Ecosystem Modeling of Red Tide Impacts on WFS Fisheries

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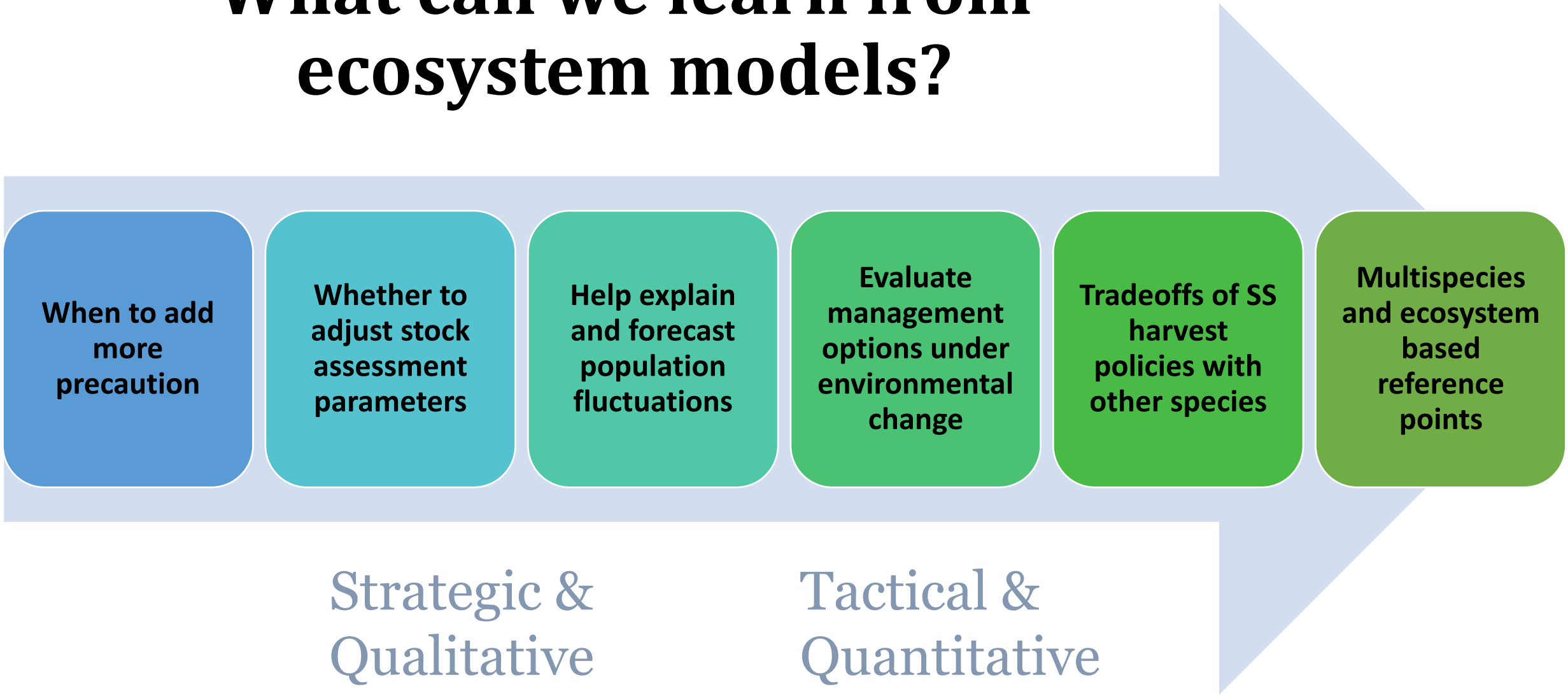
UF IFAS UNIVERSITY of FLORIDA

NATURE COAST BIOLOGICAL STATION

Ecopath International Initiative

RESTORE SCIENCE PROGRAM

What can we learn from ecosystem models?



Applications in the Gulf of Mexico

When to add more precaution

Whether to adjust stock assessment parameters

Help explain and forecast population fluctuations

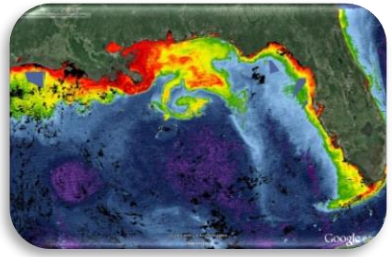
Evaluate management options under environmental change

Tradeoffs of SS harvest policies with other species

Multispecies and ecosystem based reference points

Red tide mortality

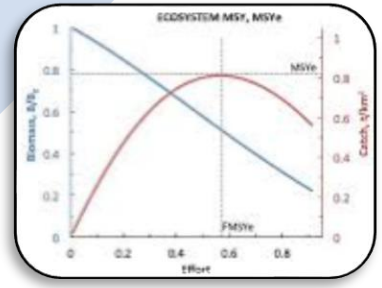
Multiple stressors



changes in primary production

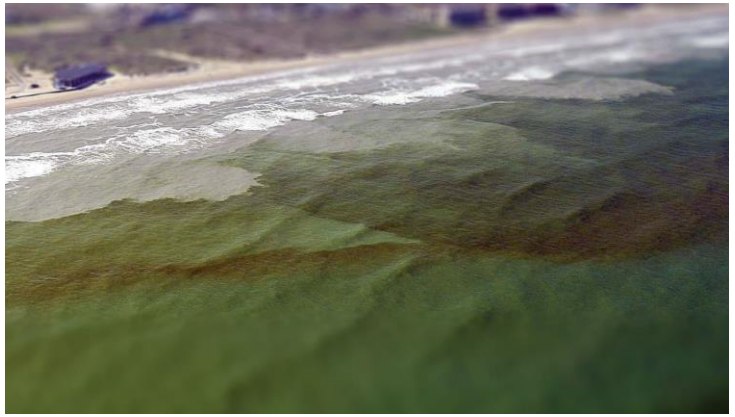
Stock Rebuilding

Forage fisheries



SS and Ecosystem targets and thresholds

Red tides, stock assessment, and ACL projections



Red tide is caused by the toxic dinoflagellate *Karenia brevis,* with records going back to 16th century.

They occur regularly on Florida's Gulf coast – most frequent and severe in SW Florida during late summer and early fall (spatial-temporal considerations)

Broad impacts across the ecosystem: mortality, movement, feeding, growth

Economic impacts on tourism and fisheries

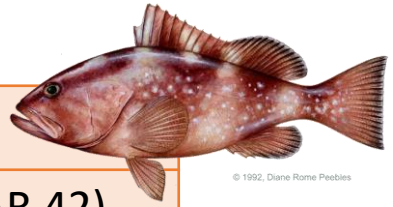
Red tides, stock assessment, and ACL projections

Incorporating Red Tide into Stock Assessments

- Gag and Red Grouper: SEDAR 10U, 33, 33U, 72, 42, and 61
  - Estimated an "F" for a red tide pseudo fishing fleet for predefined years
  - assumed full selectivity across ages
  - informed by trends in the observed indices
  - *New approaches in SEDAR 72: selectivity and M deviations*
- High but variable estimates of mortality
- Still considerable uncertainty about how to account for red tide effects in SS and projections

Gag Grouper

- Mrt_{2005} = 0.35 (SEDAR 10U)
- Mrt_{2005} = 0.71 (SEDAR 33)
- Mrt_{2005} = 0.73 (SEDAR 33U)
- Mrt_{2005} = 0.72 (SEDAR 72)
- Mrt_{2014} = 0.47 (SEDAR 72)
- Mrt_{2018} = 0.20 (SEDAR 72)



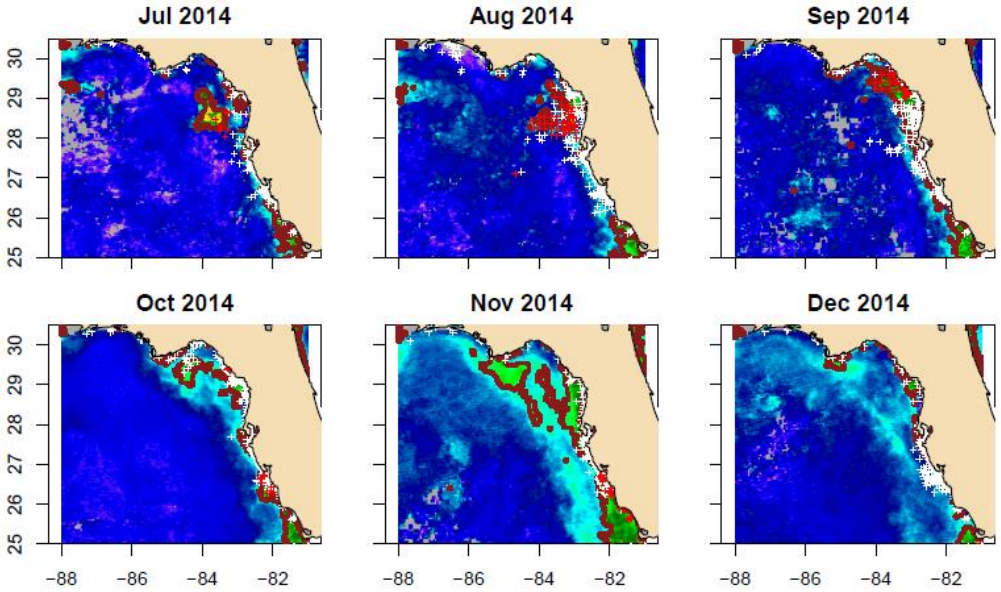
Red Grouper

- Mrt_{2005} = 0.55 (SEDAR 42)
- Mrt_{2005} = 0.34 (SEDAR 61)
- Mrt_{2014} = 0.26 (SEDAR 61)

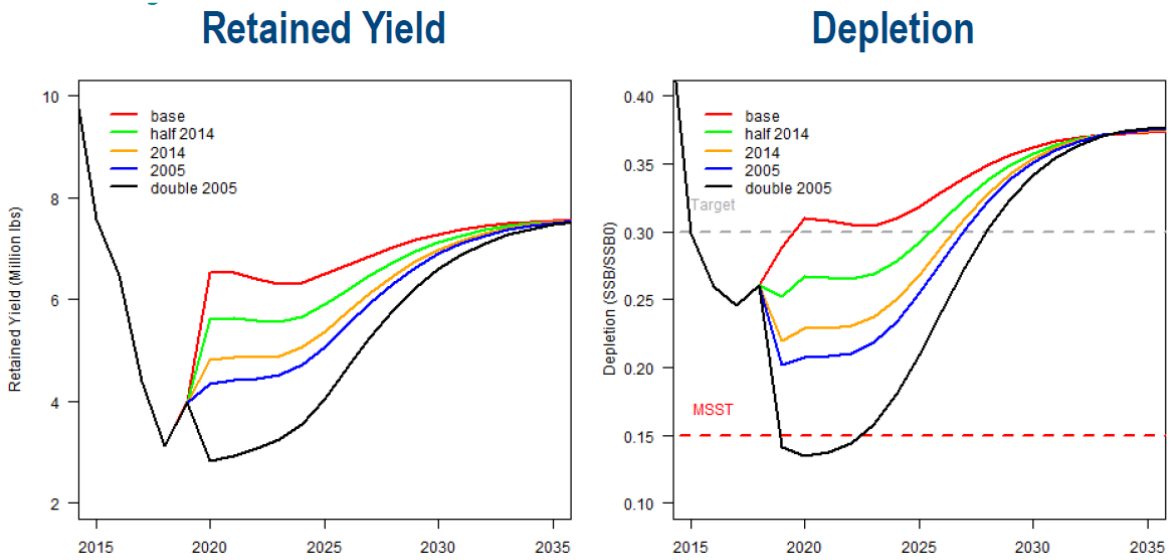
Red tides, stock assessment, and ACL projections

Accounting for Red Tide when Setting ACLs

Gag - Initial ACLs set in 2014 were based on assumptions about impacts ongoing bloom in FL Big Bend.



Red Grouper – ACL projections from SEDAR 61 were sensitive to assumptions about the 2018 red tide mortality rate



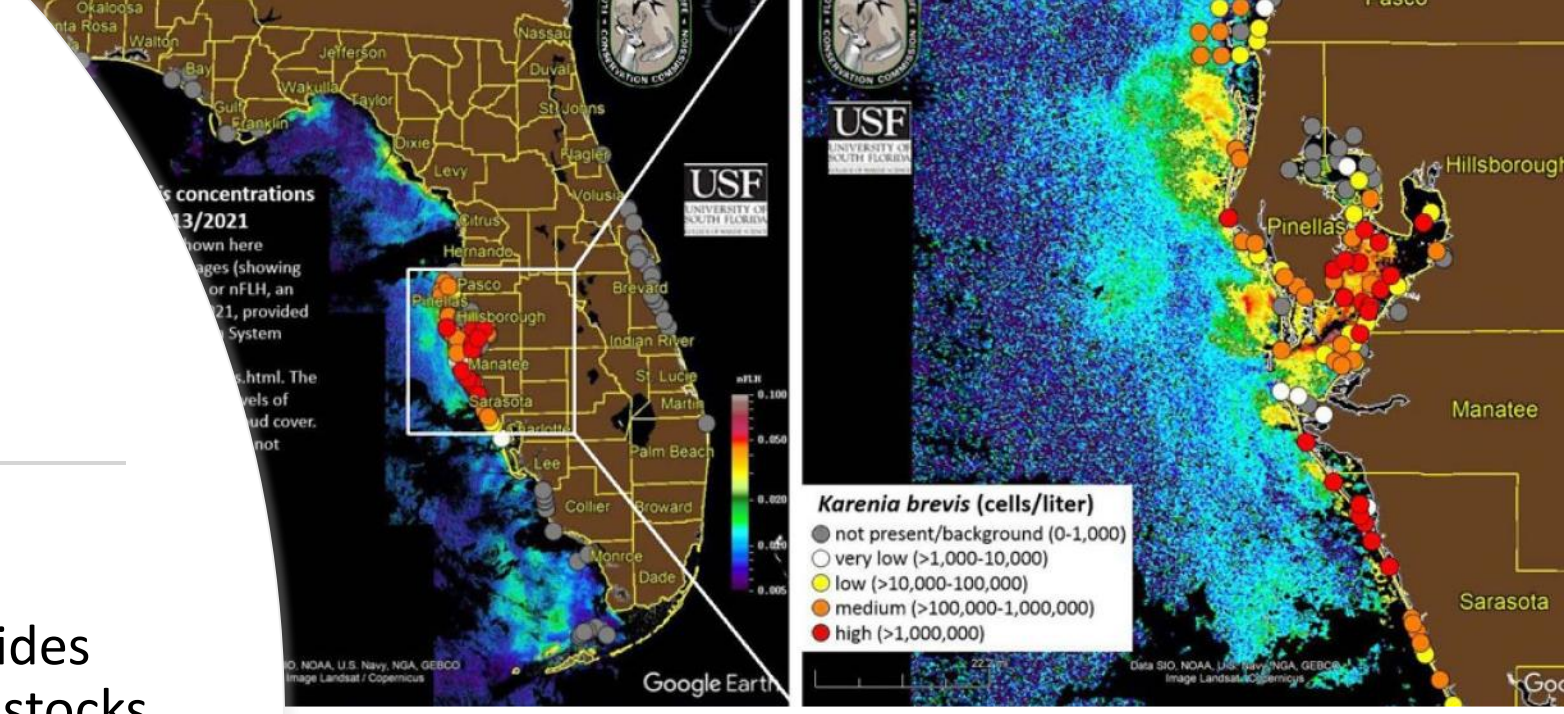
Goals & Objectives

Goal:

Enhance our ability to account for red tides when assessing and managing reef fish stocks

Objectives:

1. Provide historical estimates of red tide mortality for inclusion in the stock assessments
2. Provide contemporaneous assessments of red tide mortality for use in ACL projections and decision making

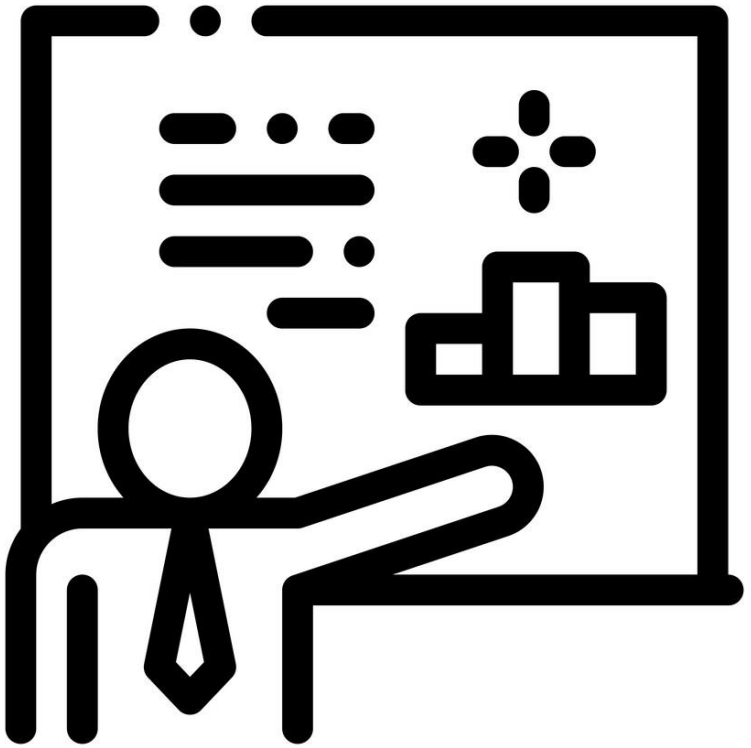


Presentation Outline

1. Brief Overview of WFS Ecospace Model
   - Development of monthly red tide maps
   - Mortality & foraging response functions
   - Model validation & calibration attempts

2. Red tide mortality estimates
   - 2005, 2014, and 2018 events
   - Mortality trend through mid-August 2021

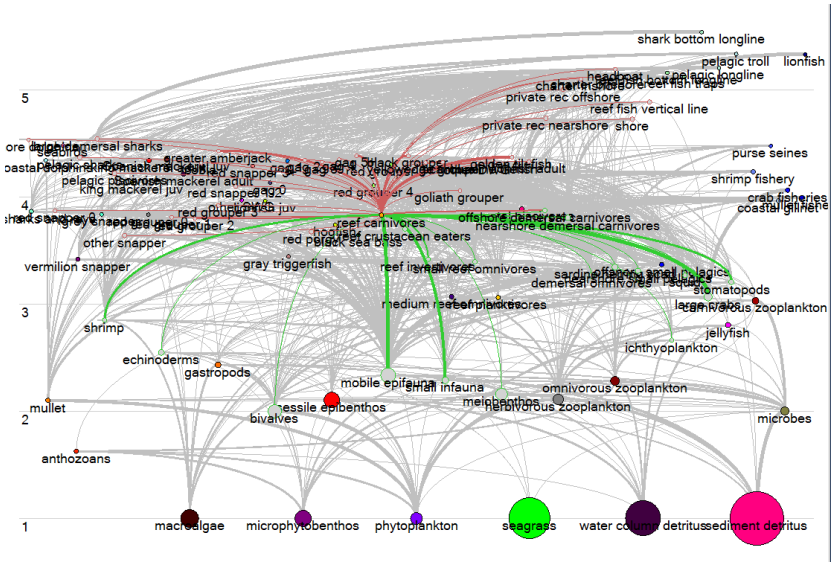
3. Next steps
   - Operationalizing the model
   - Research recommendations

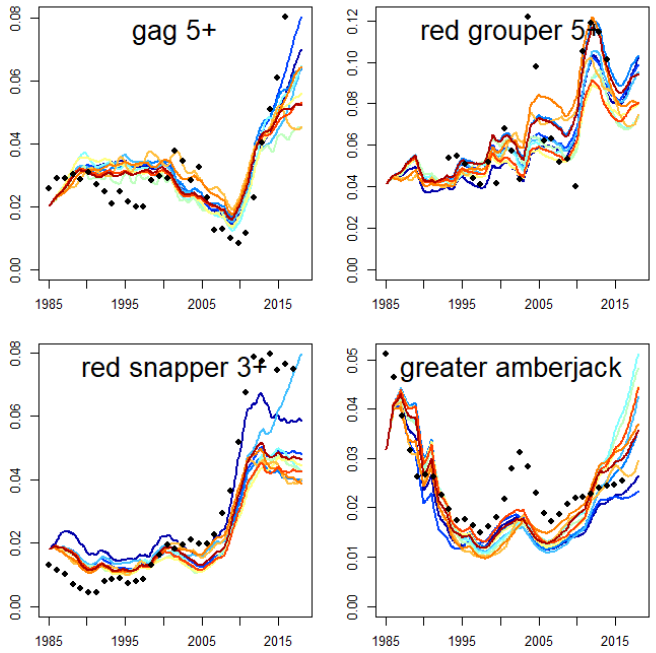


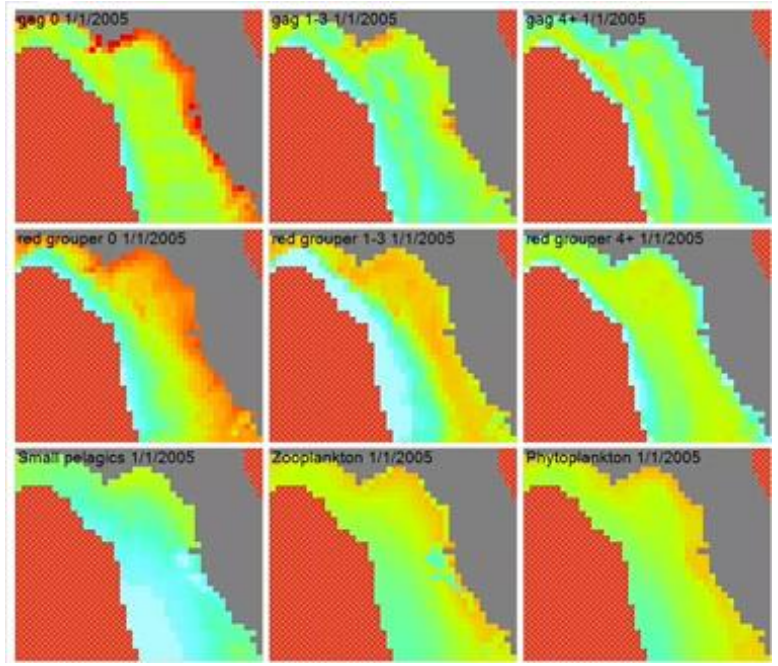
Ecopath with Ecosim

www.ecopath.org

No fish is an island







Ecopath

- Static snapshot of the ecosystem
- Input: biomass, mortality, consumption, diet, and fishery removals
- Requires mass balance
- Starting point for dynamic simulations

Ecosim

- Biomass dynamic food web model
- Environmental forcing
- Parameter estimation & time series calibration
- Future projection scenarios
- Policy analysis and tradeoffs

Ecospace

- Spatially explicit simulations
- Input: dispersal rates, habitat maps, habitat preferences, fishing areas, MPAs, port locations
- Spatial-temporal drivers
- Red tide mortality

Overview of Ecospace Dynamics

Ecospace is a spatially-explicit food web model that simulates changes in biomass and catch over space and time at a monthly time step, as a function of growth minus losses to predation, fishing, other mortality, and movement.

$$\frac{dB_{i,k}}{dt} = g_i \sum_{j=1}^{n} Q_{ji,k} - \sum_{j=1}^{n} Q_{ij,k} - B_{i,k}\left(F_{i,k} + MO_{i,k}\right) \pm \sum_{k=1}^{4} m_{i,k} B_{i,k}$$

Change in biomass (*B*) of group *i* in cell *k*

Biomass Growth

Consumption, *Qij*, predicted based on foraging arena formulations

Predation losses

Losses due to fishing, and 'other mortality'

Fishing mortality in each cell predicted by allocating effort spatially based on profitability

Other mortality is residual, or can be linked to environmental driver

Net migration to 4 neighboring cells

Movement rate between cells determined by relative 'habitat capacity', i.e. foraging arena area [0,1] for each cell

Red Tide effects

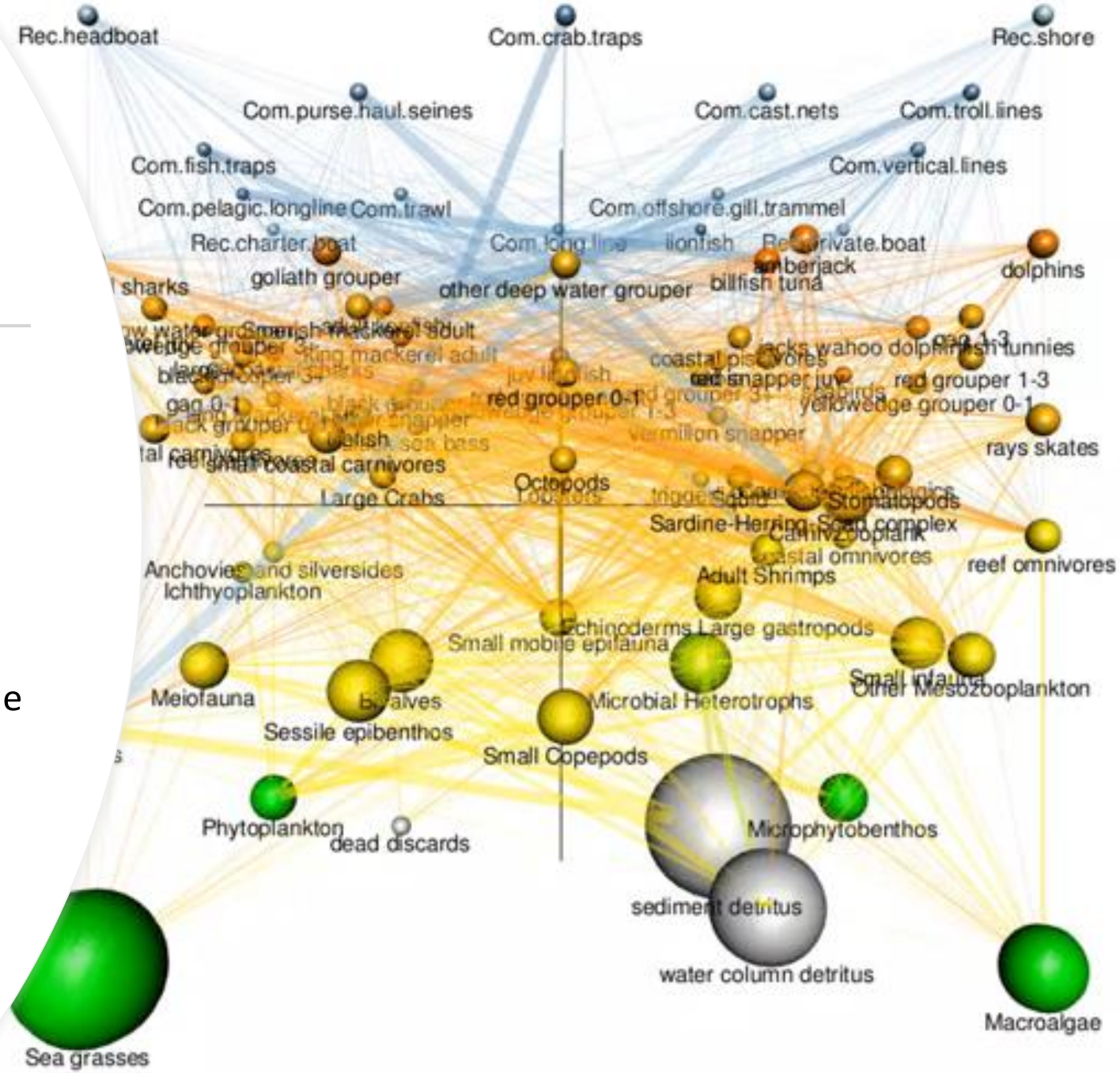
The West Florida Shelf EwE model

Model Evolution

- 2001 - original WFS model developed at FWC (Okey et al. 2004)
- 2013 - Adapted for reef fish management (Chagaris et al. 2015)
- 2017 to current – additional updates and red tide application

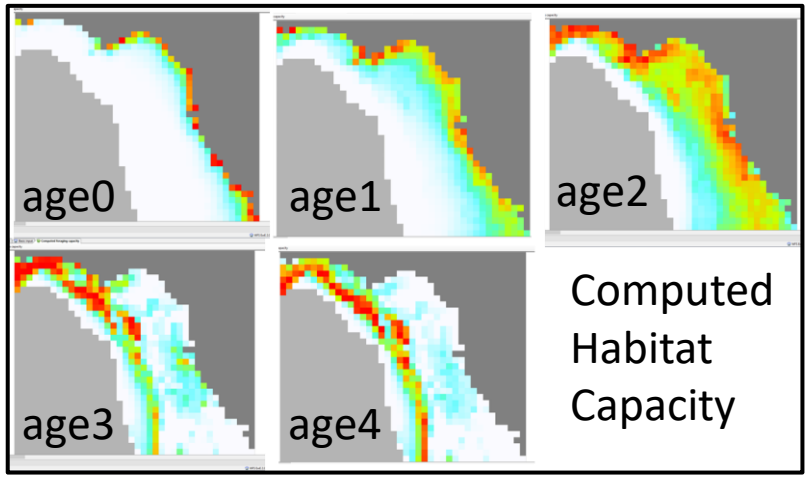
Current Version

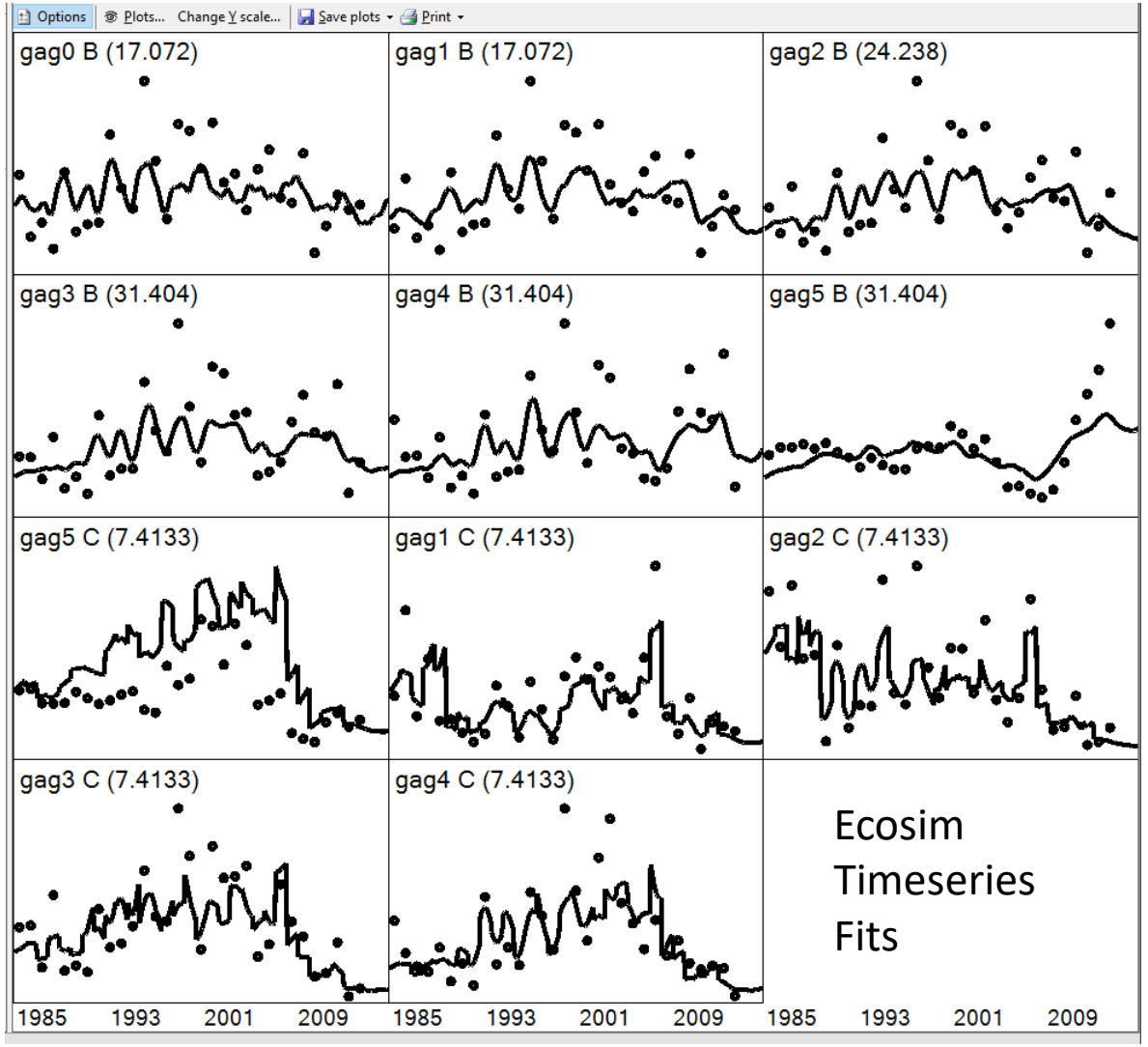
- 83 functional groups and 18 fishing fleets
- 1985 start year
- Extended calibration time series to 2017
- Development of Ecospace



Gag Grouper in WFS EwE

- 6 age stanzas: ages 0-5+
- Initialized with 1985 biomass, landings, and mortality from SEDAR 33U
- Diet composition based on 1,490 stomach samples (FWC, W. Patterson, and GoMexSI)
- Calibrated to SEDAR 33U biomass and catch 1985-2017
- Baseline dispersal rates: 30 km/yr for ages 0-1; 50 km/yr for ages 2+
- Habitat preferences for depth and rugosity

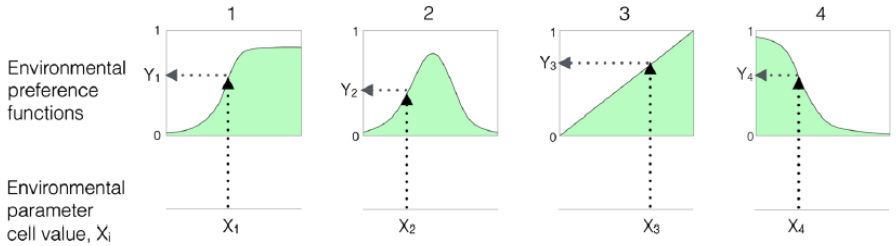




Updating WFS Ecospace

1. Habitat Preferences and Species Distributions

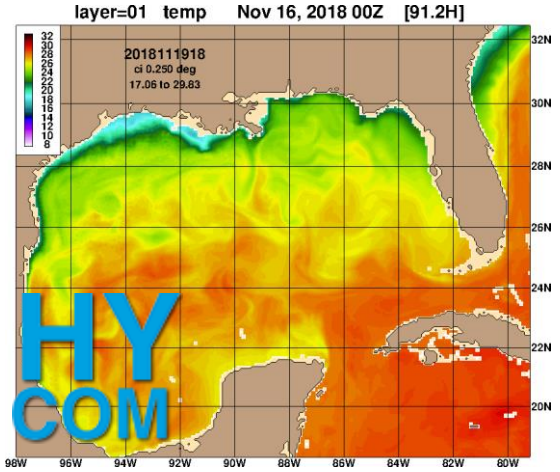
- Habitat preference functions estimated from survey datasets
  - Depth, temperature, salinity, rugosity
  - SEAMAP trawl, FWC/NMFS camera surveys, FWC baitfish cruise survey, NMFS bottom longline survey
  - GAMs, GLMs, VAST models
- Preference functions determine 'foraging capacity', *C*, in each grid cell
- Affects consumption and movement to/from cell



From Christensen et al. 2014

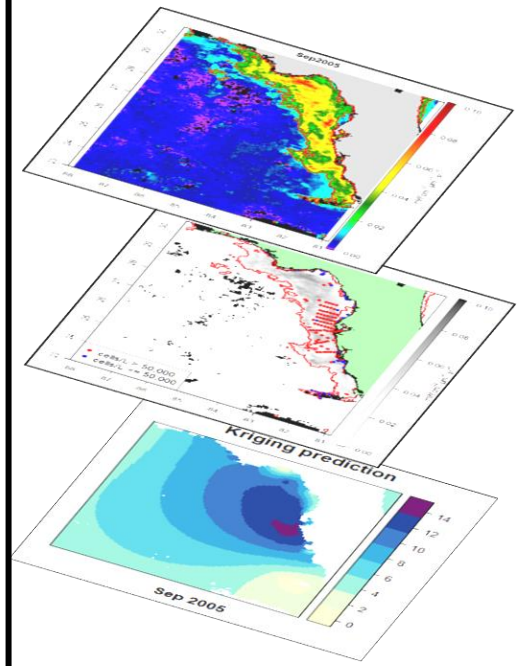
2. Spatial-Temporal Environmental Drivers

- Modifies habitat layers at monthly time steps and recomputes habitat capacity in each cell
  - Surface and bottom temperature
  - Chlorophyll-a
  - salinity
- Monthly maps obtained from MODIS satellite imagery and HYCOM oceanographic model



Red Tide Mortality in WFS Ecospace

Monthly Red Tide Maps



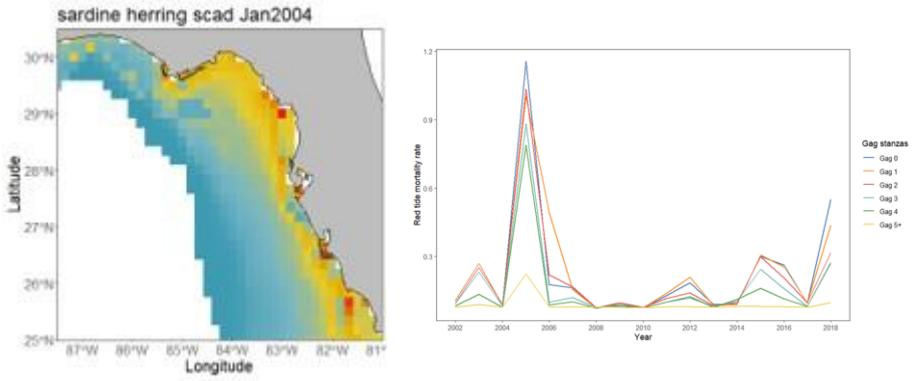
FLH monthly satellite imagery (extent, duration)

FWRI K. brevis concentrations (severity)

Krige FWRI data and clip to satellite polygons

Ecosystem Simulations

EwE spatial-temporal framework

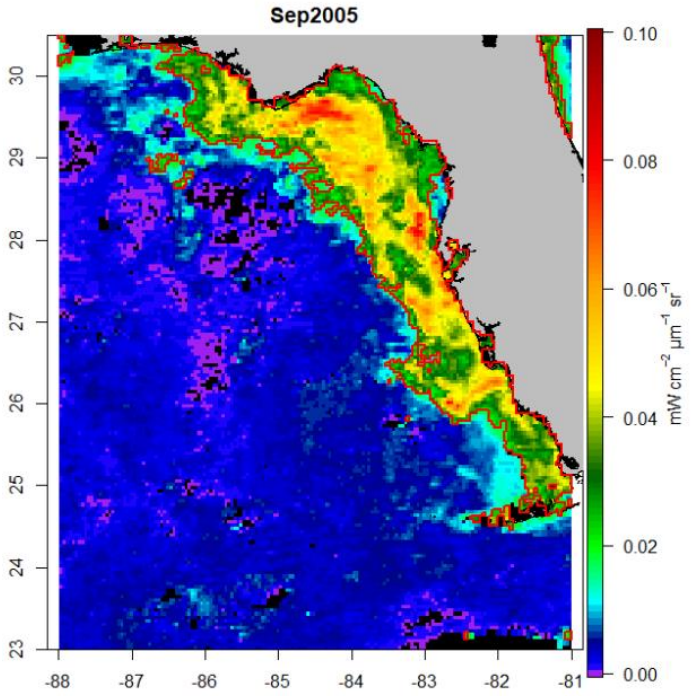


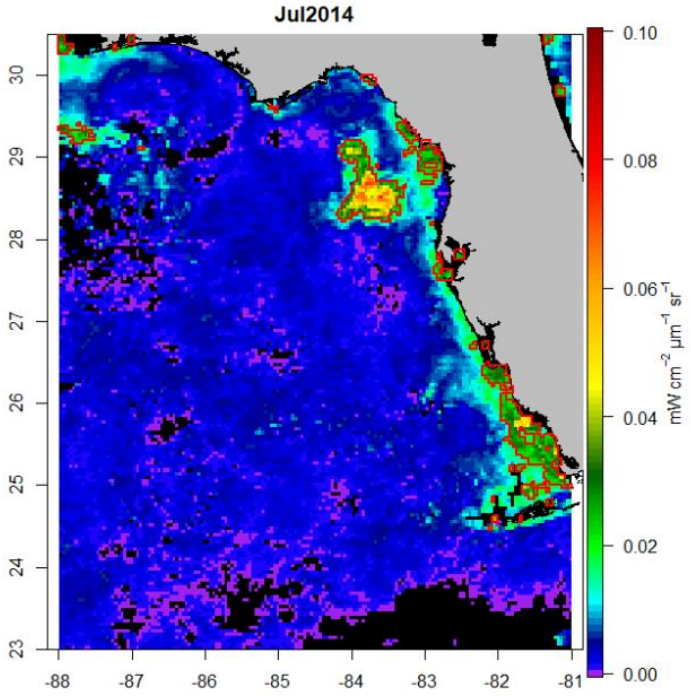
Monthly estimates of biomass loss

- ✓Spatial overlap
- ✓Bloom duration and severity
- ✓Direct mortality (new M0 forcing)
- ✓Sub-lethal effects (foraging capacity)
- ✓Avoidance
- ✓Food web effects

Developing Red Tide Maps: satellite imagery

- Normalized fluorescence line height (FLH) imagery has been used to study and monitor FL algae blooms (Hu et al. 2005; Hu et al. 2015; Soto 2013)
- FLH is an indicator of algal blooms (both harmful and not)
  - Can be contaminated/influenced by sediment resuspension
  - Must be validated with cell concentration samples and/or enhanced RGB imagery
- FLH monthly composite satellite imagery, **<u>July 2002 to August 2021</u>**, at $4km^2$
- 0.02 mW cm^{-2} um^{-1} sr^{-1} used as threshold for detection of HAB (Hu *et al*. 2005 & personal communication)
- Good indicator of presence and extent, but not severity

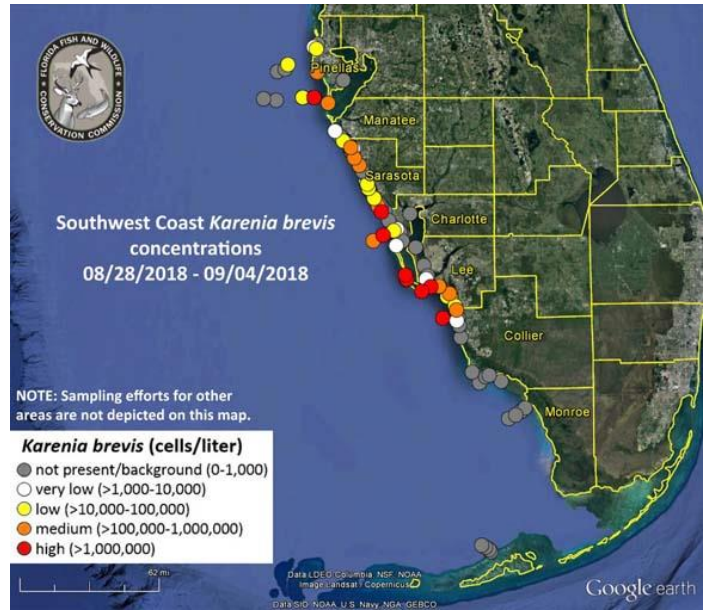


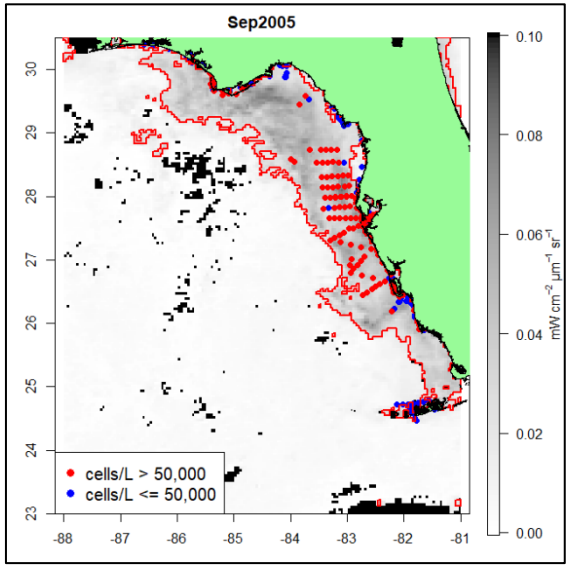


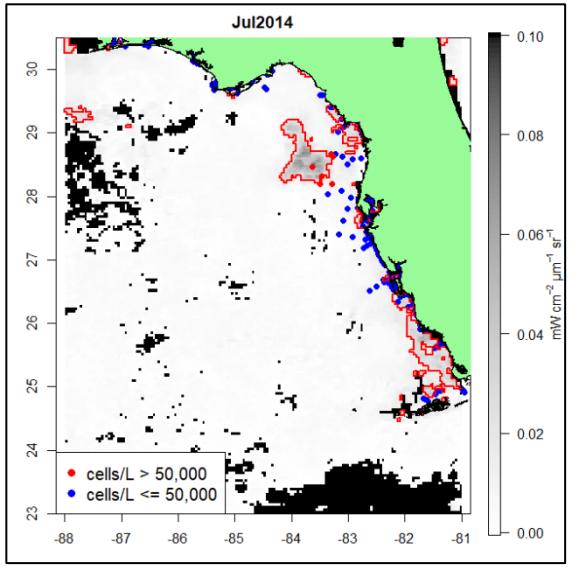
Developing Red Tide Maps: FWC HAB data

http://myfwc.com/research/redtide/statewide/

- *K. brevis* cell concentrations (cells/liter)
  - Water collections from routine monitoring and event response
  - Surface and bottom
  - Range: 0 – 162 million (cells/L)
- *Cell concentrations are not correlated well with toxicity
- Point measurements extrapolated over spatial grid

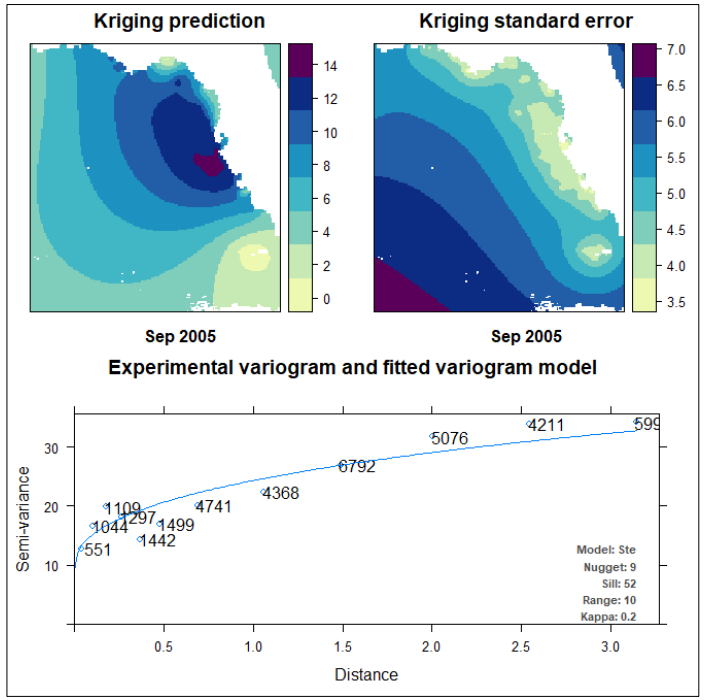


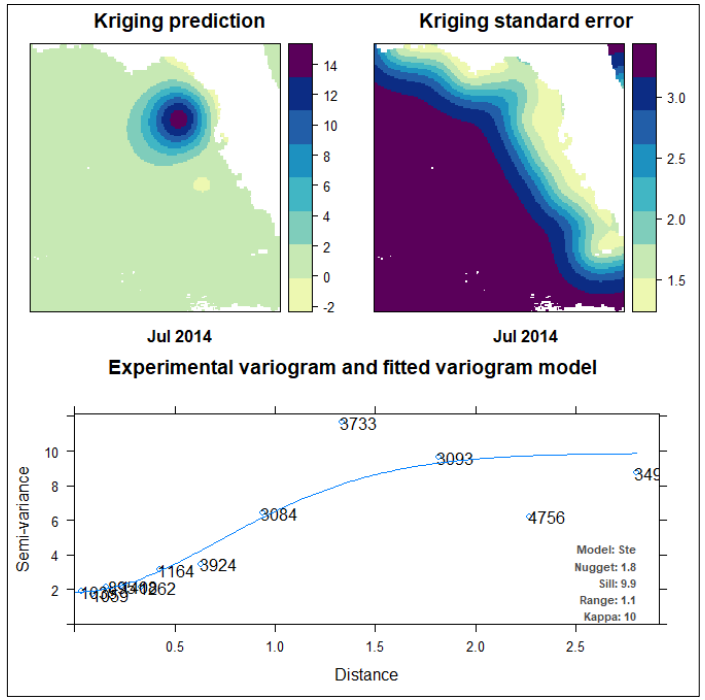


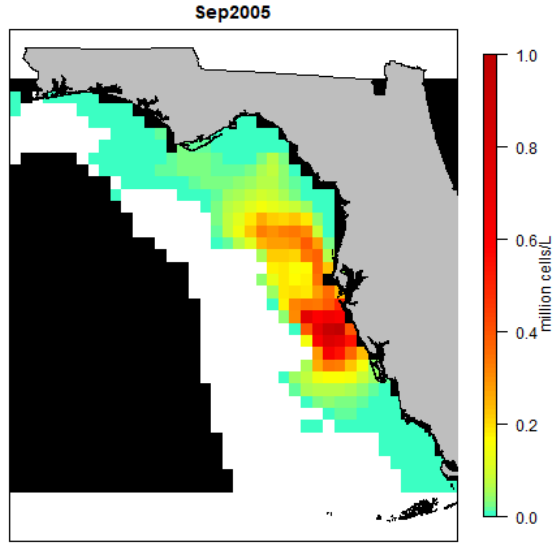


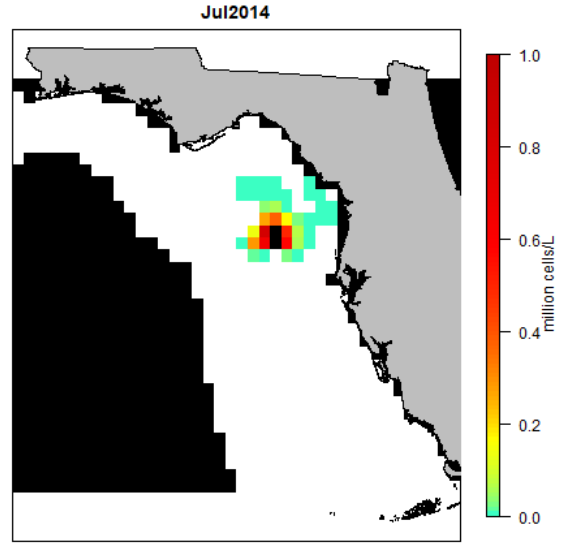
Extrapolating the FWC HAB data

- Inverse Distance Weighting and Ordinary Kriging
- Other kriging approaches tried:
  - *kriging with anisotropy*
  - *Spatial-temporal kriging*
- Predicted maps clipped to FLH polygons (>0.02 mW cm^{-2} um^{-1} sr^{-1})
- Resampled to 10 min resolution of Ecospace









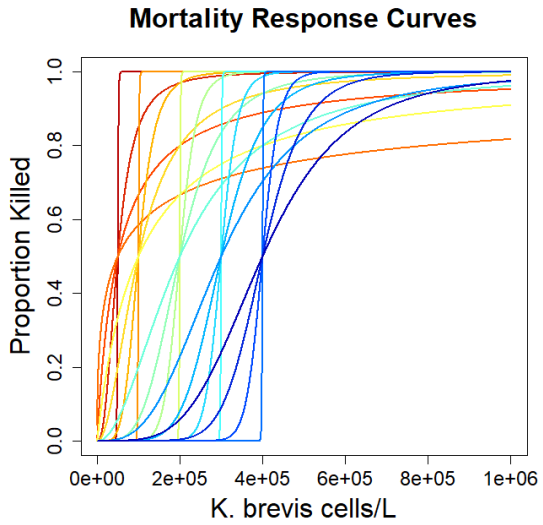
Ecospace Red Tide Response Functions

Mortality Response Functions

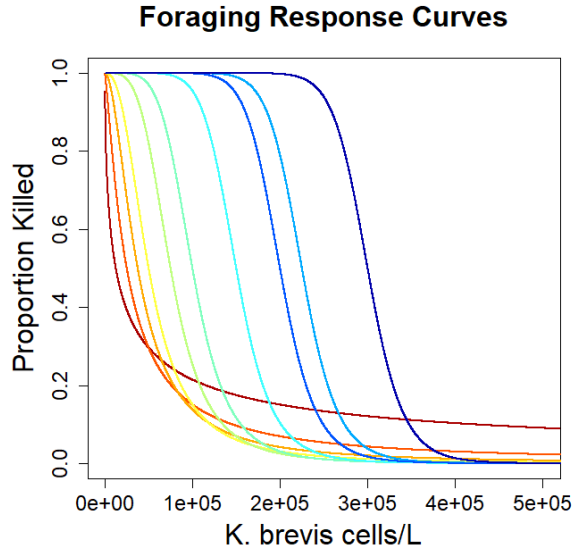
- Direct lethal effects (new feature added to EwE)
- Proportion of biomass killed in each grid cell is a function of *K. brevis* cell concentrations
- Applied as multiplier on 'other mortality' term
- Necessary to evaluate sensitivity/uncertainty associated with response function

Foraging Response Functions

- Sub-lethal effects experienced at lower concentrations than lethal effects
- Reduces 'foraging capacity' in each cell
- Causes fish to move towards more favorable cells and avoid red tide
- Mediate direct mortality response



K. Brevis abundance	Possible effects (K. brevis only)
<1,000 cell/L (background)	No effects anticipated
>1,000 – 10,000 cells/L	Shellfish harvesting closures
>10,000 – 100,000 cells/L	Possible fish kills
>100,000 – 1,000,000 cells/L	Probable fish kills
>1,000,000 cells/L	As above



Ecospace Red Tide Response Functions

Sensitivity (i.e. response fxns)	response applied to gag stanzas only		response applied to all consumer groups	
	M0	M0+foraging	M0	M0+foraging
high	run1-run4	run21-run32	run81-run84	run101-run112
medium-high	run5-run8	run33-run44	run85-run88	run113-run124
medium	run9-run12	run45-run56	run89-run92	run125-run136
medium-low	run13-run16	run57-run68	run93-run96	run137-run148
low	run17-run20	run69-run80	run97-run100	run149-run160

Ecospace evaluated over a combination of response functions applied to gag only and to all consumer groups groups (160 runs total)

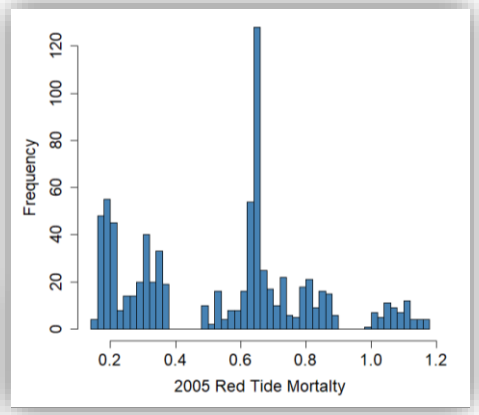
WFS Ecospace Model Red Tide Validation

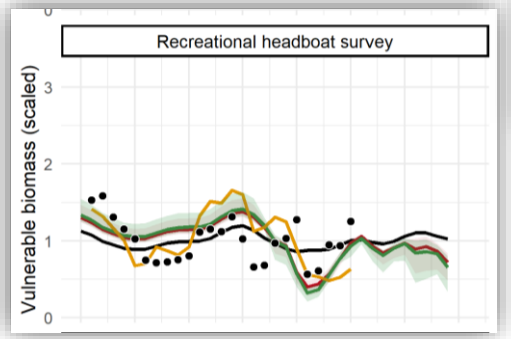
1. Compare Ecospace predictions with year-specific estimates of M_{RT} from stock assessment
   - Assume that values within +/- 2 sd (0.65-0.99) were acceptable

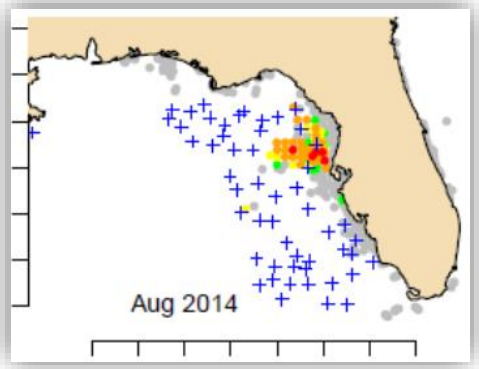
2. Compare predicted biomass trends with observed indices of abundance
   - Selection based on RMSE

3. Compare biomass differences inside-outside and before-after red tide events

Run selection based on 1 & 2 above







WFS Ecospace Model Red Tide Validation

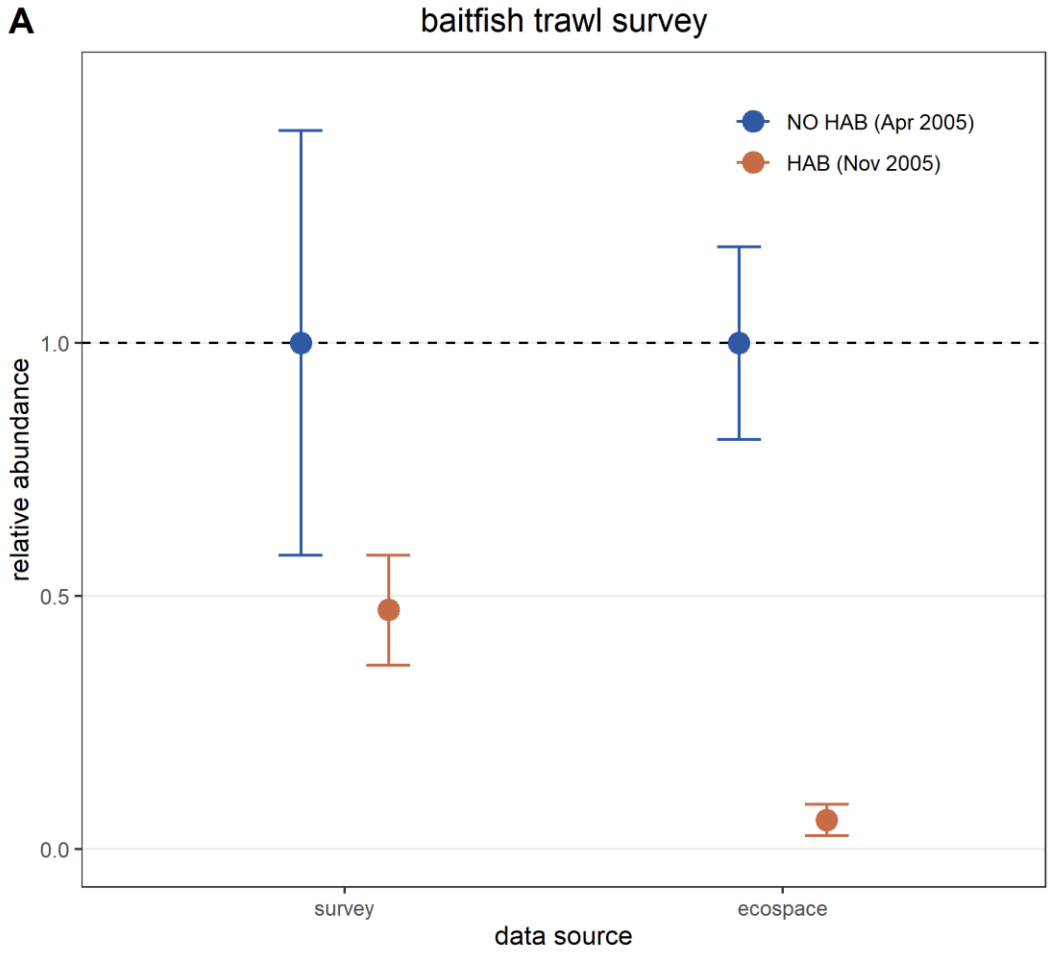
Predicted vs Observed Trends

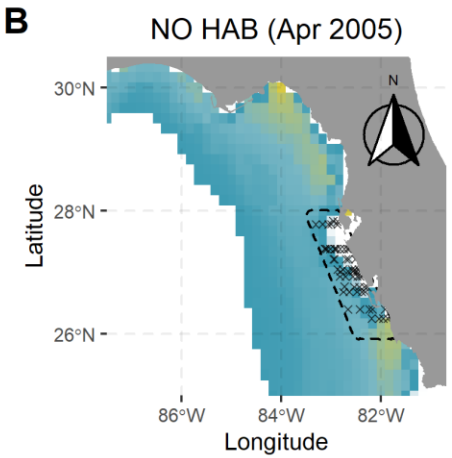
- Indices taken from SEDAR 33U assessment
- Selectivity from SS applied to convert Ecospace biomass-at-age to vulnerable biomass for each index
- RMSE within 10% of minimum considered acceptable

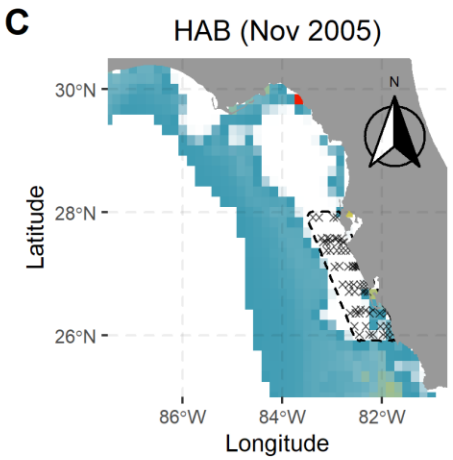
WFS Ecospace Model Red Tide Validation

2005 Before-After comparison

- FWC baitfish trawl survey samples from TB to CH April and November 2005
- Relative total fish biomass for species in the baitfish survey
- Ecospace is **potentially overestimating** red tide impacts for this event



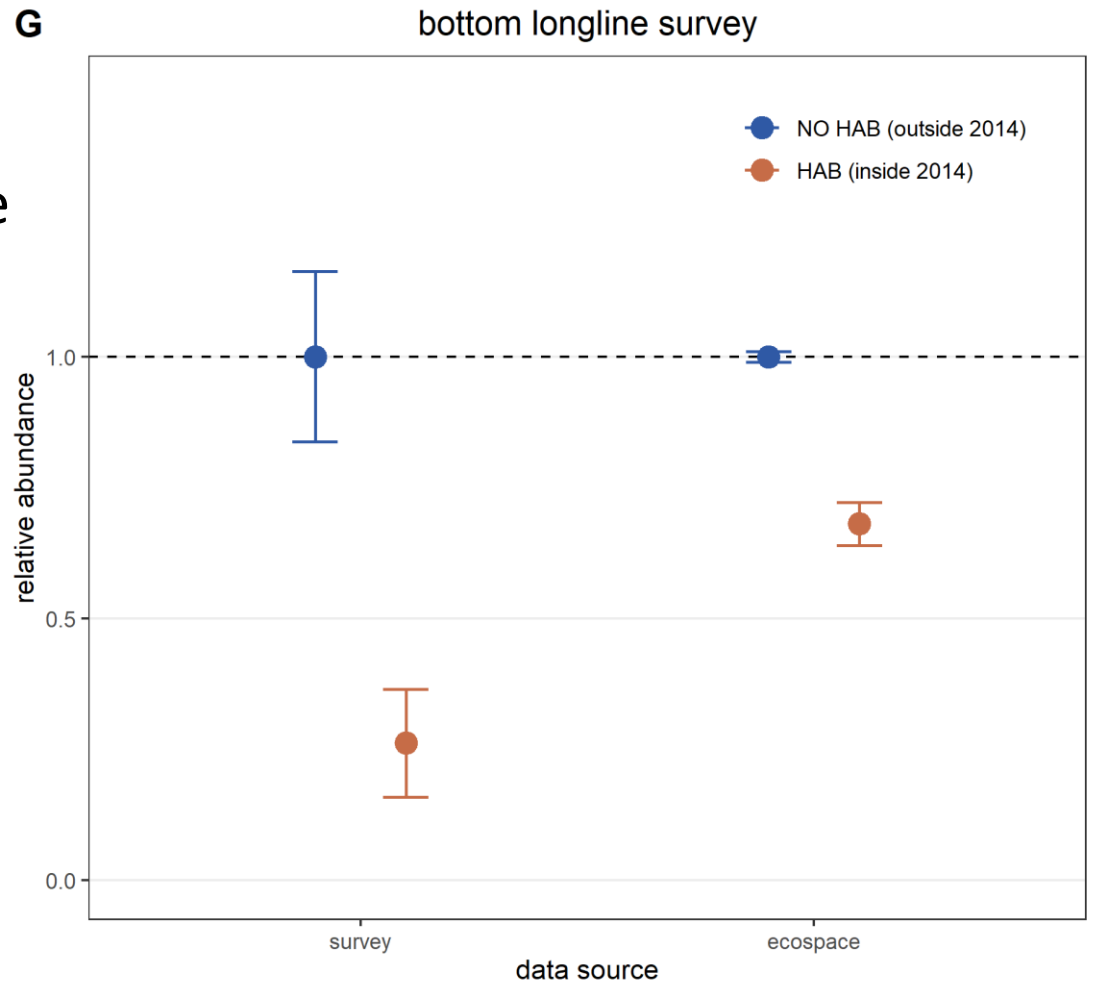


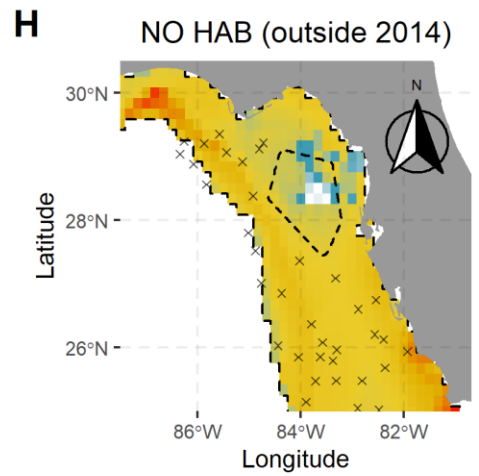


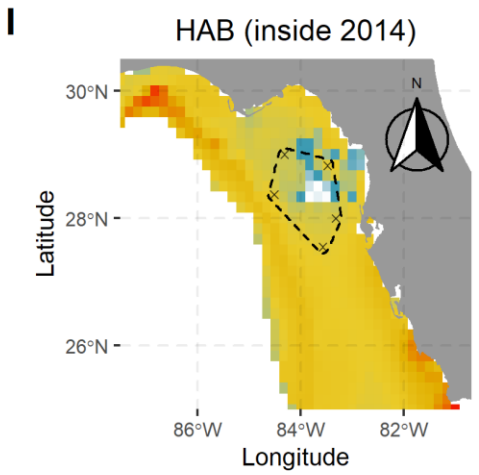
WFS Ecospace Model Red Tide Validation

2014 Inside-Outside comparison

- NMFS BLL survey sampled in the vicinity of the 2014 red tide (Driggers et al 2016)
- Relative total fish biomass for species in the BLL survey
- Ecospace is **potentially underestimating** red tide impacts for this event





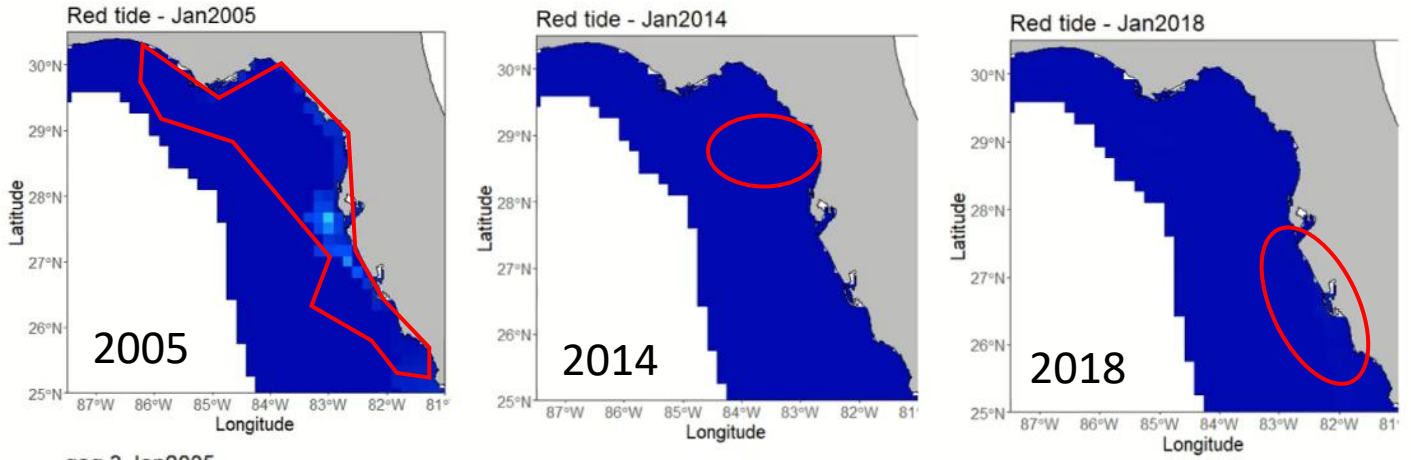


Driggers III, W.B., et al. 2016. Environmental conditions and catch rates of predatory fishes associated with a mass mortality on the West Florida Shelf. Estuarine, Coastal and Shelf Science, 168, pp.40-49.

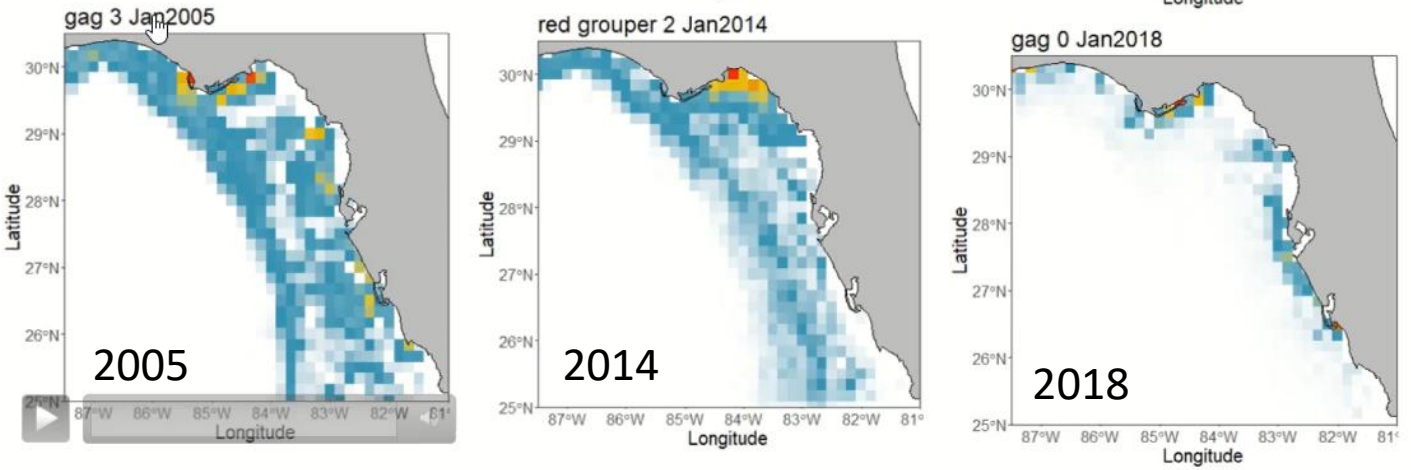
WFS Ecospace Red Tide Simulation

WFS Red tides usually occur over brief periods of time (weeks to months) and are restricted spatially (typically nearshore in the SW region)

Red tide blooms



Simulated biomass response of gag and red grouper

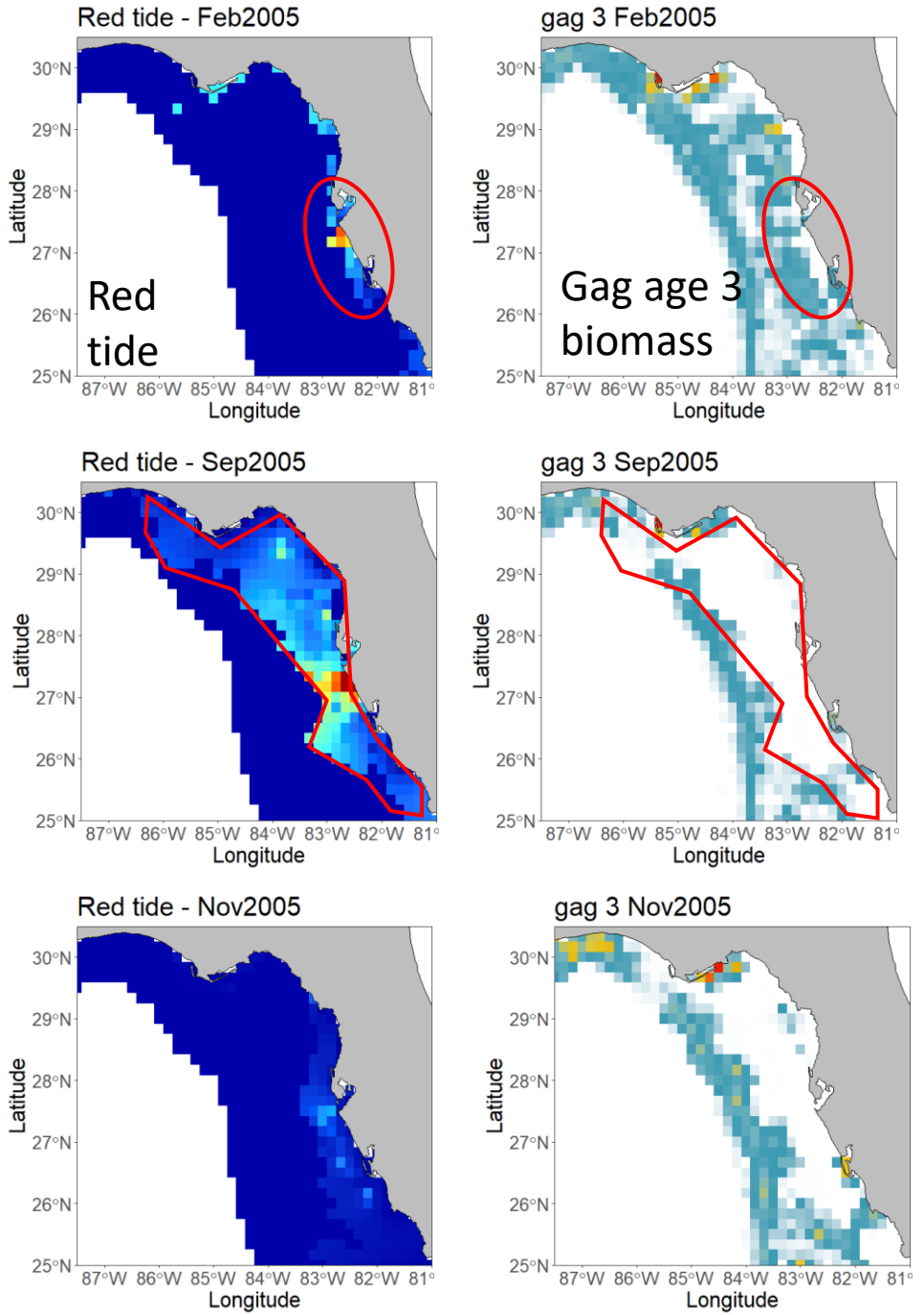


2005 Red Tide

Red tide was present in January and persisted throughout most of the year

Red tide spatial extent and severity peaked in September with broad coverage offshore

Highest estimated mortality for most species and age groups

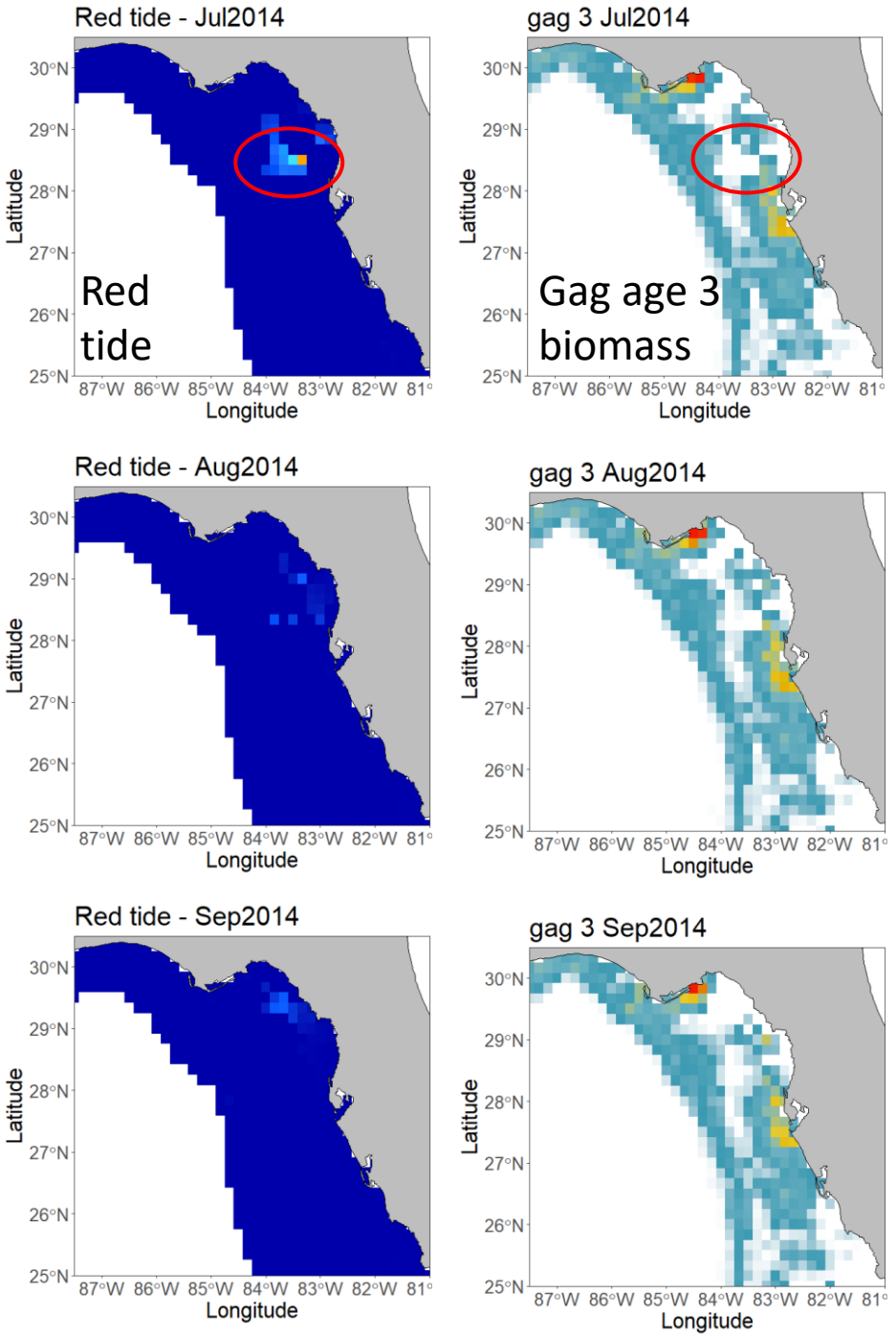


2014 Red Tide

Red tide bloom present in the FL Big Bend region during July but dissipated by September

Red tide spatial extent was limited and impacts were localized

Less severe mortality than 2005 with low mortality on juveniles

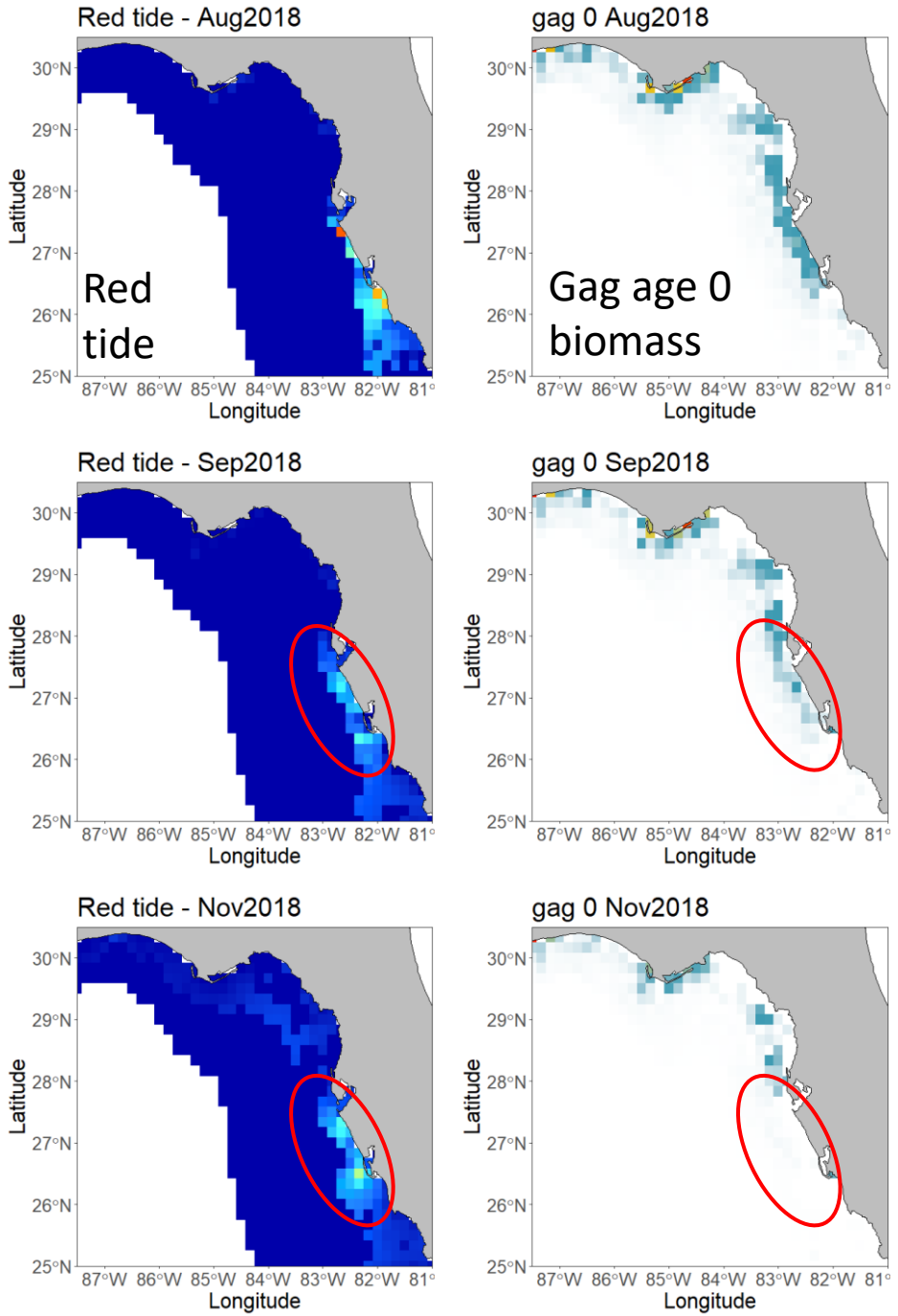


2018 Red Tide

Began in SW Florida during July and persisted through November

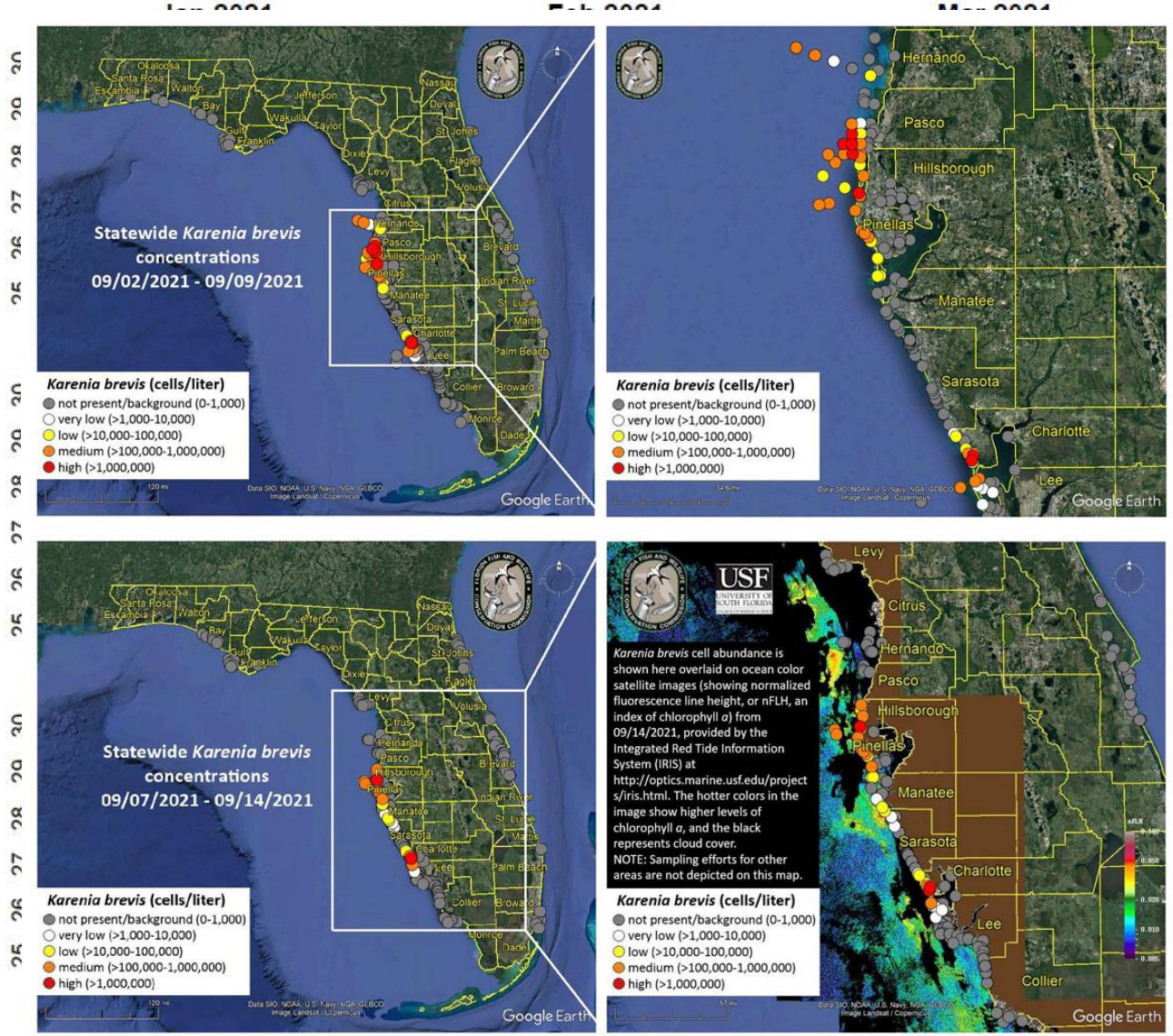
Bloom remained close to shore with peak severity in August and a northward shift in October-November

Red tide spatial extent was limited to nearshore and impacts were higher on younger ages



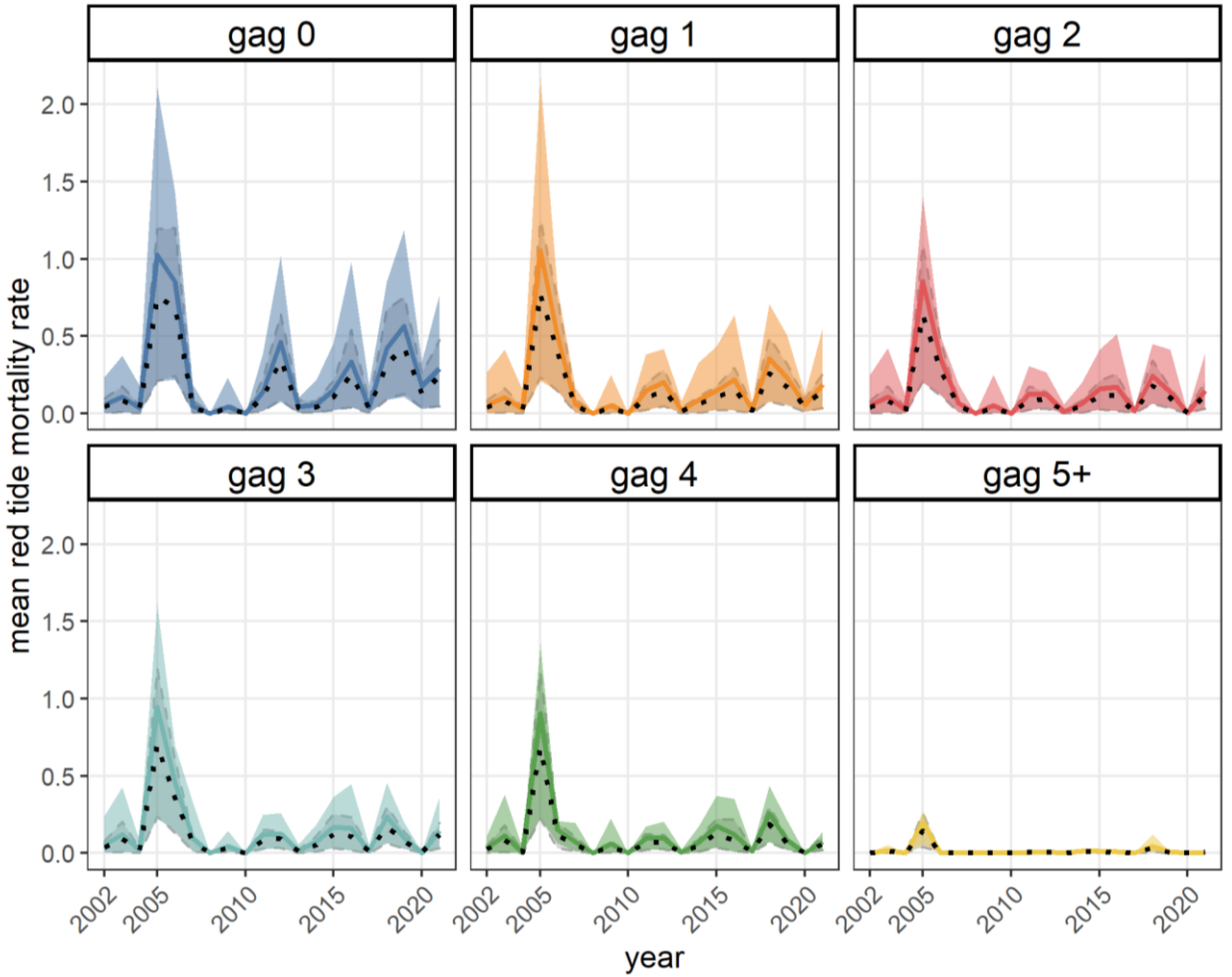
Update: 2019-2021 Red Tide

- Red tide maps and environmental drivers updated through mid August 2021
  - About a 2-week lag in data availability
  - Changes to surface chl-a vertical integration equation from SEDAR 72 WP
- 2019-2020: relatively small red tide blooms in SW Florida occurring later in the season
- 2021: Severe red tide along West Central Florida coast, in and around Tampa Bay, mostly limited to nearshore environment
  - Current sampling indicate a patchy bloom stills persists in this area



Estimated red tide mortality rates for Gag 2002- 2021 (mid Aug)

- Highest M_{RT} in 2005
  - Followed by 2006, 2018, 2012, and 2015-2016
- Higher M_{RT} for younger ages due to occurrence of blooms nearshore
- M_{RT} for age 5+ only apparent in 2005 when red tide persisted further offshore
- Low M_{RT} in 2019 & 2020
- The model estimates an **increase** in M_{RT} for 2021
  - HAB samples through Aug 16 & FLH imagery through Aug 9
  - Likely to be higher as bloom persists



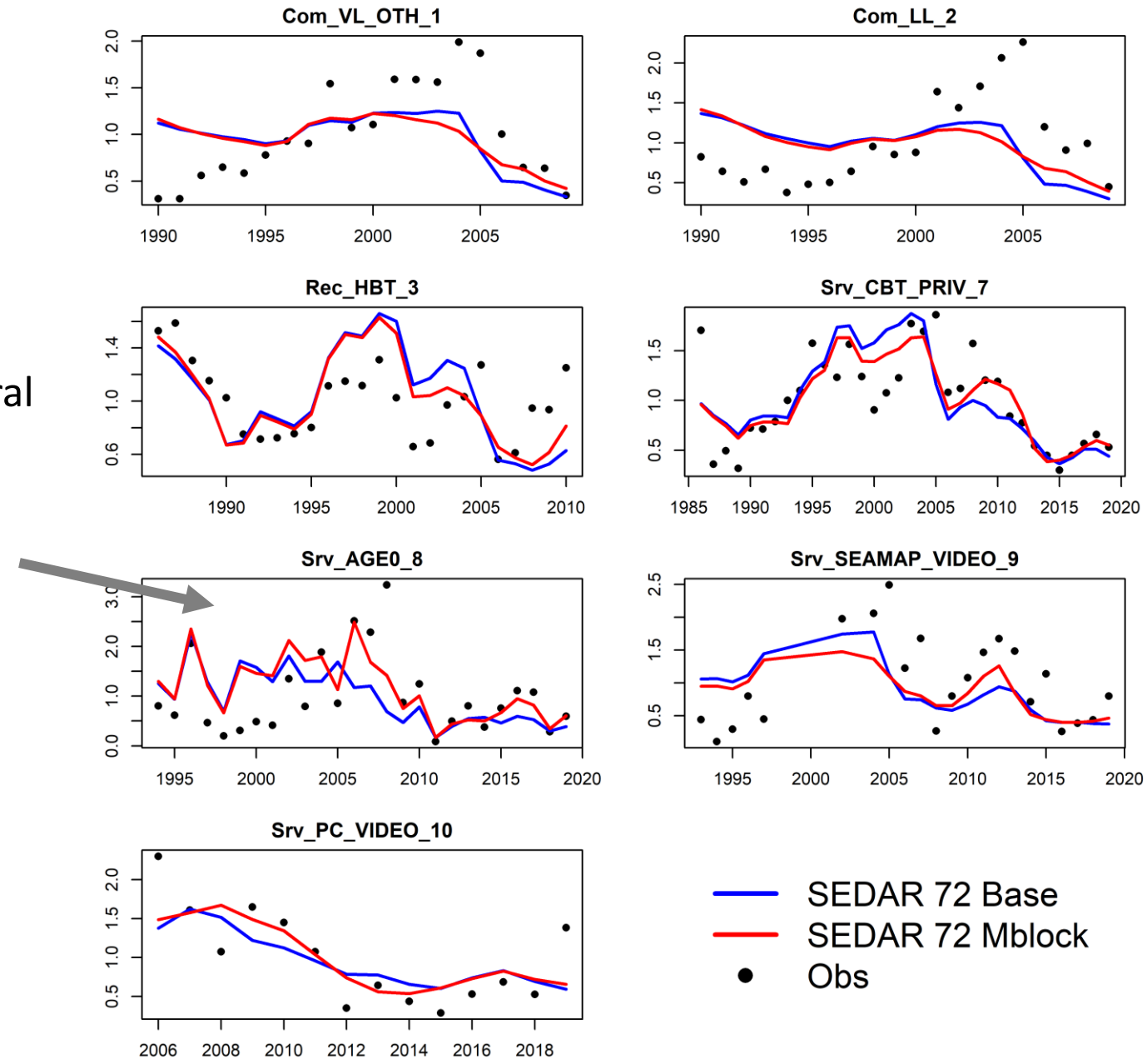
Effects on Stock Assessment Model

SEDAR 72 sensitivity run incorporated these estimates into age-specific deviations on natural mortality

Resulted in better fits to the indices (lower RMSE), especially recruitment!

Suggests that ecosystem model output is consistent with observed trends in abundance and could help improve stock assessment

However, some issues still need to be resolved in how we include red tide mortality in SS…



Red tides as a driver of population change for Gag

When red tide is included, the Ecosystem model predicts biomass trends that are similar to the stock assessment estimates that rely on recruitment deviations instead of M

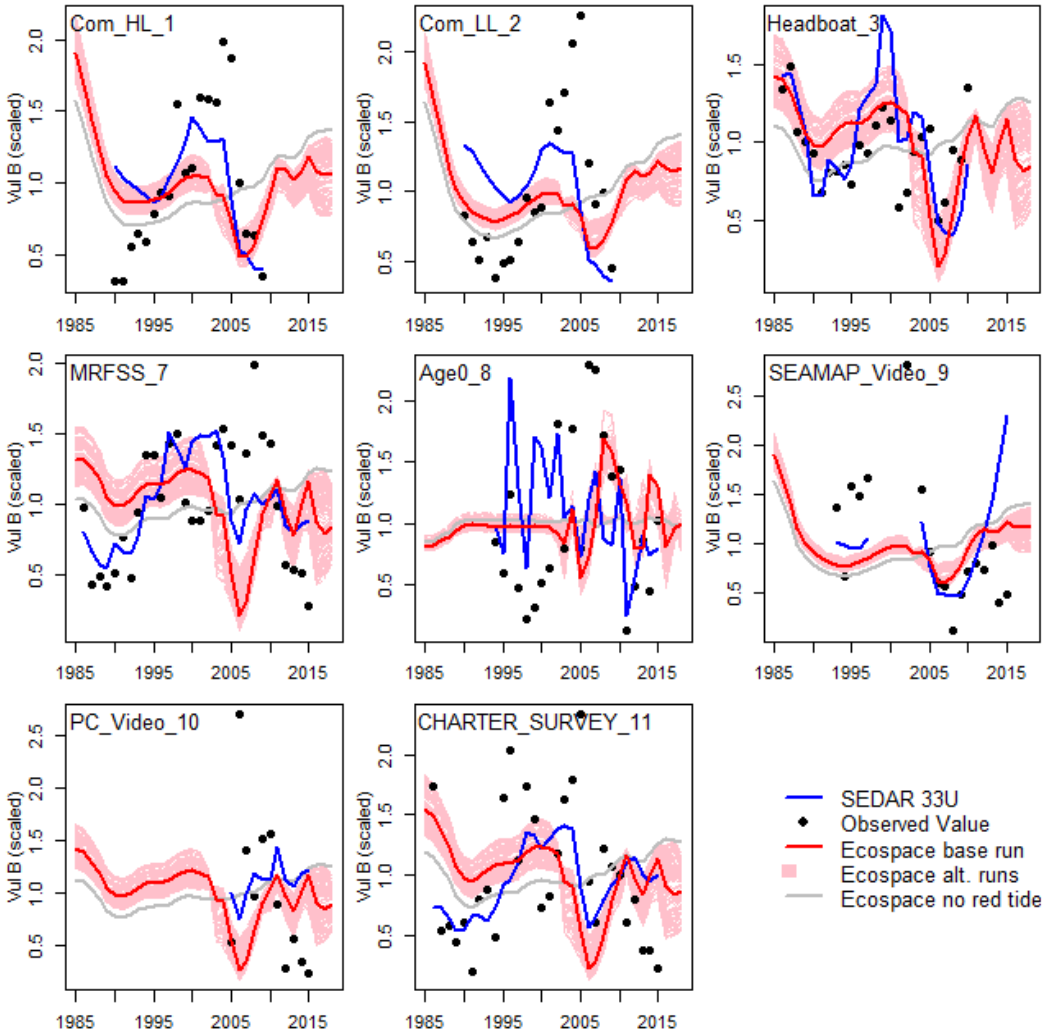
SEDAR 33U

Fishing + Recruitment Deviations

vs

WFS Ecospace

Fishing + Red Tide Effects



Red tides as a driver of population change for Gag

Ecospace also predicts increase in recruitment following red tide events, but only when red tide is affecting all species

A trophic-driven compensatory response

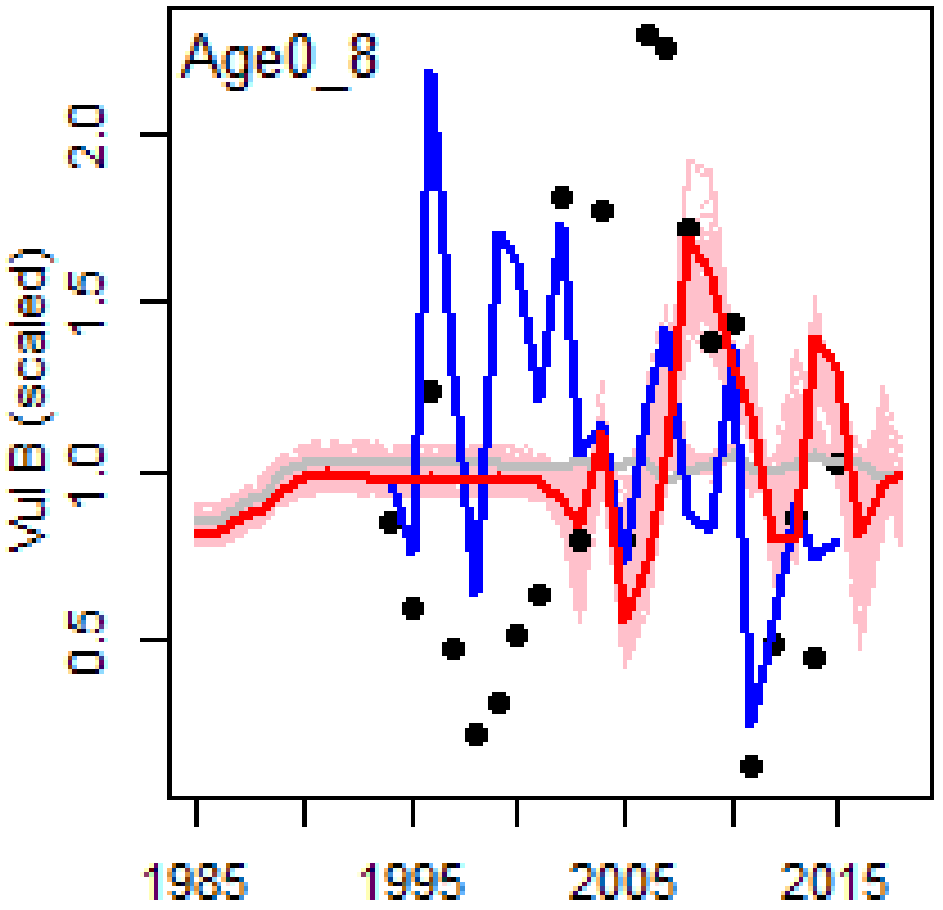
SEDAR 33U

Fishing + Recruitment Deviations

vs

WFS Ecospace

Fishing + Red Tide Effects



Uncertainties and Limitations

Relevant Uncertainties

- red tide maps – extrapolation is necessary, but introduces error
- habitat maps – especially benthic hardbottom maps that determine reef fish distribution
- Red tide response functions – shared or taxa specific
- Dispersal rates and relative movement in good vs bad habitat
- Fishing effort – spatial effort unknown for rec fleets
- Diet composition

Limitations

- Red tide maps only available beginning in 2002
- Ecospace is a simulation model only. *Parameters are not yet estimable*
- Red tide dynamics occur at finer spatial and temporal scales than model simulation
- Hypoxic conditions brought about by red tide not yet included

Ongoing & Future Modeling Work

- Construct Likelihood function to evaluate model fit
  - Regional trends
  - Map-map comparisons
  - Empirically observed effects
- Parallel computing –> 1,000s of runs per day
  - Evaluate wide range of parameter combinations
  - Additional combinations of response functions – curve shapes, affected species, etc.
- How best to incorporate into stock synthesis?

Operationalizing

- We now have capacity for timely updates to produce near real-time assessments of red tide impacts
  (2 week lag)
- Long-term maintenance should include periodic ‘benchmark’ updates (~5 years) to maintain consistency with stock assessments and new data streams
- Is a formal review and BSIA determination necessary for routine use in SEDAR assessments?

Research Recommendations

- Comprehensive sampling around red tide events – HABs, benthos, plankton, & fish
- Tagging studies to understand fish mortality and movement associated with red tides
- Mesocosm experiments to develop red tide tolerance and threshold levels of various taxa
- Simulation studies incorporating red tides into complex stock synthesis assessment models
- New algorithms to approximate red tide cell concentrations from satellite imagery
- Lab studies to understand relationship between red tide cell concentrations and bloom toxicity

Thank you!

RESTORE SCIENCE PROGRAM

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Estimated red tide mortality rates for Gag 2002- 2021 (mid Aug)

Year	age-0	age-1	age-2	age-3	age-4	age-5+
2002	0.039	0.034	0.031	0.029	0.02	0.002
2003	0.073	0.066	0.068	0.079	0.074	0.014
2004	0.018	0.016	0.014	0.013	0.004	0
2005	0.717	0.723	0.662	0.716	0.706	0.167
2006	0.675	0.403	0.266	0.347	0.118	0.003
2007	0.034	0.039	0.04	0.054	0.043	0.001
2008	0.002	0.002	0.001	0	0	0
2009	0.025	0.029	0.03	0.029	0.028	0.002
2010	0	0	0	0	0	0
2011	0.101	0.097	0.093	0.087	0.067	0.006
2012	0.274	0.164	0.093	0.104	0.069	0.008
2013	0.035	0.015	0.009	0.01	0.005	0.001
2014	0.032	0.045	0.045	0.05	0.044	0.012
2015	0.107	0.093	0.097	0.115	0.122	0.01
2016	0.217	0.144	0.106	0.106	0.074	0.006
2017	0.025	0.018	0.011	0.011	0.009	0.001
2018	0.317	0.248	0.181	0.181	0.186	0.031
2019	0.398	0.167	0.092	0.083	0.059	0.006
2020	0.122	0.044	0.006	0.006	0.002	0
2021	0.213	0.133	0.106	0.128	0.056	0.004