Addition of Ecospace Module to the South Atlantic Reef Fish (SARF) Model: Report to SAFMC SSC

Project Title
Addition of Ecospace Module to the South Atlantic Reef Fish (SARF) Model

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Purpose
South Atlantic Fishery Management Council (SAFMC) tasked the model team with developing and parameterizing an Ecospace module for the South Atlantic Reef Fish (SARF) EwE Model. The immediate objective of the SARF EwE with Ecospace model will be to explore the most likely drivers of declining black sea bass availability.

Background and Introduction

Ecopath with Ecosim and Ecospace

Ecopath with Ecosim and Ecospace (EwE) is a marine ecosystem model framework. It consists of three components: Ecopath, Ecosim, and Ecospace.
Ecopath creates a mass-balance model to represent a snapshot of the ecosystem's trophic structure during a moment in time. Inputs for each trophic group include biomass, diets, growth parameters, fishing fleets, landings, and discards. Trophic groups are linked by their diets. This portion of the model allows for exploration of key groups and ecosystem indicators that help describe the system.

Ecosim uses Ecopath as the initial starting point and simulates biomass dynamics over time for each trophic group using a system of differential equations. Ecosim forcing functions may include primary productivity, fishing mortality, fishing effort, and environmental variables. EwE models predation based on the foraging-arena theory which assumes that predator-prey interactions are not random. Prey may move from 'vulnerable' arenas (e.g., foraging in the open) to 'invulnerable' arenas (e.g., hiding). Each predator-prey pair in the model has a vulnerability parameter which is calibrated to 'fit' the Ecosim estimates to the observed data points in the time series. This may be done in both a systematic stepwise fitting routine and manually.

Ecospace consists of habitat capacity functions that incorporate environmental conditions to drive biomass movement over time and space. Specific parameters in Ecospace may include static maps (e.g., substrate maps and bathymetry), spatiotemporal data (e.g., monthly sea surface temperature and chlorophyll *a* maps) and rate variables (e.g., species' temperature tolerance curves, dispersal rates, and fishing pressure). EwE models provide a system for exploring the costs and benefits of management scenarios to all components of the ecosystem.

SAR EwE Model: High Complexity Model

The South Atlantic Region (SAR) EwE Model was adapted and refined from South Atlantic Bight models first developed in 2001 (Okey and Pugliese 2001). It has since been through 20 years of improvements and updates, with the current iteration reviewed and endorsed by the Scientific and Statistical Committee in 2020. This high complexity model serves as the primary source of data for the intermediate South Atlantic Reef Fish (SARF) Model.

SARF EwE Model: Intermediate Complexity Model

The SARF model is a model of intermediate complexity (MICE) built from the primary SAR EwE Model to address specific ecological questions. The model contains 41 functional groups (**Table 1, Table 2**) and emphasizes species in the Snapper Grouper Complex which are represented by 31 of those biomass pools. The Ecopath and Ecosim components were reviewed by the SAFMC SSC Model Workgroup and refined via a multi-day workshop. The results were presented to the SSC and Council in 2021 (SAFMC 2022). The FWRI EwE Modeling Team has been collaborating with the Scientific and Statistical Committee (SSC) Modeling Workgroup and SAFMC staff via webinars to create an Ecospace module of the SARF model and make other modifications to address questions related to black sea bass spatial dynamics. The FWRI Modeling Team has also been adding any available updated data from stock assessments, diet studies, or other literature.

The SARF model will explore possible drivers of shifting black sea bass distributions, which may include changes in habitat, productivity, competition, and predator-prey dynamics. This effort will provide the SAFMC with a tool capable of evaluating the most likely drivers of declining black sea bass availability that can easily be extended to other reef fish species that are currently experiencing declines.

South Atlantic Reef Fish (SARF) Model - Ecospace Components

Base Map and Boundaries

The spatial domain of the SARF model spans the continental shelf of the U.S. South Atlantic north of Jupiter, FL to the North Carolina northern border (**Fig. 1**). The model excludes the Florida Keys and is limited to the 600-meter isobath to include primarily those areas represented in the fisheries data included in the model parameterization. The model also represents coastal areas including estuaries, as diet information from estuaries were used in the model. This system will consist of a closed loop for its initial iterations, though future versions can potentially include migration into and out of the model area. The model area is represented as a gridded map with a spatial resolution of 15 min (~23 km^2). This resolution was selected as a compromise between computing time of spatial model runs and ability to capture meaningful fisheries and species dynamics.

Natural and Artificial Reef Habitat Layers

To drive the habitat capacity of grid cells, the model team considered multiple options for both natural and artificial reef maps. The primary layer selected was from BOEM/NCCOS 2022 predictive modeling work (Poti et al. 2022), while a compendium of natural reef points compiled by FWC (Guenther 2014, Switzer 2019) were selected as a separate layer to expand coverage of natural reef in the model. Values from each source were summed to the grid cells and imported as a portion of hardbottom coverage. Scaling these portions to values found in literature are being explored.

The artificial reef layer was compiled of points from NOAA's AWOIS and ENC shipwreck and obstruction databases, state artificial reef layers, and FWC-compiled captain-identified reef points (Guenther 2014, Switzer 2019). These points were summed and scaled to create a proportion of artificial reef likelihood in each grid cell. The team is further investigating including the temporal aspect of artificial reef deployment in the model.

Roughness

To further capture habitat dynamics, measures of rugosity, roughness, and ruggedness were examined. Roughness, calculated as the largest inter-cell difference in elevation between a pixel and its 8 neighbors, was thought to be the best measure for capturing complexity of hardbottom and non-hardbottom habitats. Two sources were reviewed: BOEM/NCCOS 2022 (Poti et al 2022) and NOAA Global Relief Topography (ETOPO 2022) with estimates of characteristics following Wilson et al. 2007. A roughness map was developed using NOAA Global Relief Model Topography.

Fishing Effort Distribution

The EwE software determines the spatial distribution of fishing effort using a gravity model in which fishing effort is distributed across cells proportional to the profitability of fishing in those cells. Profitability is determined via both the biomass value of targeted functional groups and the spatial costs that are related to distance to port for each fleet. The distribution of fishing effort from ports was derived from NOAA Fisheries of the United States Reports, ACCSP commercial catch data, and the MRIP Public Fishing Access Site Register. The entire available coastline was selected as fishing ports for private recreational boats, with specific ports for commercial and headboat fleets (**Fig. 2**).

Environmental Drivers

Ecospace's habitat capacity model determines the area each species can use in each cell by functional responses to multiple environmental factors. Spatiotemporal (ST) drivers inform habitat capacity calculations for each functional group at each time step in each cell. To inform these drivers, the model team reviewed sea surface temperature (SST), sea bottom temperature (SBT), Chlorophyll A (Chl. A), salinity, nitrates, dissolved O2, net primary production, and phytoplankton concentration data from HYCOM, MODIS, and GLORYS. Sea surface temperature (SST), sea bottom temperature (SBT), and Chlorophyll A (Chl. A) were extracted at monthly time steps through 2023 from GLORYS. GLORYS was selected in part due to the designed compatibility with climate projections. The team further decided upon two options for a basemap of GLORYS Primary Production: an average map across all months and years, and an average map across only the Ecopath base year (1995). Both of these maps will be explored in calibration to determine which is most suitable.

Environmental Preference Functions

Environmental preference functions capture each species' predicted presence across the range of each environmental driver. SARF environmental preference functions were developed using data from SERFS Chevron Traps, SERFS Video Traps, NOAA ROV Surveys, and Aquamaps. These data were fitted to binomial generalized additive models (GAMs) for each species and age stanza. Values were then predicted across the range of habitat values to create the functions (**Fig. 3, Fig. 4**). The model team is currently investigating the impacts of adding roughness to the functions.

Restricted Zones
In order to further characterize the fisheries of the South Atlantic model area, zones of restricted fishing access were added into the model's base maps. Selected areas include: Bottom Longline Restricted Zones, Black Sea Bass/Right Whale Restricted Area, Deepwater Coral Habitat Area of Particular Concern (HAPC), Oculina HAPC, and six of the Deepwater Marine Protected Areas. Some areas were deemed too small in footprint to impact the model, and thus were excluded, including the East Hump MPA, Charleston Deep Reef MPA, Oculina Experimental Closed Area, and all Spawning Special Management Zones. The restricted zones are modeled by fleet and season and are automatically applied by the model during spatiotemporal model runs. The MPA maps are also dynamic and are introduced into the model simulation the month and year that they were established. The model team is further exploring using sailing costs to limit fishing by season across larger model areas and to represent the small MPAs excluded above.

Dispersal and Migration
In Ecospace, dispersal rates for each species and age stanza control the rate at which biomass of each group can move between cells. To develop dispersal rates for the SARF model, the team reviewed tagging studies, catch and release studies, and SEDAR reviews. Dispersal was calculated as distance traveled/time at large, and values were compared against those found in other models and the 300-30-3 rule of thumb for Ecospace, which assumes dispersal rates around 300 $km \cdot year^{-1}$ for pelagic and large reef-associated species, 30 $km \cdot year^{-1}$ for small reef-associated and demersal species, and 3 $km \cdot year^{-1}$ for non-dispersing benthic or planktonic functional groups. The Dispersal Rate Estimator developed by Holden Harris was then used to further validate the dispersal estimates. The model team additionally researched large-scale species migrations (inshore vs. offshore, and north vs. south along the shelf) and determined that no population movements were significant enough to include in the model.

Ecosim Calibration
The SARF Ecosim model was calibrated for best fits to the newest available data in preparation for formal Ecospace calibration. Each predator-prey pair in the model has a vulnerability parameter which is modified by the modeler to 'fit' the Ecosim estimates to the observed data points in the time series. This was done via a systematic stepwise fitting routine followed by minor manual adjustments to fit specific features of key species' observed data. Ecosim biomass projections were fit to biomass projections from the most recent stock assessments for each multi-stanza species including the Fall 2024 SEDAR 73 update.

Review
The model team met with the SAFMC SSC Model Workgroup in June 2024 to review the model parameters and structure. The Workgroup and Model Team discussed both short-term and long-term model validation steps, as well as requested documentation. Those discussions and results are as follows:

- Artificial reefs are imported into the model as a habitat layer which is consistent throughout the model period (1995-2022). The workgroup discussed whether it would be beneficial to import layers of the artificial reefs as they were added in time.
    i. Data from state GIS services and "Artificial reef footprint in the United States ocean" (Paxton et al. 2024) indicate that the extent of known artificial reefs deployed after 1995 is approximately $0.8 km^2$. The decision was made to continue using artificial reefs as a static habitat layer, and in addition to explore the sensitivity of model outputs to using artificial reefs as a spatial-temporal variable.
- Explore scaling habitat suitability to better reflect realistic proportions of hard bottom.
    i. Habitat layers are additive, so model team is externally scaling habitat maps proportionally so as to not create unrealistic habitat capacity.

- Validate environmental data against known events
    1. The WG and SAFMC staff provided a list of large- and small-scale temperature anomalies documented during the model time period (e.g., a strong coast-wide cold water upwelling in August of 2003). The model team compared monthly bottom temperature maps from the year of the event and the years before and after. Results indicate that the GLORYS bottom temperature captured all but one known temperature anomaly events. The only reported cold water upwelling not visible in the GLORYS data was reported to have occurred overnight with temperatures returning to normal "a few days later". It was considered acceptable that such a short-lived event would not be captured in the monthly average bottom temperature. A short description and visual analysis of the full list of events is available on the Model Group Google Drive.
- Assess preference function with and without roughness.
    1. Adding roughness as a covariate to the habitat preference GAMs skewed some predictions, likely as a result of the Global Relief Topology used to predict roughness to the grid in which the data was collected. As such, the model is currently using the preference functions created from GAMs without roughness. The model team is exploring alternative data sources for deepwater species and youngest stanzas.
- Visualize preference functions for depth and bottom temperature over histograms of the model data.
    1. Depth: **Fig. 3**, Bottom temperature: **Fig. 4**. All updated figures will be available on the Model Group Google Drive as preference functions are updated for Age 0 stanzas and deepwater species.
- Explore sailing costs as a potential method to enable closed seasons and represent small MPAs.
    1. Model Team has created the associated sailing cost maps and will explore this during ecospace calibration and sensitivity testing.
- Explore the inclusion of age structure for gray triggerfish.
    1. The Model Team will reassess adding age stanzas to gray triggerfish should the species stand out as a significantly important prey or high economic value group during calibration.
- Test species movement in the model to ensure it aligns with known behaviors.
    1. This has been done throughout the Ecospace building process, and the Model Team will document specific cases during Ecospace calibration.
- Compare model dispersal rates with dispersal rate estimator based on Harris model.
    1. The Model Team met with Holden Harris to compare dispersal rates from literature review and the Holden estimator. Results were consistent for all groups and well within the 3-30-300 rule of thumb. Minor differences will be explored in Ecospace calibration to determine sensitivity of model outputs to changes in dispersal rates.
- Consider ways to compare models, focusing on emergent properties and key trends.
    1. The Model Team used the calibrated SARF Ecosim module to repeat the Red Snapper Recruitment Scenario Testing from 2021 to compare the magnitude and direction of results between the high complexity SAR EwE Model and SARF Model. Details and preliminary results below.
- Write up the methodology for future reference and consistency in creating mice models.
    1. Document the species included and excluded in the model.
        1. A spreadsheet documenting the inclusion/exclusion process during the SARF Model development is available in the Model Group Google Drive linked below.
    2. Document data treatment
        1. Ongoing

Red Snapper Recruitment Scenario Testing – SARF Model

Following the most recent Ecosim calibration, two Ecosim scenarios were created to repeat the 2021 Red Snapper Recruitment Scenario Testing originally undertaken using the high complexity SAR EwE Model (SAFMC 2021). Fishing mortality and fishing effort timeseries were extended to 2044 for all groups and fleets, and the vulnerabilities of Red Snapper Age 0, Red Snapper Age 1-3, and Red Snapper Age 4+ were adjusted to simulate the long-term average recruitment biomass projections from SEDAR 73 Scenario 7. To simulate the biomass projections for the high recent recruitment Scenario 13, a vulnerability forcing function time was scaled directly from the projections. This was linked only to the Red Snapper Age 0 and Age 1-3 vulnerabilities, simulating recruitment increases (**Fig. 5**).

The final (2044) biomass projections for all model groups were compared (longterm average recruitment scenario vs. high recent recruitment scenario) to assess the impact of the increased red snapper biomass on other groups. Results were similar to those of the 2021 analysis. Increased red snapper biomass resulted in a small (<3%) increase in the biomass of four Age 0 groups and forage fish, and a small (<5.5%) decrease in the biomass of other groups including black seabass (all ages), greater amberjack (all ages), red porgy (youngest and middle age stanza), and snowy grouper (middle and oldest age stanza) (**Fig. 6**). These results being of similar magnitude and direction as the 2021 analysis suggest that the SARF model is capturing similar ecosystem dynamics and trophic interactions as the high complexity SAR EwE model. The model team will continue to explore sensitivity analyses similar to the 2021 Red Snapper analysis, and will also repeat this analysis with the calibrated Ecospace model.

Next Steps

Following presentation to and feedback from the SAFMC SSC, the Model Team will begin formal spatial calibration of the Ecospace model. Calibration includes sensitivity testing of parameters that inform specific outputs, and results will be documented. The calibrated Ecospace model and preliminary black seabass hypothesis testing will be presented to the Model Workgroup. After incorporation of their feedback, final results will be presented via seminar series presentation.

References

Guenther, C.B., T.S. Switzer, J. Carroll, R.B. Brodie, J.J. Solomon, J.T. Sauer, and R. Paperno. 2014. The utility of a hooked-gear survey in developing a fisheries-independent index of abundance for red snapper along Florida's Atlantic coast. SEDAR41-DW08. SEDAR, North Charleston, SC. 52 pp.

Paxton, A.B., Steward, D.N., Mille, K.J. *et al.* Artificial reef footprint in the United States ocean. Nat Sustain 7, 140–147 (2024). https://doi.org/10.1038/s41893-023-01258-7

Poti M, Goyert HF, Salgado EJ, Bassett R, Coyne M, Winship AJ, Etnoyer PJ, Hourigan TF, Coleman HM, Christensen J. 2022. Data synthesis and predictive modeling of deep-sea coral and hardbottom habitats offshore of the southeastern US: guiding efficient discovery and protection of sensitive benthic areas. New Orleans (LA): US Department of the Interior, Bureau of Ocean Energy Management. 224 p. Contract No.: M16PG00010. Report No.: OCS Study BOEM 2022- 038. Okey and Pugliese 2001

SAFMC (South Atlantic Fishery Management Council). 2021. Findings of EwE South Atlantic Region Ecosystem Model Exploration of High Red Snapper Recruitment Impacts: Report to SSC. South Atlantic Fishery Management Council, 4055 Faber Place Drive, Ste 201, North Charleston, SC 29405

SAFMC (South Atlantic Fishery Management Council). 2022. Ecosystem Model of Intermediate Complexity for Snapper Grouper Complex. South Atlantic Fishery Management Council, 4055 Faber Place Drive, Ste 201, North Charleston, SC 29405

Switzer, T.S., R.B. Brodie, R. Paperno, and J.J. Solomon. 2019. Is there evidence of the size and age composition of U.S. South Atlantic Red Snapper expanding under an ongoing fishing moratorium? Cooperative Research Program (CRP) Final Report: Grant# NA17NMF4540139.

Link to Model Workgroup Google Drive:
https://drive.google.com/drive/folders/1EWvWcBHANTpa_KwGeVKcgdCjCnkqWk4F?usp=drive_link

Tables and Figures

Table 1. 41 functional groups of South Atlantic Reef Fish (SARF) EwE Model. Numbers at the end of group names indicate ages in years.

1. Sharks
2. Pelagic Piscivores
3. Greater Amberjack 0
4. Greater Amberjack 1-2
5. Greater Amberjack 3+
6. Gag 0
7. Gag 1-4
8. Gag 5+
9. Red Grouper 0
10. Red Grouper 1-3
11. Red Grouper 4+
12. Snowy Grouper 0
13. Snowy Grouper 1-4
14. Snowy Grouper 5+
15. Black Sea Bass 0
16. Black Sea Bass 1-3
17. Black Sea Bass 4+
18. Golden Tilefish 0
19. Golden Tilefish 1-3
20. Golden Tilefish 4+
21. Red Snapper Age 0
22. Red Snapper Age 1-3
23. Red Snapper Age 4+
24. Vermilion Snapper 0
25. Vermilion Snapper 1-3
26. Vermilion Snapper 4+
27. Red Porgy 0
28. Red Porgy 1-2
29. Red Porgy 3+
30. Gray Triggerfish
31. Other Groupers
32. Other Snappers
33. Grunts
34. Demersal Fish
35. Forage Fish
36. Cephalopods
37. Shrimp
38. Benthic Invertebrates
39. Zooplankton
40. Phytoplankton
41. Detritus

Table 2. Select Representatives of Aggregated Species Group. These lists are not comprehensive but provide an idea for the general types of species included in each group.

Sharks: bull, tiger, sand tiger, night, silky, spinner, dusky, blacktip and dogfish sharks
Pelagic piscivores: king mackerel, dolphinfish, marlin, bluefin/blackfin tuna, bonito, little tunny
Other Groupers: scamp, goliath, nassau, red hind, yellowmouth, coney, warsaw, speckled hind
Other Snappers: yellowtail, mutton, gray, lane, mahogany, schoolmaster, puddingwife, silk
Grunts: white grunt, tomtate, margate, sailors choice, cottonwick, spanish grunt
Demersal Fish: eels, catfish, pompano, puffers, pinfish, searobin, lizardfish, gobies, sheepshead
Forage Fish: herrings, menhaden, sardines, anchovies, halfbeaks, scads, chub mackerel
Cephalopods: octopods, squids
Shrimp: white shrimp, brown shrimp, pink shrimp, rock shrimp
Benthic Invertebrates: blue crabs, stone crabs, crabs, starfish, worms, oysters, urchins

Figure 1. Basemap of depth (derived from NOAA Bathy Database) for South Atlantic Reef Fish (SARF) EwE Model.

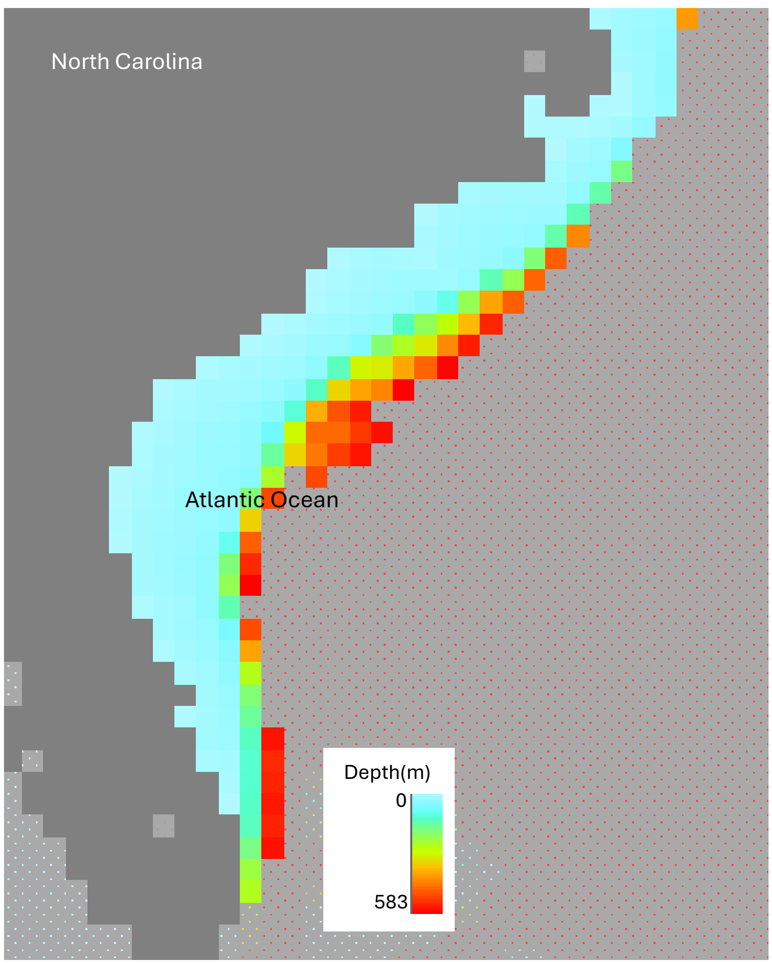


Figure 2. Maps of Ports and EwE-calculated Sailing Costs for **A)** all Commercial fleets, **B)** Recreational Headboat fleet, and **C)** Recreational Other fleets. Ports outside the model area will be removed during calibration. These sailing cost maps do not include MPAs.

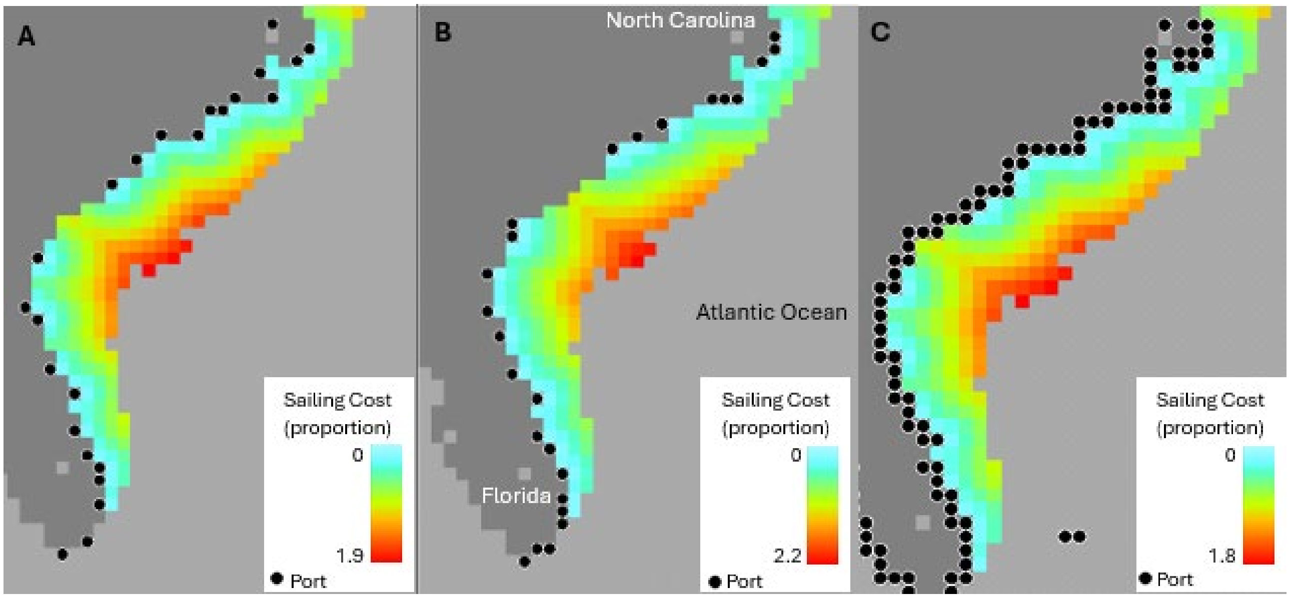


Figure 3. Depth preference functions for model groups and age stanzas overlayed on histograms of grid cells of each depth available in the Ecospace depth basemap.

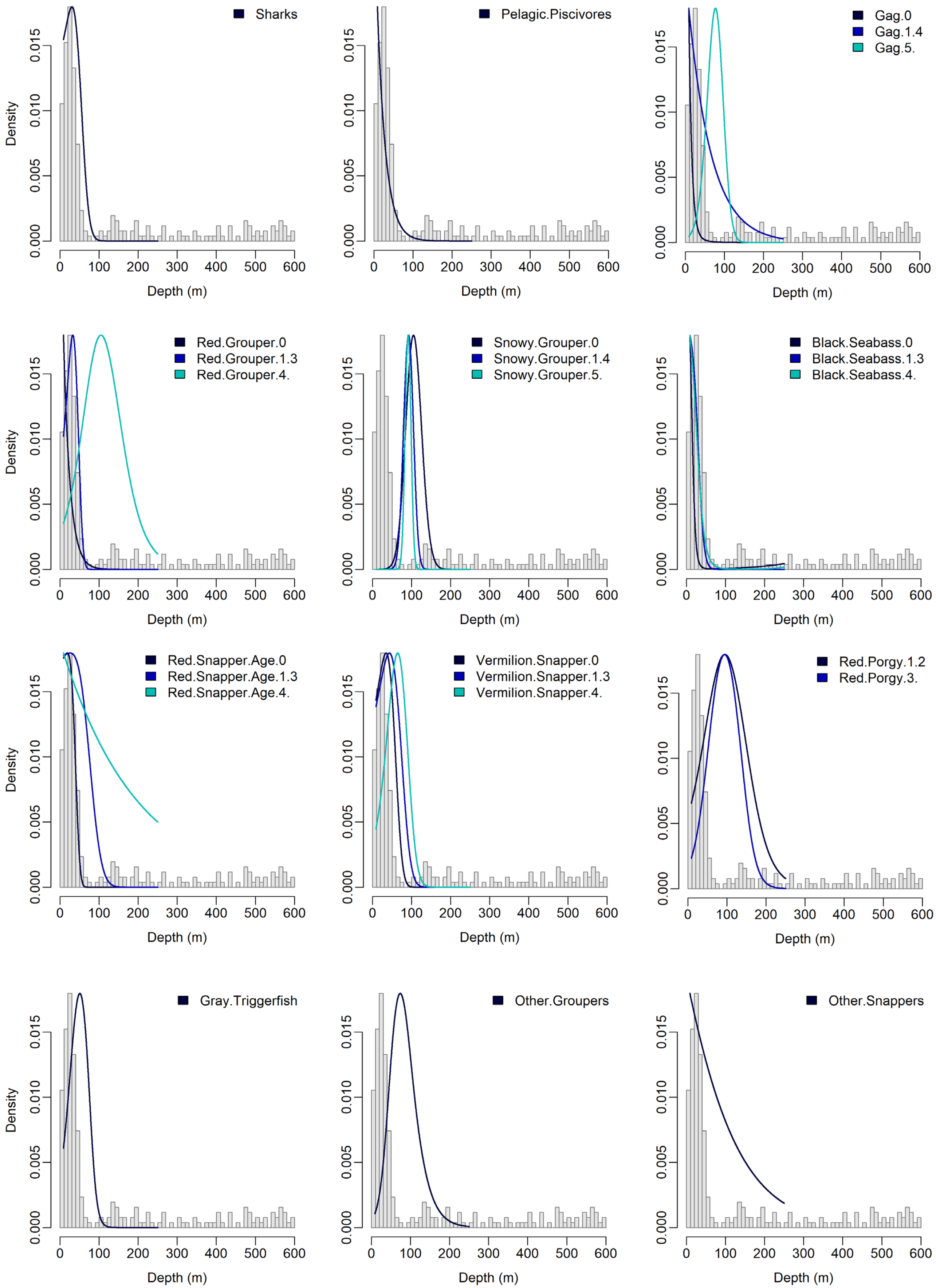
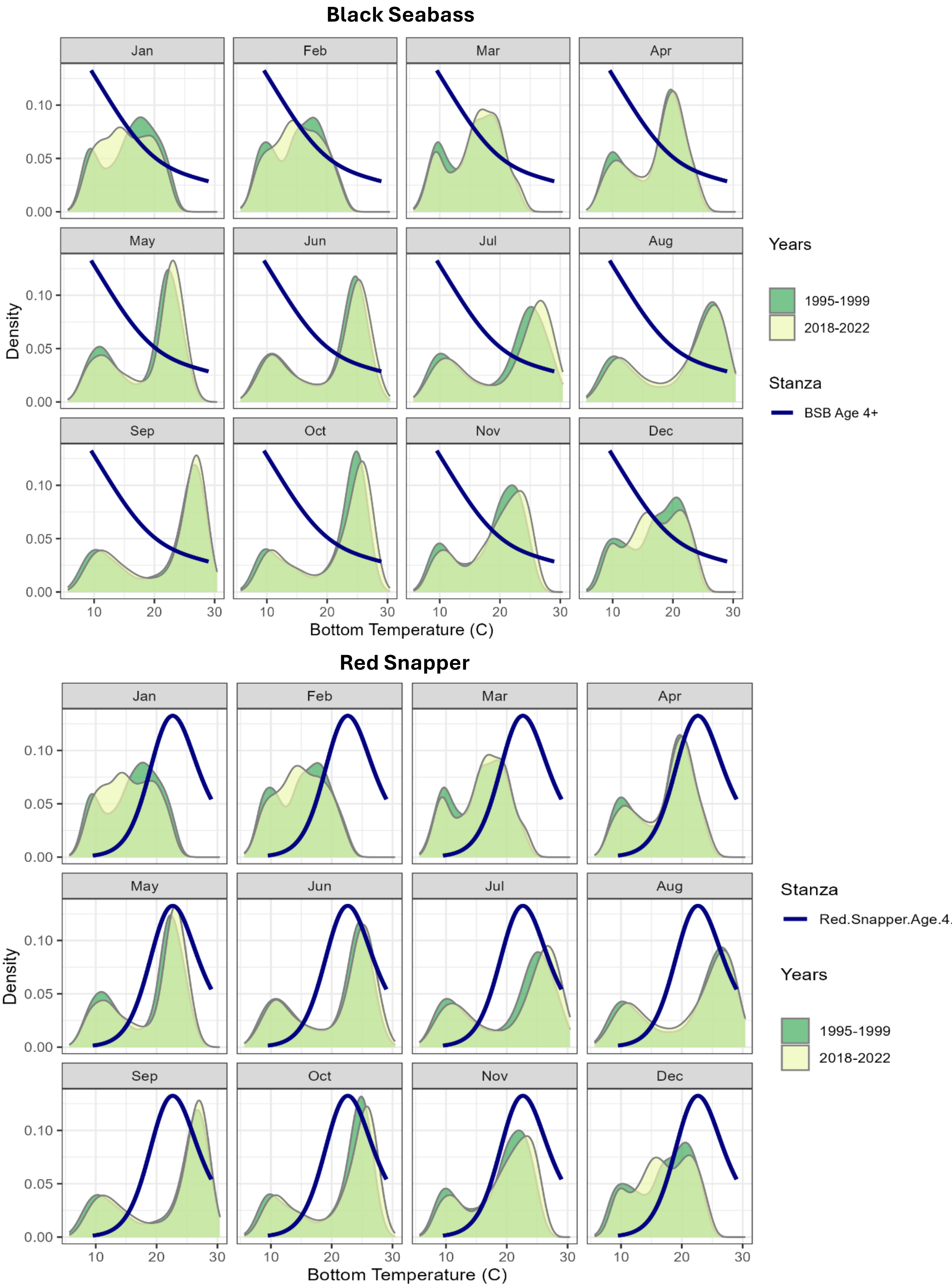
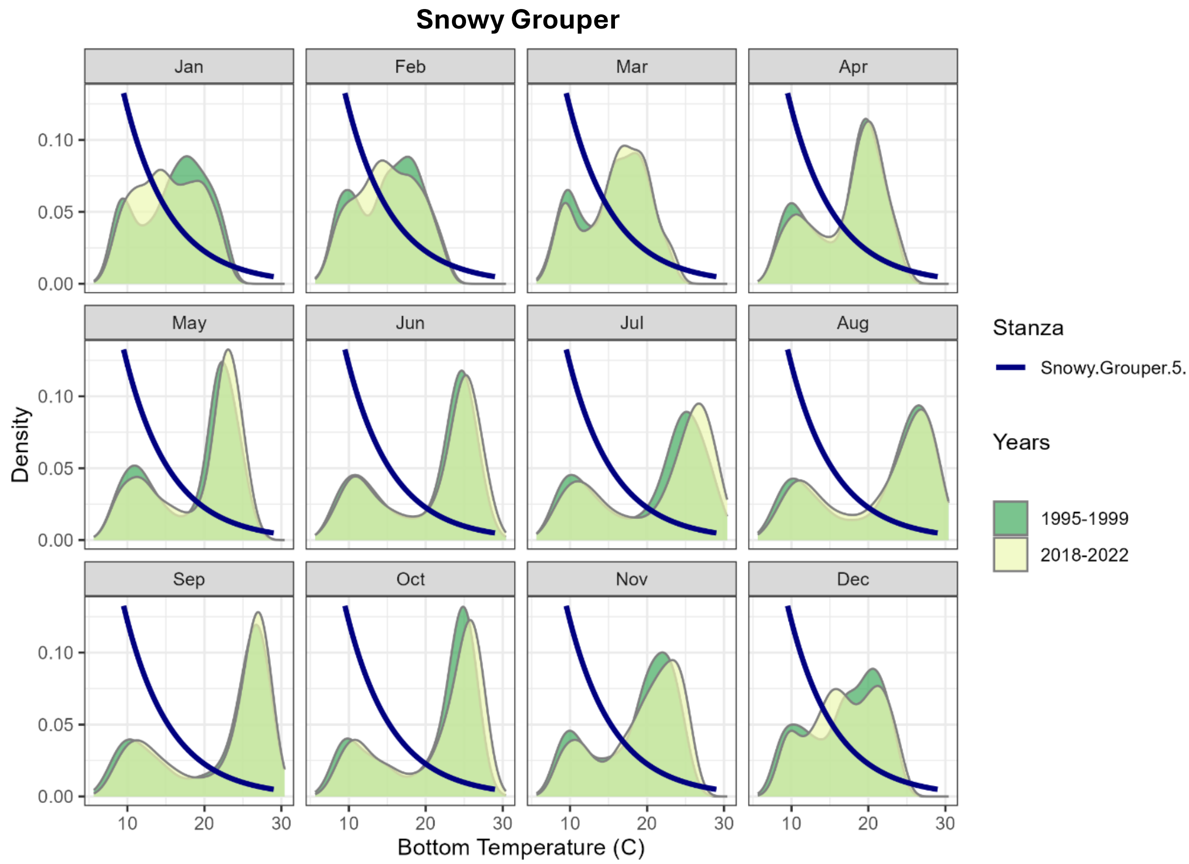


Figure 4. Bottom temperature preference functions for select model groups (adult age stanzas) overlayed on smoothed histograms of grid cells of average monthly temperatures in GLORYS spatial temporal driver maps. To visualize changes in temperature over the model period, average monthly temperatures from the first five years of the model (1995-1999) are shown in dark green, with average monthly temperatures from the last five years of the model (2018-2022) shown in yellow.




Snowy Grouper
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
0.10
0.05
0.00
Density
10
20
30
Bottom Temperature (C)
Stanza
Snowy.Grouper.5.
Years
1995-1999
2018-2022

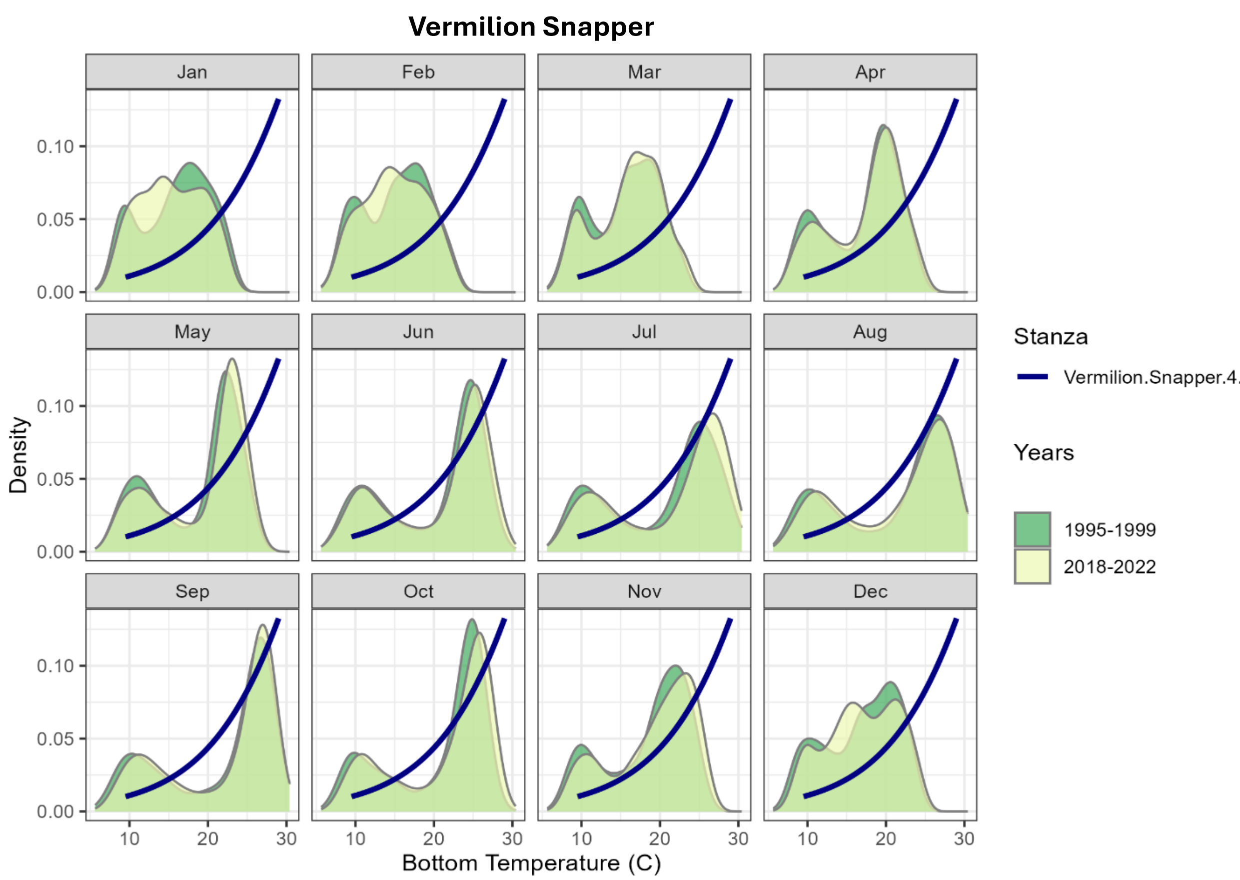

Vermilion Snapper
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
0.10
0.05
0.00
Density
10
20
30
Bottom Temperature (C)
Stanza
Vermilion.Snapper.4.
Years
1995-1999
2018-2022

Figure 5. Red Snapper biomass projections from SEDAR 73 (shown in blue) and the corresponding SARF Model Ecosim biomass projections for all red snapper (longterm average recruitment scenario shown in purple, high recent recruitment scenario shown in pink). Longterm Average Recruitment SEDAR biomass estimates are from SEDAR 73 Scenario 7, and High Recent Recruitment SEDAR biomass estimates are from SEDAR 73 Scenario 13.

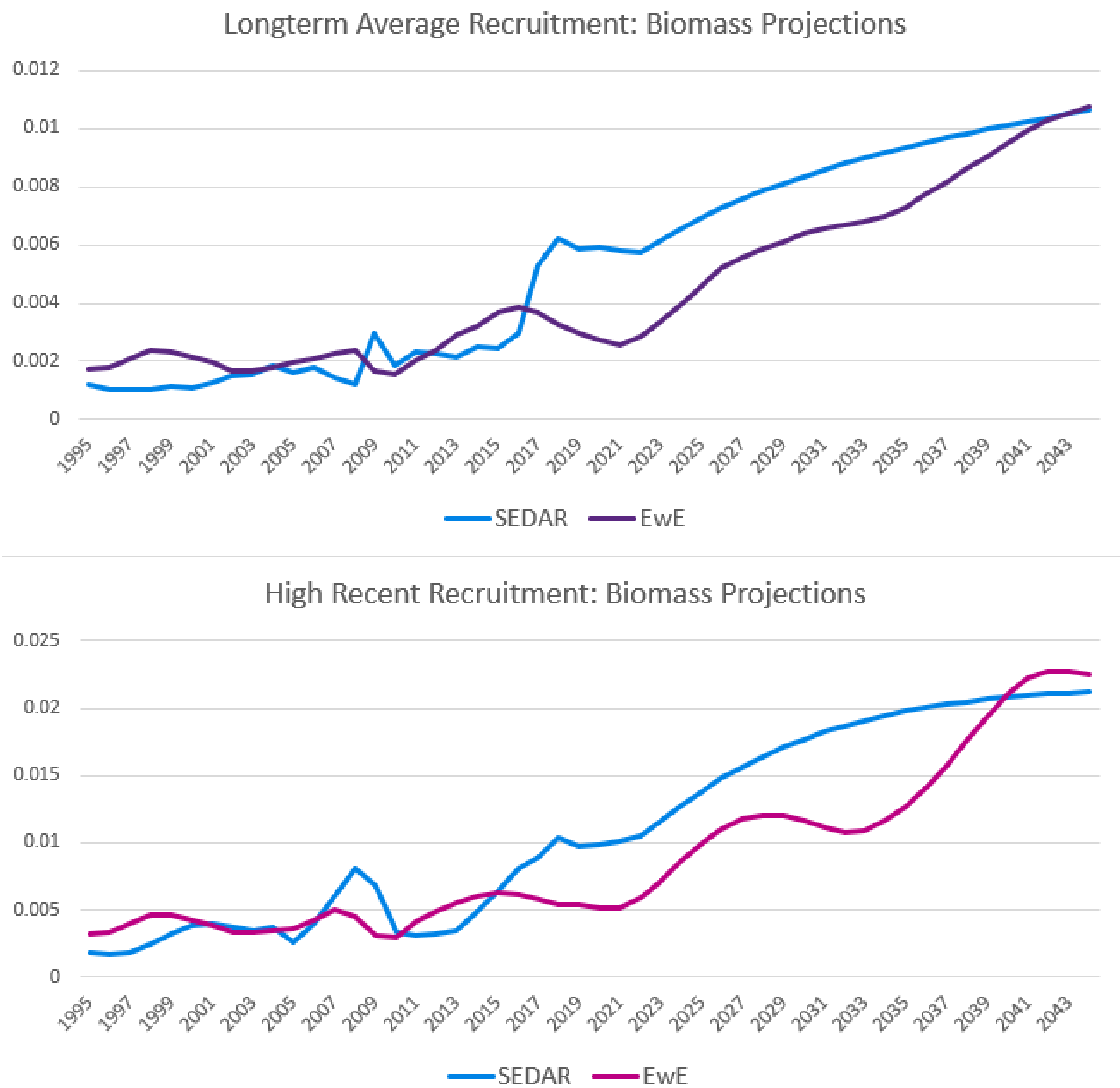


Figure 6. "Winners and Losers" from the red snapper recruitment scenario testing performed with both the high complexity SAR EwE Model (SAFMC 2021) and intermediate complexity SARF Model. Values represent the percent change of each group's 2044 biomass under high recent red snapper recruitment as compared to their 2044 biomass under longterm mean red snapper recruitment. The top and bottom of the ranked list are shown here, representing the groups most sensitive to an increase in red snapper biomass. An asterisk (*) denotes a group which is in the diet of at least one red snapper age stanza.

2021 SAR EwE Model: High Complexity | **2025 SARF Model: Intermediate Complexity**