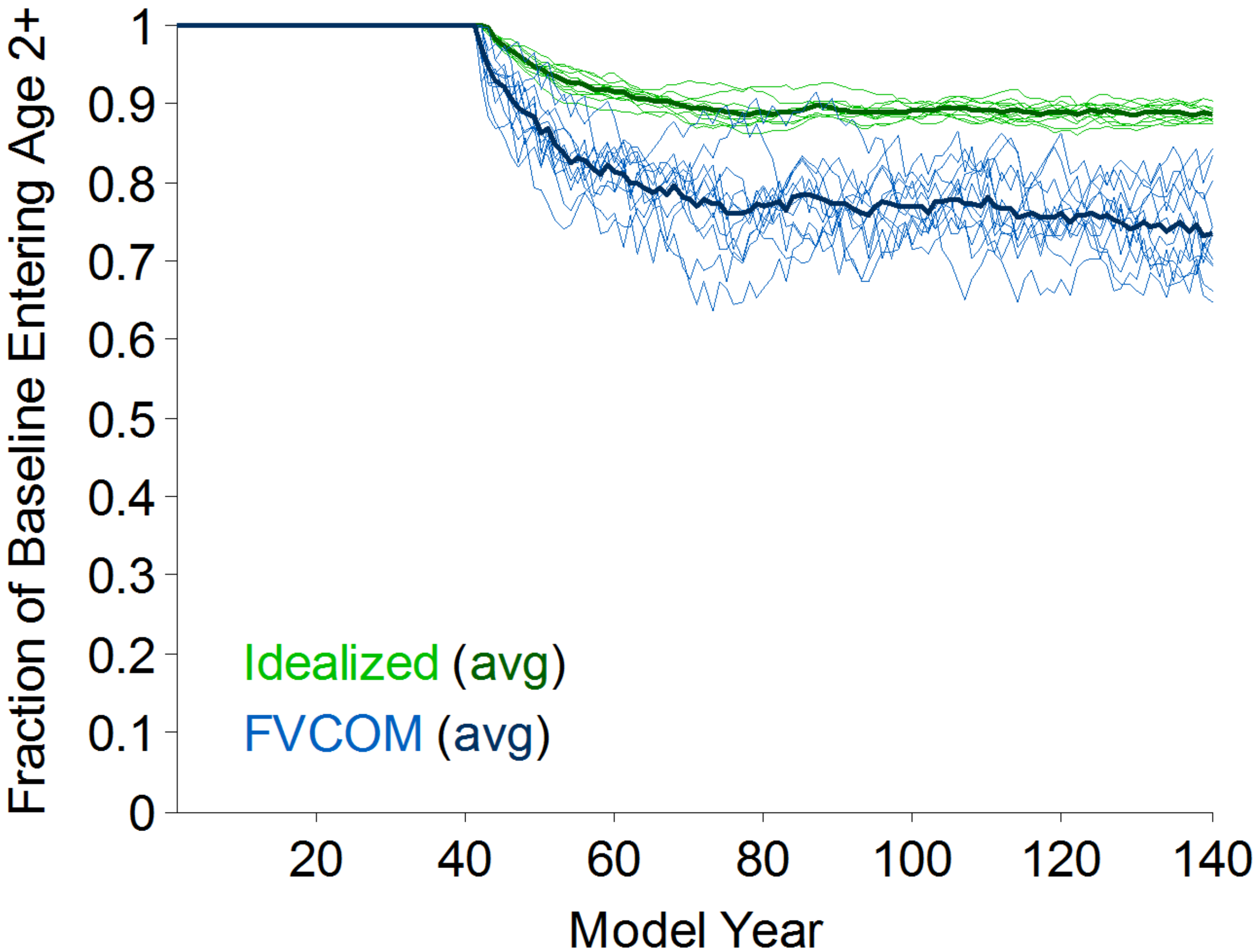


- 140 year simulations
  - 40 years of spin-up

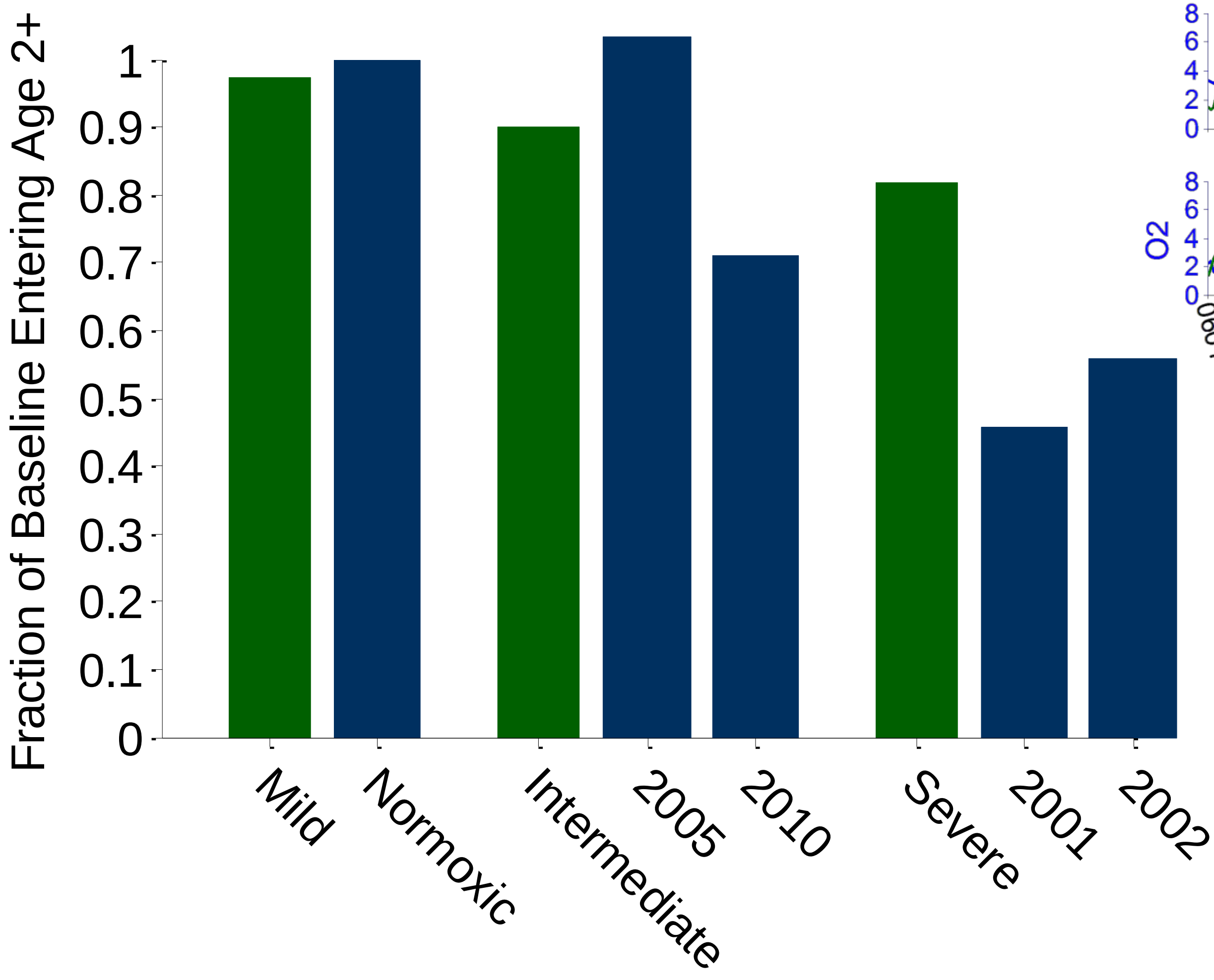
Design of Simulations

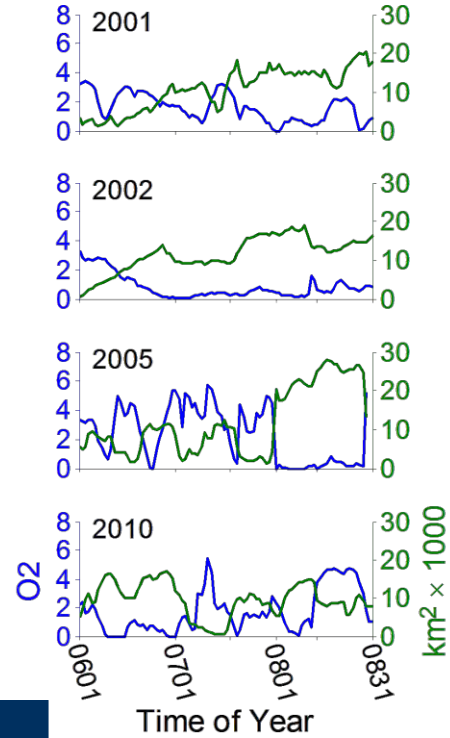
- Baseline: normoxic all year
- Time series simulations (12 replicate runs)
- Each year had probability of being mild, intermediate, or severe based on the July areal extent:
  - 0.18 mild (< 10,000 km^2)
  - 0.52 intermediate (10,000–20,000 km^2)
  - 0.30 severe (> 20,000 km^2)
- Frequencies estimated from Obenour et al. (2013) areal estimates of the mid-summer extent of hypoxia for 1985-2011
- Sensitivity analyses (Replicate #3)

Time Series Simulations

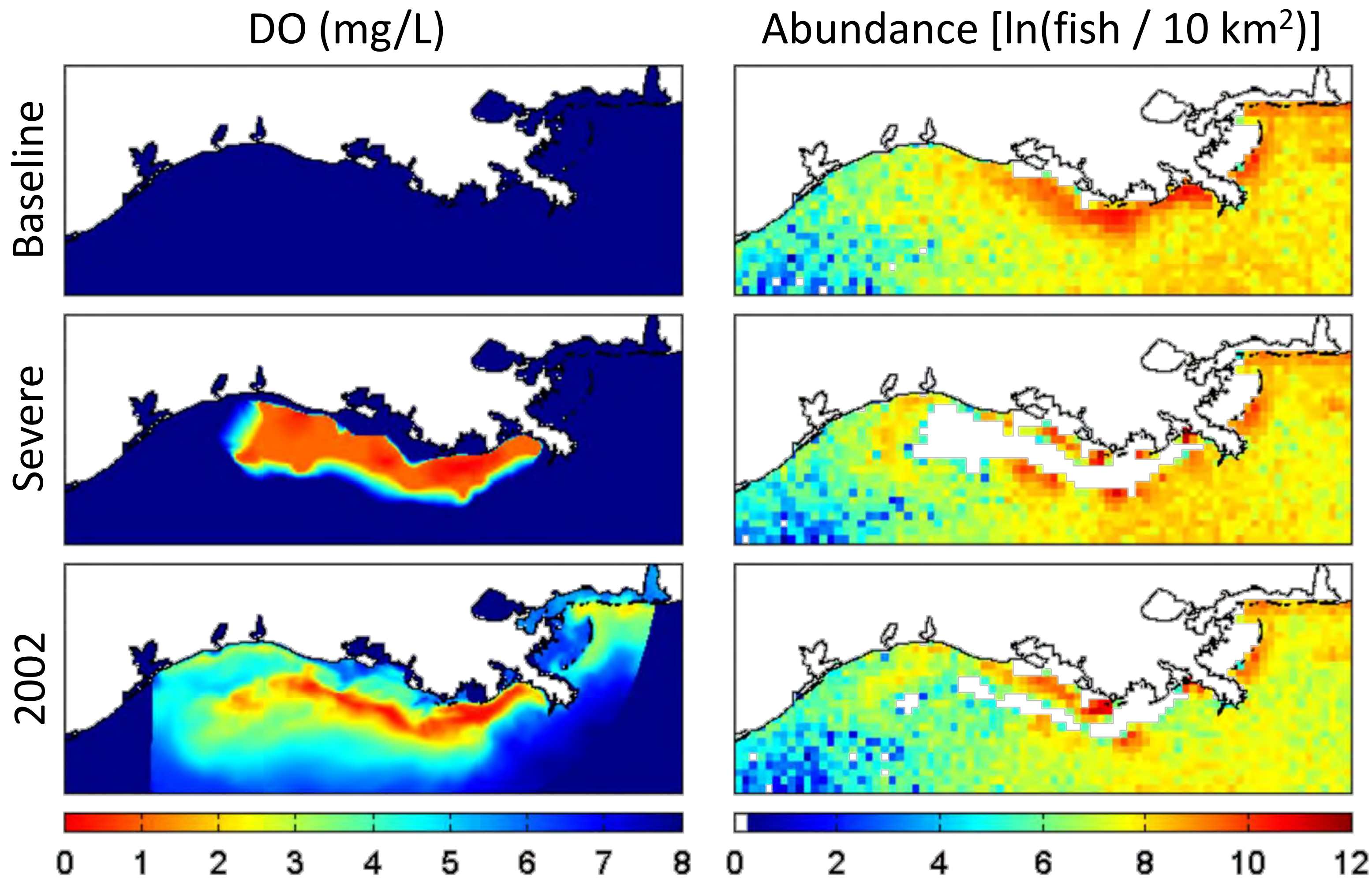


Biological Response

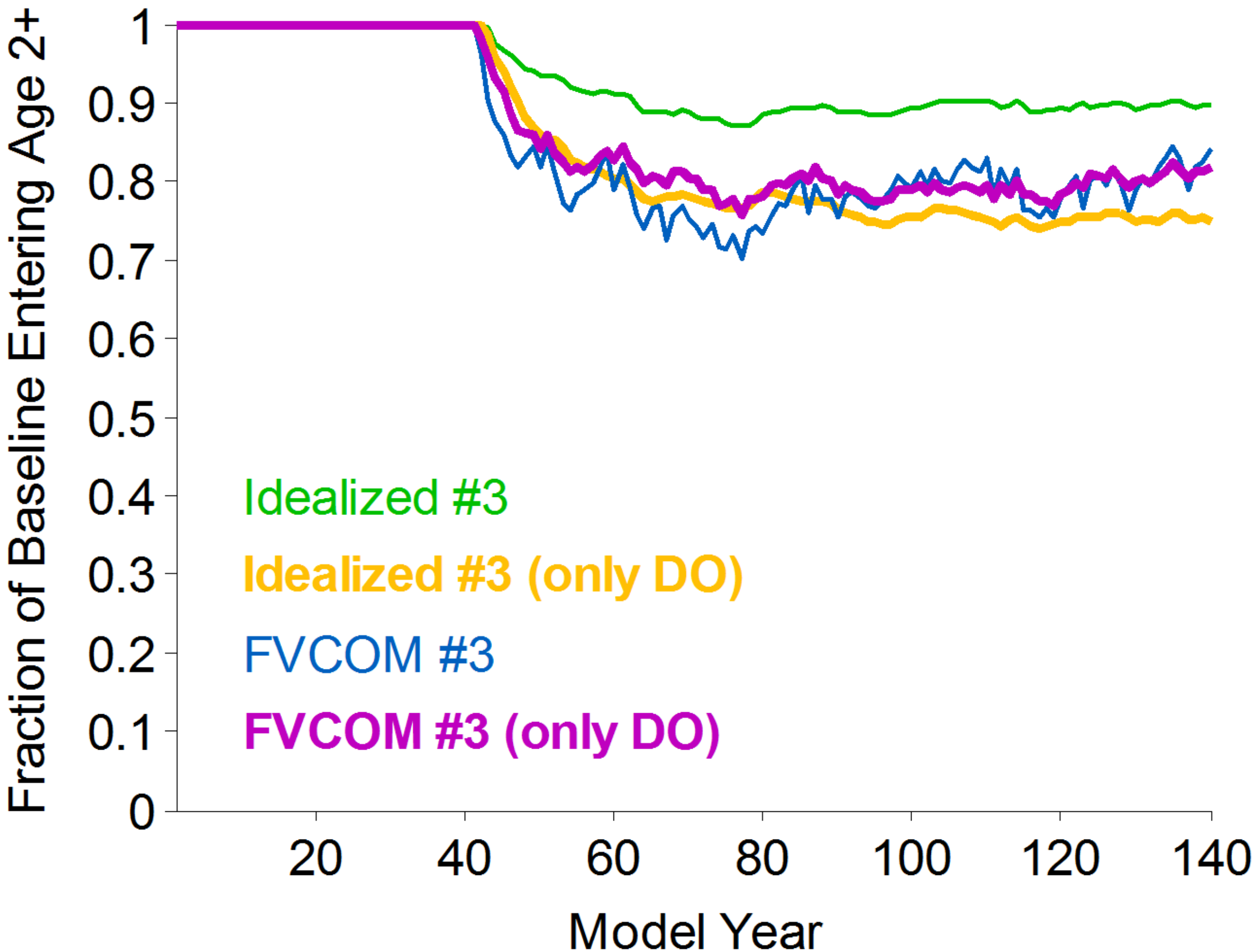




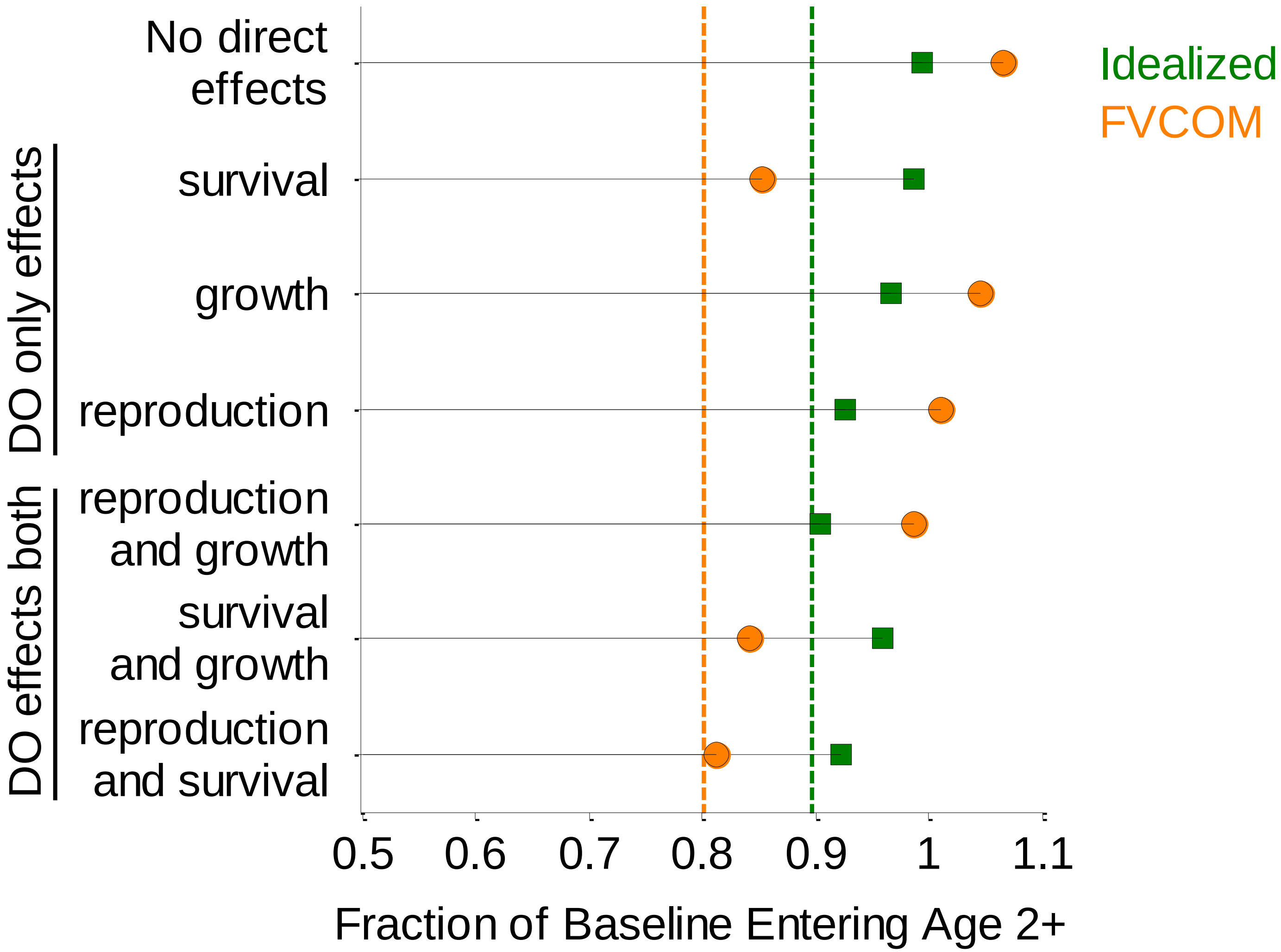
Avoidance
(July 16th)



Avoidance Based on DO Only
(Ignore temperature)



Sensitivity Runs (some)



Conclusions

- Potential effects of hypoxia (in isolation) on growth, reproduction, and survival were predicted for Atlantic croaker in the NWGOM to better understand and quantify how fish populations are impacted by hypoxia.
- A 2-D spatially explicit IBM was used to quantify exposure.
- Effects were imposed using sub-models assembled from laboratory data.

Conclusions

- A 20% decline in age 2+ croaker abundance was predicted after 100 years of exposure to realistic DO conditions.

- Simulations under ideal vs. FVCOM DO showed:
  - Variability in DO resulted in larger reductions
  - Avoidance depends more on departure than destination

- Sensitivity analyses indicated:
  - Response mostly due to direct effects (no effects results)
  - Reproduction very important under idealized DO
  - Survival, combined with reproduction or growth effects were important under realistic (FVCOM) DO.

Possible Next Steps

- Integrate the laboratory, field, and modelling efforts.
  - e.g., use HIF and SEAMAP data to corroborate exposure estimates from the IBM
- Refine model predictions.
  - e.g., incorporate more years from FVCOM when they become available
- Look at the likelihood of detection under increasingly variable conditions.
  - e.g., add variability to egg mortality