2022

Synergistic Impacts of Climate Change and Human Induced Stressors on the Apalachicola Bay Food Web

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STARS Citation
Allen, Kira, "Synergistic Impacts of Climate Change and Human Induced Stressors on the Apalachicola Bay Food Web" (2022). *Electronic Theses and Dissertations, 2020-*. 1355.
https://stars.library.ucf.edu/etd2020/1355

SYNERGISTIC IMPACTS OF CLIMATE CHANGE AND HUMAN INDUCED STRESSORS ON THE APALACHICOLA BAY FOOD WEB

by

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A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Biology
in the College of Sciences
at the University of Central Florida
Orlando, Florida

Fall Term
2022

ABSTRACT

Apalachicola Bay, an estuary located in northwest Florida, is likely to experience an increase in climate change and human-induced stressors, such as sea level rise and changes in freshwater inflow, in the future. A coupled hydrodynamic and food web modeling approach was used to simulate future scenarios of low and high river flow and sea level rise in Apalachicola Bay from 2020 to 2049 and demonstrate the range of temporal and spatial changes in water temperature, salinity, fisheries species populations and the broader food web. Concurrent with model development, a survey of Apalachicola Bay stakeholders was conducted to assess stakeholder knowledge and concerns regarding species and environmental changes within the system. Model results indicated an increase in annual average biomass for white shrimp and blue crab under low river flow scenarios and decrease in Gulf flounder and red drum biomass. High river flow scenarios resulted in an increase in annual average biomass for blue crab and red drum and decrease for white shrimp and Gulf flounder. For all modeled simulations, the largest differences in future environmental variables and species biomasses were between scenarios of low and high river flow, rather than low and high sea level rise. Stakeholders anticipated a future reduction in river flow and increase in sea level rise as both having some negative impacts to the Franklin County economy and stakeholders' personal interaction with the Apalachicola Bay ecosystem. The use of the ensemble modeling approach combined with the stakeholder survey highlights the use of multiple knowledge types to better understand abiotic and biotic changes in the estuarine system. Results provide insight on the synergistic effects of climate change and human-induced stressors on both the estuarine food web and human community of Apalachicola Bay.

ACKNOWLEDGMENTS

I would like to thank the Lewis Lab of Applied Coastal Ecology (LLACE) for their support in making this thesis possible. Thank you to my advisor, Dr. Kristy Lewis, for encouraging me to pursue a graduate degree at UCF and always looking for ways to support my research and professional growth. Thank you to my lab mates, Victoria Roberts, Michelle Shaffer, Emma Morgan, Katherine Thompson and J.K. Andres for their support and advice throughout this whole process. A special thank you to Katherine Thompson for helping to create map images using her superior ArcGIS skills. I would also like to thank my committee members, Jason Garwood and Dr. Geoffrey Cook. Their feedback as I developed and refined my thesis was critical to its success.

I greatly appreciate the work done by my collaborators at Apalachicola National Estuarine Research Reserve (ANERR) and Tulane University in contributing to this project. ANERR's biological and environmental monitoring data were essential to developing the food web model. Jason Garwood's guidance as my mentor at ANERR was invaluable. I would also like to thank Megan Lamb for helping me sort through ANERR's monitoring data and familiarizing me with ANERR's trawl surveys. An additional thank you to Anita Grove who discussed stakeholder engagement plans with me and provided contacts to reach out to. My appreciation extends to all the staff at ANERR who provided support throughout the project, whether through the trawl surveys or helping me reach out to stakeholders. This project would also not have been possible without the work done by Dr. Kelin Hu and Dr. Ehab Meselhe at Tulane University to develop the hydrodynamic model of Apalachicola Bay. Dr. Hu was especially helpful in meeting with me to discuss the model and simulations, spearheading the

model development and communicating with me throughout the course of the project. The hydrodynamic model was essential to creating informative simulations of river flow and sea level rise in Apalachicola Bay.

I would also like to thank those who provided additional assistance in creating the food web model for Apalachicola Bay. David Gandy's help in providing Florida Fish and Wildlife Conservation Commission's fisheries independent monitoring data to supplement the food web model was greatly appreciated. Joe Buszowski provided valuable support in setting up Ecospace and assisting with any questions or problems I encountered with EwE.

I acknowledge support from the NOAA Office of Coastal Management Margaret A. Davidson Fellowship (Award #NA20NOS4200126) in providing me with funding and the resources with which to complete this thesis. I am grateful for the network I developed through the Fellowship and opportunities it presented me. I would also like to acknowledge the support of the Florida Forage Fish Research Program Fellowship in providing supplemental funds to complete my degree. This Fellowship was funded by Fish Florida and the Florida Forage Fish Coalition consisting of the International Game Fish Association, Pew Charitable Trusts, Wild Oceans, American Sportfishing Association, Florida Wildlife Federation and the Angler Action Foundation.

Finally, I give thanks to both my Florida family and Pacific Northwest family for their constant love and support over the past few years. Their belief in my success has given me strength and determination and helped me become the scientist I am today.

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1. INTRODUCTION

The combined impacts of climate change and anthropogenic factors can alter the abiotic characteristics of estuaries. At the intersection between marine and freshwater systems, estuaries are subject to the synergistic influences of warming temperatures, sea level rise, changes in precipitation and upstream re-allocation of river flow for human consumption (Trenberth 2011, Dutterer et al. 2013, Hoegh-Guldberg et al. 2014). These additive stressors have already been found to alter the dynamics of estuarine systems around the world. Estuarine water temperatures have increased over the past several decades (Seekell and Pace 2011, Scanes et al. 2020). Increases in estuarine salinity have been linked with both sea level rise and reduced river flow during drought periods (Mosley 2015, Little et al. 2017) and decreases in salinity have been linked to higher river flow due to increased precipitation (Levinton et al. 2011). Future climate change projections suggest sea level rise and warming water temperatures are likely to continue, along with the potential for both increased drought and precipitation events (Najjar et al. 2000, Trenberth 2011, Yang et al. 2015, Vargas et al. 2017, Mulamba et al. 2019).

Changes in environmental conditions through natural and anthropogenic factors have cascading impacts on estuarine food webs. Temperature changes affect the abundance and distribution of estuarine fish species based on their thermal tolerances (Roessig et al. 2004, Gillanders et al. 2011, James et al. 2013). Upstream freshwater diversions (mostly for drinking water allocation) during times of drought can negatively affect primary and secondary production in an estuary (Palmer and Montagna 2015). Changes in estuarine community structures (planktonic, benthic and nektonic) have been found to be correlated with salinity and river inflow (Greenwood et al. 2007, Telesh and Khlebovich 2010, Gillanders et al. 2011, Guenther and MacDonald 2012, Little et al. 2017). More extreme salinity events as a result of increased drought severity have adverse effects on fish survival and development (Bachman and Rand 2008) and may result in rapid changes to nekton communities (Guenther and MacDonald 2012). An increase in estuarine salinity due to the combined impacts of sea level rise and river flow reduction has consequences for estuarine structure and function, despite the known tolerance of estuarine communities to fluctuating salinity levels (Little et al. 2017).

Apalachicola Bay, Florida, is one such ecosystem influenced by climate and human-induced stressors, particularly changes in freshwater inflow and sea level rise. Apalachicola Bay is part of Apalachicola National Estuarine Research Reserve (ANERR) and is regarded as one of the most biologically diverse and productive estuaries in North America (Couch et al. 1996, Edmiston 2008). Apalachicola River is the main source of freshwater inflow to Apalachicola Bay (Huang and Spaulding 2002), driving much of the bay's productivity (Livingston 1997). A series of barrier islands border Apalachicola Bay and more saline waters from the Gulf of Mexico enter the system through several passes, flowing from east to west (Edmiston 2008). Apalachicola Bay supports productive commercial and recreational fishing industries (Edmiston 2008). The region is well known for its Eastern oyster (*Crassostrea virginica*) production and historically provided approximately 90% of Florida's oyster harvest and 10% of the national oyster demand (Couch et al. 1996). The bay's oyster reefs and wetland areas also function as important nursery habitats for other commercially valued species such as white shrimp (*Litopenaeus setiferus*), blue crab

(*Callinectes sapidus*) and a variety of fish species (Berrigan 1990). In 2007, the total commercial fishing industry in Apalachicola Bay was estimated to contribute $134 million in annual economic output to the state (Crist 2007). Recreational fishing is also highly popular in Apalachicola Bay and was reported in 2008 as contributing approximately $1.5 million annually to the local economy (Edmiston 2008). Many of the commercially and recreationally valued species, such as oysters, blue crab, shrimp and flounders, are influenced by changes in freshwater inflow and sea level rise (Livingston et al. 1997, Ruhl 2005, Solomon et al. 2014, Alizad et al. 2016), which affects the productivity of Apalachicola Bay.

One of the main stressors affecting Apalachicola Bay is reduced freshwater inflow from Apalachicola River as a result of drought and increased water withdrawals upstream. The Apalachicola-Chattahoochee-Flint (ACF) river basin encompasses roughly 30,000 km across Alabama, Florida and Georgia and terminates at Apalachicola Bay (Ruhl 2005). In the 1980s, a legal dispute began between the three states over Georgia's increasing water usage (Ruhl 2005). A decades-long United States Supreme Court legal battle ensued, which primarily focused on arguments between Florida and Georgia. Georgia called for increasing freshwater withdrawals upstream to support its growing metropolitan population's drinking water needs, especially in times of drought, while Florida argued that the reduced amount of freshwater reaching Apalachicola Bay was ecologically harmful, especially to the bay's oyster fishery (Corn et al. 2008). In 2008, Apalachicola town officials reported that four oyster beds had died due to high salinity levels (Corn et al. 2008). After a significant drought in 2012, Florida attributed the subsequent collapse of the Apalachicola Bay oyster fishery to insufficient freshwater inflow as a result of upstream water withdrawals (Hallerman 2021). The court case was eventually dismissed in 2021, maintaining the established minimum river flow regulations and allowing Georgia to continue their freshwater withdrawal practices (Hallerman 2021).

Sea level rise is another factor that impacts the salinity regime in Apalachicola Bay. Sea level rise can result in an increase in Apalachicola Bay salinity through saltwater intrusion (Huang et al. 2015) and there is a direct correlation between salinity levels in the bay and Apalachicola River flow (Huang and Spaulding 2000). Changes in both freshwater inflow and sea level rise can also act in combination with each other to influence Apalachicola Bay salinity (Sun and Koch 2001).

The effects of freshwater inflow and sea level rise on the salinity regime of Apalachicola Bay drive changes in populations of species that inhabit the system and overall biological productivity. The increase in salinity levels from sea level rise and reduced river flow impacts the bay's oyster population by creating conditions more suitable for salt-tolerant predators (Wilber 1992, Solomon et al. 2014), increased disease-related mortality, and physiological stress effects on oyster growth and reproduction (Petes et al. 2012, Huang et al. 2015). Nekton community assemblages in Apalachicola Bay and at the mouth of Apalachicola River exhibit spatial variation across distinct salinity gradients (Gorecki and Davis 2013, Garwood et al. *in review*). Fish species in Apalachicola Bay each have distinctive responses to the fluctuations in freshwater inflow, and previous drought periods have led to reduced fish species richness and trophic diversity in the system (Livingston 1997). Lower Apalachicola River flow levels are also associated with lower phytoplankton productivity, which affects the productivity of higher trophic levels (Putland and Iverson 2007c), while sea level rise is associated with lower marsh productivity (Alizad et al. 2016).

The likelihood of future changes in both freshwater inflow and sea level rise is a cause for concern in Apalachicola Bay. Climate change is expected to increase drought frequency across the United States over the next several decades (Strzepek et al. 2010). With the recent Supreme Court ruling over water usage in the ACF river basin (Hallerman 2021), Apalachicola River flow will be maintained at historically low levels during times of drought, greatly reducing the amount of freshwater inflow to Apalachicola Bay (Corn et al. 2008). There is also the potential for increased intensity of extreme rainfall events in the Apalachicola Bay region, resulting in greater river inflow (Wang et al. 2013, Chen et al. 2014). Since 1967, sea level recorded at the NOAA tide station in Apalachicola, FL has risen by approximately 0.2 m, with a linear rate of change of about 2.82 mm per year (National Oceanic and Atmospheric Administration 2022). However, global sea level trends are becoming increasingly non-linear as sea level rise interacts with tides and storm surges (Bacopoulos and Hagen 2014) and is accelerated by ocean warming and land-ice melt (Sweet et al. 2014). Future sea level rise in the Apalachicola Bay system is expected to be 22% greater than the global average, and likely to increase anywhere from 0.2 to 1.2 meters by 2060 (Osland 2020). Changes in freshwater inflow coupled with sea level rise will likely impact many of the species who inhabit Apalachicola Bay (Livingston et al. 1997, Putland and Iverson 2007b, Huang et al. 2015).

While there have been investigations on freshwater inflow and sea level rise impacts to certain individual species in Apalachicola Bay, more information is needed to better understand how the combined influence of these climate and human-related stressors can collectively impact multiple species and the overall food web. Much of the previous research on changes in freshwater inflow and sea level rise has examined the effects on Apalachicola Bay oyster populations (Livingston et al. 2000, Oczkowski et al. 2011, Petes et al. 2012, Huang et al. 2015, Fisch and Pine 2016, Kimbro et al. 2017). The response of phytoplankton and zooplankton to changes in river flow has also been studied (Putland and Iverson 2007a, Putland and Iverson 2007b, Putland and Iverson 2007c), while other investigations have evaluated the relationship between Apalachicola River flow and nekton communities (Livingston 1982, Livingston et al. 1997, Gorecki and Davis 2013, Garwood et al. *in review*). However, there is a lack of recent studies that examine how changes in both river flow and sea level rise in Apalachicola Bay can impact individual species populations as well as trophic dynamics in an estuarine food web. Moreover, outside of oysters, there are a lack of studies investigating the effects of these stressors on other species relevant to commercial and recreational fishing interests in Apalachicola Bay.

It is also important to consider local ecological knowledge and perceptions (LEK) of abiotic and biotic changes in the Apalachicola Bay system, and how these changes impact the human community. Assessing LEK in combination with scientific studies provides a more complete representation of the ecosystem and potential stressors it faces (Sánchez-Jiménez et al. 2019). Incorporating both scientific findings and LEK into ecosystem assessments is important for developing sustainable management actions that are supported by both scientific research and community stakeholders (Mackinson et al. 2011). Existing stakeholder engagement by scientific researchers in Apalachicola Bay has primarily focused on the impacts of the oyster fishery collapse and oyster reef restoration efforts (Camp et al. 2015), but there is a lack of LEK incorporation into studies investigating climate and human-related stressors on other species within the Apalachicola Bay system.

This study aims to address how the Apalachicola Bay food web (both estuarine species and human dimensions) may be affected by the combined impacts of climate change and human induced stressors, specifically changes in freshwater inflow and sea level rise. A coupled hydrodynamic and food web modeling approach was used to simulate future changes in Apalachicola River flow and sea level rise in Apalachicola Bay from 2020 to 2050. The food web response to these stressors was measured in terms of shifts in individual species biomasses over time and space, along with changes in total biomass and upper trophic level diversity. Additionally, a survey of Apalachicola Bay stakeholders was conducted to examine local ecological knowledge (LEK) on Apalachicola Bay species and environmental changes. Survey results were used to determine species of commercial and recreational fishing importance to community members, assess whether stakeholder ideas about future abiotic and biotic changes were aligned with the model simulations and better understand how such changes could impact stakeholders themselves. Analyses of the model simulations and stakeholder survey results were tailored around three central research questions:

1) How will changes in freshwater inflow and sea level rise affect the environmental characteristics (water temperature and salinity) of Apalachicola Bay?
2) How will changes in freshwater inflow and sea level rise affect species of commercial and recreational fishing importance?
3) How will changes in freshwater inflow and sea level rise affect the broader food web (total biomass and upper trophic level diversity) and human community of Apalachicola Bay?

The methods of this study rely on a synthesis of long-term monitoring data, LEK, and previous studies to create a localized portrayal of the collective effects of climate and human-induced stressors on the Apalachicola Bay system. Results provide insight on the implications of future changes in freshwater inflow and sea level rise for estuarine food web dynamics and the human communities that rely on the living resources of the estuary.

2. METHODS

This study uses a coupled hydrodynamic and food web modeling approach to address the effects of changes in freshwater input and sea level rise on the species biomasses and distributions within Apalachicola Bay. The methods draw heavily from those used in De Mutsert et al. (2017) to investigate the effects of river diversions on fish and fisheries in the lower Mississippi River Deltaic Plain. A Delft3D hydrodynamic model representative of the Gulf of Mexico was adapted for the Apalachicola Bay area and used to represent changes in hydrological conditions. The food web was modeled using the spatial-temporal data framework within the Ecopath with Ecosim and Ecospace software (EwE, www.ecopath.org, Steenbeek et al. 2013). Outputs from the hydrodynamic model served as environmental drivers in the food web model, resulting in changes in species abundances and distributions over time.

2.1 Study area

Apalachicola National Estuarine Research Reserve (ANERR) spans 246,766 acres and encompasses Apalachicola Bay and its associated tidal creeks, marshes, the lower 52 miles of Apalachicola River and its floodplain, along with portions of the offshore barrier islands (Edmiston 2008). The area encompassed by the models used in this study pertains to the species and habitat found in the Apalachicola Bay region of ANERR (Figure 1). The Apalachicola Bay system covers an area of approximately 340 km^2 behind a chain of barrier islands, receives the majority of freshwater input from Apalachicola River, and is connected to the Gulf of Mexico through two major channels in the western and eastern regions of the bay (St. Vincent Sound and St. George Sound) along with several small passes in the southern region (Edmiston 2008). The majority of species data used for this study was collected from eight sampling sites throughout Apalachicola Bay (Figure 1), which are routinely visited as part of ANERR's quarterly trawl monitoring surveys.

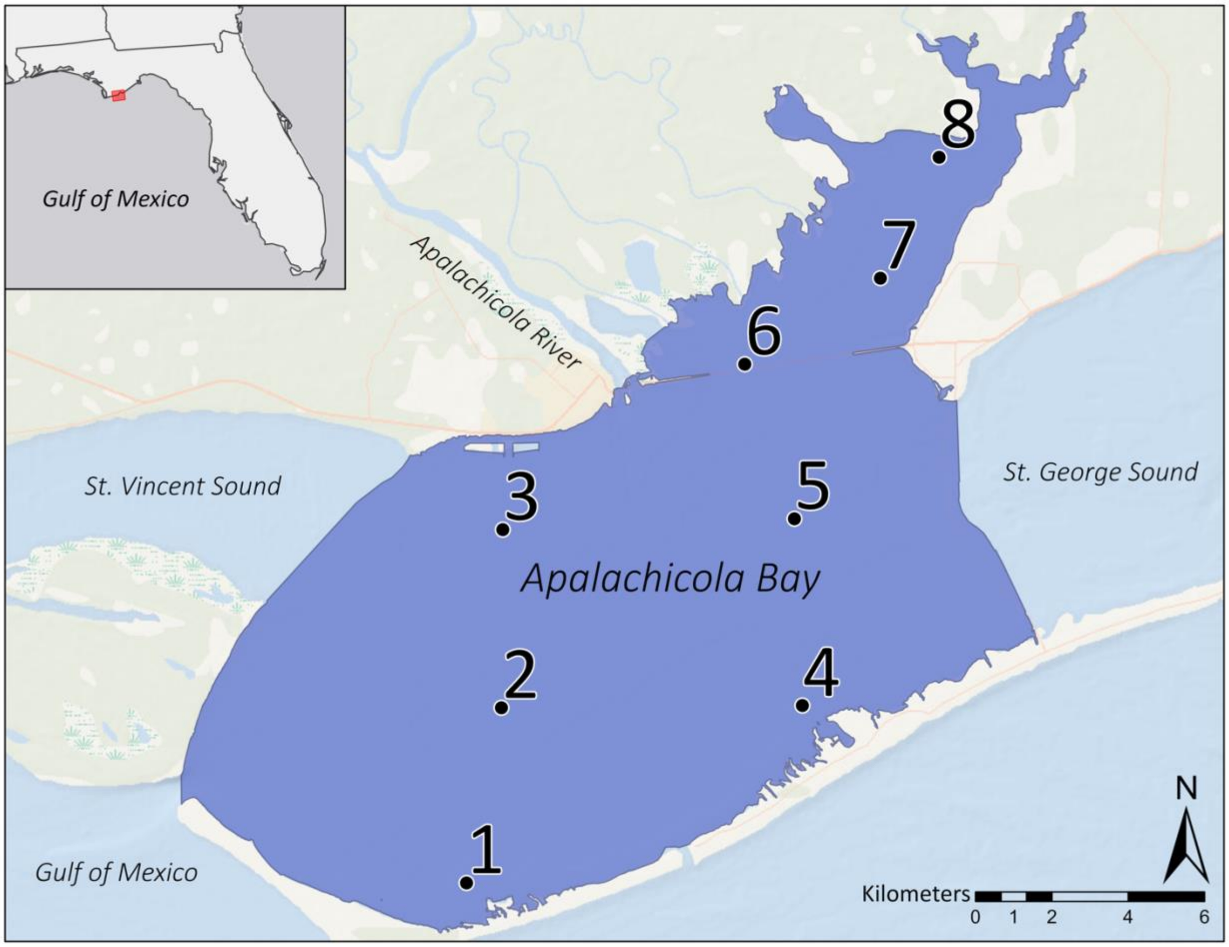


Figure 1: Location of eight ANERR long-term monitoring sample sites within Apalachicola Bay used for this study, with their associated station number. The purple shaded area encompasses approximately 249 km^2 of Apalachicola Bay. This area indicates the spatial domain of the food web model, which was limited to the region where ANERR's long-term monitoring data were available.

2.2 Development of mass-balanced food web model using Ecopath

The Apalachicola Bay food web was modeled using Ecopath with Ecosim and Ecospace software (EwE, www.ecopath.org). Developing a mass-balanced representation of the food web using Ecopath is the first step in creating an EwE model. Ecopath relies on two master equations for model parametrization. The first master equation in Ecopath pertains to the production of each functional (species) group in the model (Christensen and Walters 2004):

Production = predation mortality + fishery catches + net migration + biomass accumulation + other mortality (1)

The second master equation in Ecopath pertains to energy balance within a group (Christensen and Walters 2004):

Consumption = production + respiration + unassimilated energy (2)

The list of species represented as functional groups in the Apalachicola Bay Ecopath model was based on observed species occurrences from ANERR's trawl monitoring survey data from 2000 to 2019 and supplemented with data from Florida Fish and Wildlife Conservation Commission's (FWC) Fisheries Independent Monitoring (FIM) program within Apalachicola Bay (Table 1). The species from the ANERR data included in the model were based on the top 99% caught as part of the trawl monitoring surveys from the 20 years for which data was available. Certain additional species represented in the FIM data were added based on high catch abundance and association with popular fisheries in the area. Functional groups representing upper and lower trophic levels not often encountered in the ANERR and FWC monitoring surveys were added to the Ecopath model based on groups included in other northern Gulf of Mexico food web modeling studies, as well as in consultation with ANERR staff.

Table 1: Mass-balanced Ecopath model outcomes showing biomass ($g\ m^{-2}$), production to biomass ratio (P/B), consumption to biomass ratio (Q/B) and ecotrophic efficiency (EE). Age stanza breaks and Von Bertalanffy Growth Function (VBGF) K values are listed for multi-stanza groups. Italicized numbers indicate metrics estimated by Ecopath.

Functional group	**Biomass ($g\ m^{-2}$)**	**P/B**	**Q/B**	**Stanza break (months)**	**VBGF K**	**EE**
Large Coastal Sharks	0.0844[1]	0.30[1]	3.20[1]			*0.62*
Small Coastal Sharks	0.0757[1]	0.51[1]	4.70[1]			*0.54*
Dolphins	0.0020[2]	0.10[2]	30.00[2]			*0.80*
Seabirds	0.0080[2]	1.00[2]	17.74[2]			*0.40*
Atlantic Stingray	0.1200[3]	0.59[1,7,8]	4.26[1,7,8]			*0.11*
Snapper	0.0011[3]	1.17[8,9]	8.84[8,9]			*0.57*
Black Drum	0.0177[4]	0.58[1]	3.65[1]			*0.76*
Red Drum	0.4670[4]	1.60[8]	8.50[8]			*0.36*
Mullet	0.7530[4]	3.10[8]	19.40[8]			*0.35*
Juvenile Sand Seatrout	0.0119[3]	3.70[2]	38.61[2]			*0.62*
Adult Sand Seatrout	*1.190*	0.70[2]	*7.65*	8[11]	0.31[11]	*0.87*
Juvenile Silver Perch	0.1000[3]	3.70[2]	17.31[2]			*0.44*
Adult Silver Perch	*0.0378*	1.40[2]	*12.05*	12[11]	3.06[11]	*0.51*
Inshore Lizardfish	0.0078[3]	0.93[9]	7.33[9]			*0.40*
Fringed Flounder	0.0101[3]	0.78[1]	4.52[1]			*0.28*
Gulf Flounder	0.0117[3]	0.78[1]	4.52[1]			*0.47*
Juvenile Spot	0.3060[3]	2.00[2]	8.70[2]			*0.31*
Adult Spot	*0.1140*	1.10[2]	*5.11*	24[11]	0.89[11]	*0.42*
Southern Kingfish	0.0018[3]	1.17[10]	13.58[10]			*0.34*
Juvenile Atlantic Croaker	0.0758[3]	2.00[2]	9.34[2]			*0.35*
Adult Atlantic Croaker	*0.5420*	1.50[2]	*3.52*	12[11]	0.27[11]	*0.58*
Juvenile Pinfish	0.7270[3]	1.02[2]	19.19[2]			*0.29*
Adult Pinfish	*5.992*	0.30[2]	*8.36*	28[11]	0.33[11]	*0.49*
Juvenile Pigfish	0.1370[3]	0.80[7]	4.00[7]			*0.43*
Adult Pigfish	*0.3430*	0.80[7]	*2.08*	28[12]	0.30[12]	*0.48*
Juvenile Hardhead Catfish	0.0428[3]	2.00[2]	6.17[2]			*0.37*
Adult Hardhead Catfish	*0.2650*	0.80[2]	*2.18*	18[13]	0.25[13]	*0.88*
Gulf Butterfish	0.0006[3]	2.75[1,8]	11.45[1,8]			*0.31*
Atlantic Bumper	0.0045[3]	1.20[7]	12.00[7]			*0.33*
Menhaden	0.0079[3]	2.30[2]	19.50[2]			*0.30*
Mojarra	0.0054[3]	1.90[7]	15.00[7]			*0.42*
Brief Squid	0.0018[3]	3.35[1,9]	15.38[1,9]			*0.52*
Juvenile Bay Anchovy	0.0876[3]	3.00[2]	39.78[2]			*0.35*
Adult Bay Anchovy	*0.1150*	2.53[2]	*19.40*	12[11]	0.60[11]	*0.41*
Juvenile Striped Anchovy	0.0029[3]	2.97[1,8]	14.69[1,8]			*0.36*
Adult Striped Anchovy	*0.0031*	2.97[1,8]	*7.42*	12[11]	0.60[11]	*0.44*
Sardines	0.0917[4]	1.40[10]	12.61[10]			*0.48*
Menidia Silversides	0.2050[4]	2.30[2]	19.40[2]			*0.01*
Hogchoker	0.0021[3]	0.84[10]	15.57[10]			*0.28*
Mantis Shrimp	0.0005[3]	2.40[7]	18.00[7]			*0.37*
Roughback Shrimp	0.0005[3]	2.40[7]	19.20[7]			*0.38*
Brown Shrimp	0.0062[3]	3.00[2]	66.65[2]			*0.66*
Pink Shrimp	0.0032[3]	3.00[2]	66.65[2]			*0.59*
Juvenile White Shrimp	0.0169[3]	3.00[2]	66.65[2]			*0.77*

Functional group	**Biomass (g m^{-2})**	**P/B**	**Q/B**	**Stanza break (months)**	**VBGF K**	**EE**
Adult White Shrimp	*1.228*	2.40[2]	*19.53*	3[11]	1.55[11]	*0.72*
Arrow Shrimp	0.00002[3]	2.40[1]	18.00[1]			*0.24*
Blue Crab	0.0097[3]	3.00[2]	17.04[2]			*0.32*
Oysters	576.9[5]	2.40[2]	10.00[2]			*0.01*
Zoobenthos	24.99[1]	4.50[2]	22.00[2]			*0.77*
Macrozooplankton	6.434[1]	22.00[1]	67.00[1]			*0.74*
Microzooplankton	6.460[1]	36.00[1]	89.00[1]			*0.93*
Seagrass	13.33[6]	9.00[9]				*0.62*
Phytoplankton	25.00[1]	182.00[1,7,9]				*0.58*
Detritus	100.00[1]					*0.62*

[1]Geers et al. 2016, [2]De Mutsert et al. 2017, [3]ANERR trawl monitoring surveys, [4]FWRI FIM surveys, [5]DACS and FWC oyster monitoring surveys, [6]Apalachicola Bay Aquatic Preserve seagrass monitoring surveys, [7]Walters et al. 2008, [8]Sagarese et al. 2017, [9]Chagaris et al. 2020, [10]Abascal-Monroy et al. 2016, [11]www.fishbase.org, [12]Munyandorero and Addis 2020, [13]Flinn et al. 2019

For all functional groups in the model, Ecopath requires three out of four of the following parameters to satisfy its master equations: biomass, production to biomass ratio (P/B), consumption to biomass ratio (Q/B) and ecotrophic efficiency (EE). Ecopath parameterizes the model by solving for the fourth parameter using a system of linear equations:

$$\left(\frac{P_i}{B_i}\right) \cdot \mathrm{B_i} \cdot \mathrm{EE_i} - \sum_{j=1}^{n} B_j \cdot \left(\frac{Q_j}{B_j}\right) \cdot \mathrm{DC_{ji}} - \mathrm{Y_i} - \mathrm{E_i} - \mathrm{BA_i} = 0 \tag{3}$$

$\left(\frac{P_i}{B_i}\right)$ is the production to biomass ratio for group *i*, $\mathrm{EE_i}$ is the ecotrophic efficiency, $\mathrm{B_i}$ and $\mathrm{B_j}$ are the biomasses of prey and predators, $\left(\frac{Q_j}{B_j}\right)$ is the consumption to biomass ratio, $\mathrm{DC_{ji}}$ is the fraction of prey *i* in predator *j*'s diet, $\mathrm{Y_i}$ is the catch rate for the fishery for group *i*, $\mathrm{E_i}$ is the net migration rate, and $\mathrm{BA_i}$ is the biomass accumulation for group *i* (Christensen and Walters 2004). In this study, biomass, P/B and Q/B values were entered for each of the functional groups, while EE was left to be calculated by Ecopath. P/B and Q/B values for all species were derived from previous Gulf of Mexico food web modeling studies. Biomass (g m^{-2}) was calculated for all species from the ANERR and FIM data by converting species length measurements taken as part of the monitoring surveys into weight using length-weight regression equations and then dividing by the area sampled. To calculate average biomass values for all species for each year, all length measurements were first divided into quartiles. Length-weight regression equations ($W_i = aL^b{}_i$, where a and b are specific parameters, L_i is length of a specific species and W_i is the weight of the same species) were applied to the average length for each quartile to generate a measure of average weight (g) for each quartile. Since the number of specimens from which length measurements are taken is only a subset of the total catch of each species, the average weight for each length quartile was applied to a proportion of the total catch equal to the proportion of length measurements within each quartile (e.g. if 1/3 of the length measurements fit into the 2nd quartile, then 1/3 of the total annual catch for that species would be attributed a weight equal to the average weight of the 2nd quartile). The species weight sum (g) for each year was divided by the total area sampled (m^2) for the year to obtain an average measure of biomass (g m^{-2}).

For species making up 95% of the total catch from the ANERR surveys, length and weight measurements were collected during ANERR's quarterly trawls over a year long period to create localized length-weight regression equations (Table 2). For each trawl survey, up to three specimens of the 15 focal species were collected for length and weight measurements at each of the eight sampling sites shown in Figure 1 (for a maximum total of 96 specimens of each species for the year; IACUC approval in Appendix A). Once the year-long sampling period was complete, the length-weight regression equations were developed and used to calculate measures of species biomass, allowing for a more localized representation of those species in the food web model.

Table 2: Length-weight regression equations derived from specimens collected in Apalachicola Bay, along with average lengths and weights, and sample size (n). All lengths are standard lengths in mm (SL) and all weights are in grams.

Functional group	**Length-weight regression**	**Average length (mm)**	**Average weight (g)**	**n**
Arrow Shrimp	$W = e^{-10.24} SL^{1.89}$	30.74	0.03	19
Atlantic Croaker	$W = e^{-12.24} SL^{3.24}$	64.29	12.75	96
Bay Anchovy	$W = e^{-11.72} SL^{2.94}$	37.47	0.56	96
Brief Squid	$W = e^{-7.64} SL^{2.41}$	23.83	1.31	24
Hardhead Catfish	$W = e^{-10.93} SL^{2.88}$	113.75	36.96	79
Menhaden	$W = e^{-14.47} SL^{3.65}$	37.48	6.83	93
Pigfish	$W = e^{-15.80} SL^{4.13}$	85.28	15.47	61
Pinfish	$W = e^{-14.46} SL^{3.85}$	94.90	138.3	77
Sand Seatrout	$W = e^{-10.23} SL^{2.76}$	47.19	3.27	96
Silver Perch	$W = e^{-11.15} SL^{3.03}$	113.74	28.46	96
Spot	$W = e^{-12.57} SL^{3.31}$	57.6	14.33	96
Striped Anchovy	$W = e^{-13.90} SL^{3.53}$	41.47	1.58	30
White Shrimp	$W = e^{-11.73} SL^{2.90}$	66.46	2.66	96

Species that contributed the top 90% of biomass across all years of the ANERR survey data were selected and divided into multi-stanza groups (adult and juvenile) to better represent ontogenetic differences across a species life history (particularly in regard to diet; Christensen and Walters 2004). The majority of specimens observed in ANERR's trawl surveys tend to be of juvenile age classes, so juvenile was selected as the "leading" stanza (used to calculate estimates for the non-leading stanza) for all multi-stanza species in the food web model. For multi-stanza groups, Ecopath requires biomass, P/B and Q/B values for the leading stanza and only a Q/B value for the non-leading stanza. Von Bertalanffy Growth Function K and age at maturity values are also required for each multi-stanza species. Once all multi-stanza parameters are entered, Ecopath estimates biomass and P/B values for the non-leading stanza of each multi-stanza species.

Additional species known to belong to the Apalachicola Bay food web, but not well-represented in the ANERR and FIM sampling data, were included in the food web model to better represent upper and lower trophic level groups. For species with insufficient local monitoring data available, biomass values were based on those reported by other northern Gulf of Mexico food web modeling studies (Table 1). This method was used for Large and Small Coastal Sharks, Dolphins, Seabirds, Zoobenthos, and Macro and Microzooplankton. Initial phytoplankton biomass was based on Steidinger's (1973) estimate, an approach often used across food web modeling studies. Oyster biomass was calculated by converting length measurements collected in surveys done by the Florida Department of Agriculture and Consumer Services (FDACS) and FWC into weights using a length-weight regression equation developed by FWC (M. Davis, *unpublished data*). Oyster biomass was subsequently multiplied by 0.1 to better represent the historical 10% coverage area of oyster bars in the whole of Apalachicola Bay (Livingston 1984). Seagrass biomass was calculated by converting Braun-Blanquet scores and blade lengths collected by Apalachicola Bay Aquatic Preserve into Leaf Area Index (LAI; Pocock et al. 2010). LAI was subsequently converted into weight (Hill et al. 2014) and divided by the area sampled to obtain biomass. The resulting biomass value was multiplied by 0.07 to account for seagrass areas covering approximately 7% of Apalachicola Bay (Edmiston 2008).

A diet matrix was developed to represent the proportion of prey items in each functional group's diet and drive the trophic interactions in the model (Supplemental Table 1). Diet proportions were based on information provided by previous diet studies, and the FishBase (fishbase.se) and GoMexSI (gomexsi.tamu.edu) databases (diet sources described in Appendix B). Through its master equations, Ecopath is able to calculate ecotrophic efficiency (EE) values for each functional group in the model, which serves as an indicator of how much each group is consumed in the system. An EE value greater than 1 indicates that a species is being overconsumed, which prevents the food web model from reaching a mass-balanced state. To reduce a group's EE value and reflect a more reasonable level of consumption, the amount that group was being consumed by other species in the model was sequentially reduced until the EE value reached an acceptable level. In some cases, the EE value for a species was too low considering the status of that species as a common prey item. For these species, their proportions in various consumer diets were increased to result in a higher EE value. Once the EE values for all functional groups in the model reflected a reasonable level of consumption, the model was considered mass-balanced.

Commercial and recreational fishery fleets and landing amounts were also included in the Ecopath model (Table 3, Supplemental Table 2). Commercial fishing fleets were defined based on their target species, and landing amounts were derived from FWC trip ticket data. Apalachicola Bay species are influenced by commercial fishing both within Apalachicola Bay and the greater northern Gulf of Mexico region when their populations seasonally migrate in and out of the system. To proportionally represent how much Apalachicola Bay is affected by commercial fishing in both the bay itself and surrounding area, landing weights for each species were divided by the area of the northern Gulf of Mexico (310000 km^2, Sagarese et al. 2017) to obtain landings in $t\ km^{-2}$ (metric tons per square kilometer), which are the units required by the model. For fishing fleets with multiple target species (e.g. sharks, bait fish, etc.), landing amounts were divided across the target species according to the proportion of each species' biomass in relation to the total biomass available to the fleet (e.g., if bay anchovy made up 30%

of the biomass available for the bait fish fleet, then 30% of the fleet landing amount would be bay anchovy). Bycatch amounts for commercial fishing fleets were based on available bycatch ratios presented in National Marine Fisheries Service National Bycatch Report documents (U.S. Department of Commerce et al. 2011, Benaka et al. 2019). Recreational fishery landings in the model were derived from NOAA Marine Recreational Information Program (MRIP) surveys. As recreational fishing is more localized to Apalachicola Bay, recreational landing weights were divided by the area of the bay (337.962 km^2, Edmiston 2008) to get landings in terms of t km^{-2}. As with consumer diets in the food web model, the EE values output by Ecopath also reflect how much each species' biomass is consumed by fishing fleets. Adjustments to the diet matrix were able to lower EE values for species being over-consumed in most cases, in some instances fishery landing amounts needed to be reduced as well. Once fishery and diet amounts for all functional groups in the model were adjusted to reflect reasonable EE values, the Ecopath model balancing process was complete.

Table 3: Fishery fleets in the food web model with their target species and bycatch. A ~ indicates no bycatch was represented for that fleet in the food web model. Fishing fleet information was sourced from FWC trip tickets and Marine Recreational Information Program surveys. Bycatch information was sourced from National Marine Fisheries Service Bycatch Report documents (U.S. Department of Commerce et al. 2011, Benaka et al. 2019).

Fleets	**Target species**	**Bycatch**
Bait fish	Atlantic Bumper Bay Anchovy Menhaden Mullet Pigfish Pinfish Sardines Striped Anchovy	~
Blue Crab	Blue crab	~
Catfish	Hardhead Catfish	~

Fleets	**Target species**	**Bycatch**
Commercial Shrimp	Brown shrimp Pink shrimp White shrimp	Atlantic Croaker Black Drum Large coastal sharks Red Drum Sand Seatrout Small coastal sharks Snapper
Atlantic Croaker	Atlantic Croaker	~
Dolphin	Dolphins	~
Black Drum	Black Drum	~
Flounders	Fringed Flounder Gulf Flounder	~
Menhaden	Menhaden	~
Mojarra	Mojarra	~
Mullet	Mullet	~
Other Shrimp	Roughback shrimp	~
Oysters	Oysters	~
Pinfish	Pinfish	~
Rays and Skates	Atlantic stingray	~
Recreational	Atlantic Bumper Atlantic Croaker Black Drum Dolphins Gulf Flounder Hardhead Catfish Inshore Lizardfish Large coastal sharks Menhaden Pigfish Pinfish Red Drum Sand Seatrout Sardines Silver Perch Small coastal sharks Snapper Southern Kingfish Spot	~
Sand Seatrout	Sand Seatrout	~
Sharks	Large coastal sharks Small coastal sharks	Atlantic stingray Red Drum
Snapper	Snapper	~

Fleets	**Target species**	**Bycatch**
Spot	Spot	~
Squid	Brief squid	~

2.3 Model calibration in Ecosim

Ecosim is the time-dynamic module of EwE. Ecosim uses the initial conditions defined in the mass-balanced Ecopath model and defines changes in biomass over time through a series of coupled differential equations:

$$\frac{\mathrm{d}B_i}{\mathrm{d}t} = g_i \sum Q_{ji} - \sum Q_{ij} + I_i - (M0_i + F_i + e_i) \times B_i \tag{4}$$

These equations are derived from the Ecopath master equation (Eq.1). Growth rate is represented by $\frac{\mathrm{d}B_i}{\mathrm{d}t}$, where B_i is the biomass of a species in the model and t is the time interval, g_i is the net growth efficiency and is the quotient of $(P/B)_i$ and $(Q/B)_i$, $\sum Q_{ji}$ is the total consumption by group i, $\sum Q_{ij}$ is the total predation on group i by predators in the model, I_i is immigration rate, $M0_i$ is the non-predation mortality rate, F_i is the fishing mortality rate, and e_i is the emigration rate (Christensen and Walters 2004). Consumption rates (Q_{ij}) are defined in Ecosim by:

$$Q_{ij} = \frac{a_{ij} v_{ij} B_i B_j T_i T_j S_{ij} \frac{M_{ij}}{D_j}}{v_{ij} + v_{ij} T_i M_{ij} + a_{ij} M_{ij} B_j S_{ij} \frac{T_j}{D_j}} \tag{5}$$

where a_{ij} is the search rate for prey I by predator j, v_{ij} is the vulnerability of prey to predation, B_i is the biomass of the prey, B_j is the predator biomass, T_i is prey relative feeding time, T_j is predator relative feeding time, S_{ij} represents environmental forcing functions (defined by the user), M_{ij} is mediation forcing effects (when a third organism affects a predator-prey interaction) and D_j is the effect of handling time on limiting consumption rate (Christensen and Walters 2004).

Model calibration in Ecosim relies on the input of time series representing species biomass, fishery catch and effort, and environmental conditions. Hindcasting the food web model using these historical data improves the confidence of the simulated future model runs by fitting modeled outcomes to observed data. Annual time series of species biomass from 2000 to 2019 were developed for all species where long-term monitoring data were available during this period, resulting in a total of 36 biomass time series. Biomass data for the time series were derived from the same sources as the initial measures of biomass for each species in the Ecopath module (Table 1). Annual time series of fishery catch and effort from 2000 to 2019 were derived from FWC trip ticket data for all commercial fleets and NOAA MRIP surveys for the recreational fleet. Bycatch amounts for commercial fishing fleets were calculated in the same manner as before (see section 2.2). Monthly measures of water temperature and salinity over the 20-year time period were included as environmental forcing functions in the model (Figure 2). These data were derived from ANERR’s System-Wide Monitoring Program (SWMP), a network of six environmental monitoring stations located throughout Apalachicola Bay (NOAA National Estuarine Research Reserve System).

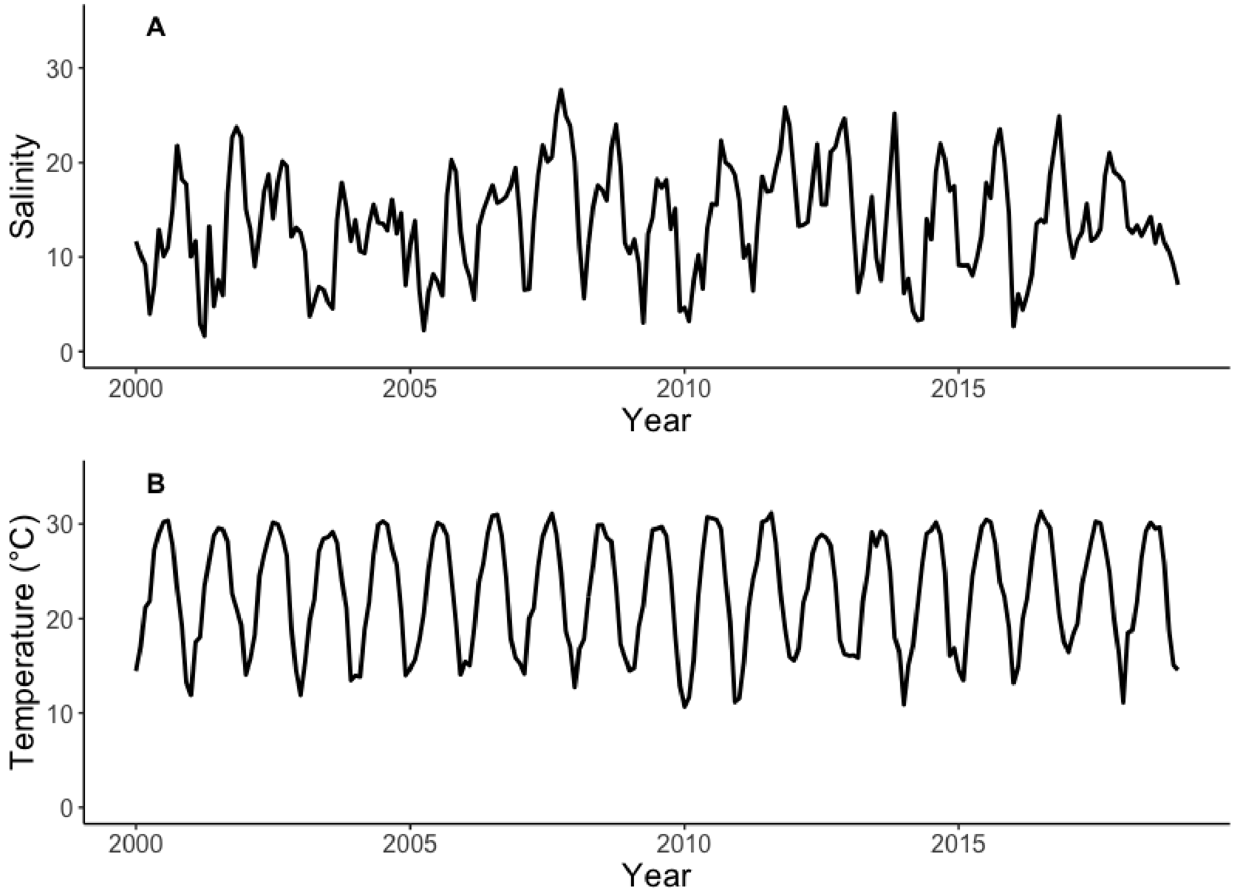


Figure 2: Time series of monthly average observed salinity and water temperature (°C) with a 95% confidence interval (not visible) in Apalachicola Bay from 2000 to 2019. A) Pertains to salinity and B) pertains to water temperature. Data were sourced from the ANERR System-Wide Monitoring Program.

Species responses to environmental changes over time in the food web model are dictated using functional response curves that define each species' tolerance to different environmental parameters (Appendices C and D), using the habitat capacity model in EwE (Christensen et al. 2014). Species response curves represent a species' tolerance to environmental conditions as a habitat capacity value between 0 and 1 (1 being optimal). The capacity value modifies a species' feeding rate (with a lower capacity value resulting in lower levels of consumption by that species), which drives changes in species biomass (Christensen et al. 2014). Water temperature and salinity tolerance ranges were determined for species caught in ANERR's trawl monitoring surveys by plotting species catch per unit effort against temperature and salinity measurements collected during the surveys (following the methods described in De Mutsert et al. 2012). This method was used to develop functional response curves for all species that exhibited a clear salinity or temperature optima from the available monitoring data. Response curves for remaining species in the model (those that exhibited an unclear response to salinity and temperature or did not have sufficient monitoring data available) were developed based on values obtained through a literature search.

The Fit-to-Time Series module in Ecosim was used to calibrate the model over time. This built-in procedure takes into consideration the time series of observed species biomasses and fishing effort, along with the environmental forcing functions and species response curves, and estimates species vulnerability values (v_{ij} from Eq. 5) for species groups where time series data are available (Christensen and Walters 2004). Ecosim then estimates measures of species biomass over time (using Eq. 4) and the modeled output of species biomass is compared to observed biomass time series by assessing the sum of squared deviations (SS). A series of iterations of the Fit-to-Time Series procedure were run to determine the best fit model (model version with the lowest SS). For each iteration, different combinations of species response curves were activated. The iteration that yielded the lowest SS was determined to be the model version to be used for further analysis (Appendix E). The Fit-to-Time series calibration reduced the food web model SS from 16262 down to 3912. This model version consisted of 53 activated species response curves (25 salinity response curves and 28 temperature response curves; Appendices C and D).

The Monte Carlo routine in Ecosim was used to perform a sensitivity analysis of Ecosim model outputs to the Ecopath inputs (Appendix F). This routine assesses the effect of uncertainty in the model input parameters by providing a range of model outputs based on variations in the model input (Heymans et al. 2016). Input parameters are randomly sampled from a uniform distribution centered on the initial values and coefficient of variation equal to 0.1 (Christensen and Walters 2004). Multiple Monte Carlo trials were run to test different combinations of input parameters to be varied, with each trial consisting of a total of 20 iterations. The trial and iteration yielding the lowest SS was selected as the final model version to be used. It is worth noting that the comparison of these SS values is only useful between different Monte Carlo runs and not across other food web models. Prior to running the Monte Carlo routine in Ecosim, the model SS was 3912. The best fit model version produced by the Monte Carlo routine reduced the SS to 3667. This model version was obtained by varying the initial biomass, biomass accumulation and production to biomass ratio parameters within a 10% confidence interval (Appendix F).

2.4 Hydrodynamic model development and simulations using Delft3D

Development of the Delft3D hydrodynamic model of Apalachicola Bay was carried out by my collaborators at Tulane University. Delft3D is a modeling suite developed by Deltares that can conduct simulations of flows, sediment transports, waves, water quality, morphological developments and ecology. A two-dimensional Delft3D-based model system was created to represent hydrodynamic, salinity and temperature conditions in Apalachicola Bay, FL. The model consisted of three nested models representing the entire Gulf of Mexico and part of the Atlantic Ocean, the north-east region of the Gulf of Mexico, and Apalachicola Bay. The Gulf-Atlantic model provided water level and temperature boundaries for the regional model. The regional model captured ten major freshwater inputs from rivers along the Florida coast and provided hydrodynamics, water level, salinity and temperature to the Apalachicola Bay model. Bathymetric data from U.S. Geological Survey (USGS) and digital elevation data from NOAA's Coastal Relief Model (NOAA National Geophysical Data Center 2001) were used to interpolate bed level in the Apalachicola Bay model (Figure 3).

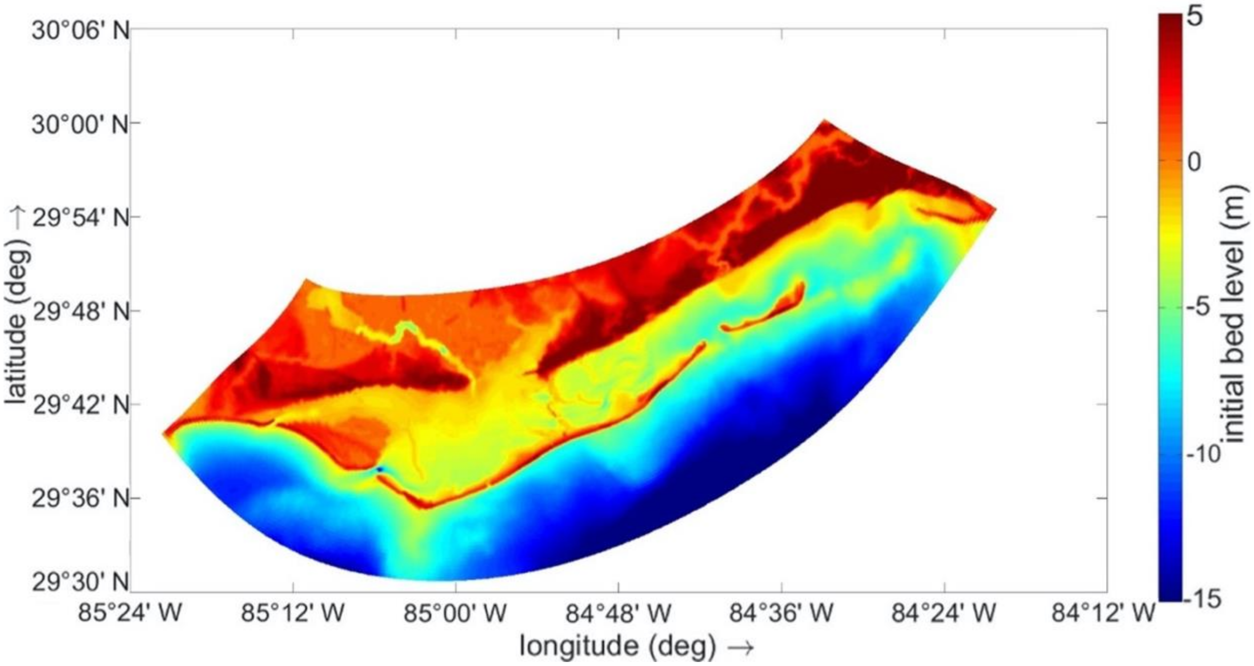


Figure 3: Bathymetry (m) across the Apalachicola Bay Delft3D model domain. Warm colors indicate land masses and shallow water areas (between -5 and 5 m) while cool colors indicate deeper water (between -5 and -15 m).

Observed hydrodynamic data from 2000 through 2019 were used to hindcast the model for calibration and validation. The year 2019 was used for calibration of the Apalachicola Bay Delft3D model, and the years 2000 through 2018 used for model validation. Water level, salinity and temperature data collected at the NOAA tidal station and SWMP stations in Apalachicola Bay were used for model-data comparisons (Appendix G). Modeled water level, salinity and temperature all agreed well with observed measurements, meaning the model reasonably captured the hydrodynamic and transport processes of the system and was acceptable to use for simulating future conditions.

After the Delft3D model calibration and validation were complete, four future scenarios of varying Apalachicola River flow and sea level rise conditions were simulated for a 30-year period (2020 through 2049; Table 4). Each scenario used a combination of either low or high river flow and low and high sea level rise. Low and high river flow conditions were based on historically observed measures of Apalachicola River flow taken by the USGS river gage at Chattahoochee, FL. Historically low river flow was observed in the year 2012 (annual average flow of 215.33 m^3/s) and historically high river flow was observed in the year 1964 (annual average flow of 1132.71 m^3/s). Monthly flow patterns from these years were repeated for each year of the 30-year low or high river flow simulations (Figure 4). Sea level rise conditions were based on observed rates of sea level rise in the Apalachicola Bay region over the course of 54 years (1967 to 2021) taken from the NOAA tide gage in Apalachicola, FL. The current observed rate of sea level rise (2.82 mm/year) was chosen to represent “low” sea level rise conditions for the future simulations and a doubled rate of sea level rise (5.64 mm/year) was chosen to represent “high” sea level rise. Each of these rates of sea level change were applied across the 30-year low or high sea level rise simulations (Figure 5). The four scenarios (Low River Flow–Low Sea Level Rise, Low River Flow–High Sea Level Rise, High River Flow–Low Sea Level Rise, High River Flow–High Sea Level Rise) were simulated through the hydrodynamic model, which provided resulting outputs of monthly Apalachicola Bay salinity and water temperature in the form of ASCII grid files over the 30-year simulation period. These grid files were cropped to fit the spatial domain of the food web model (Figure 1) and served as inputs to Ecospace to drive changes in species biomass over time and space.

Table 4: River flow and sea level rise conditions observed from 2000 through 2019 used to hindcast the hydrodynamic model (Observed scenario) and future scenario parameters used to simulate different combinations of river flow and sea level rise in Apalachicola Bay from 2020 through 2049. River flow metrics were sourced from the USGS Apalachicola River gage in Chattahoochee, FL and sea level rise metrics were sourced from the NOAA tide gage in Apalachicola, FL.

Duration of simulation	**Scenario**	**River flow**	**Sea level rise**
2000-2019	Observed	Observed (512.87 m^3/s 20-year average)	Observed (2.82 mm/year)
2020-2049	Low-Low	Low (215.33 m^3/s annual average)	Low (2.82 mm/year)
2020-2049	Low-High	Low (215.33 m^3/s annual average)	High (5.64 mm/year)
2020-2049	High-Low	High (1132.71 m^3/s annual average)	Low (2.82 mm/year)
2020-2049	High-High	High (1132.71 m^3/s annual average)	High (5.64 mm/year)

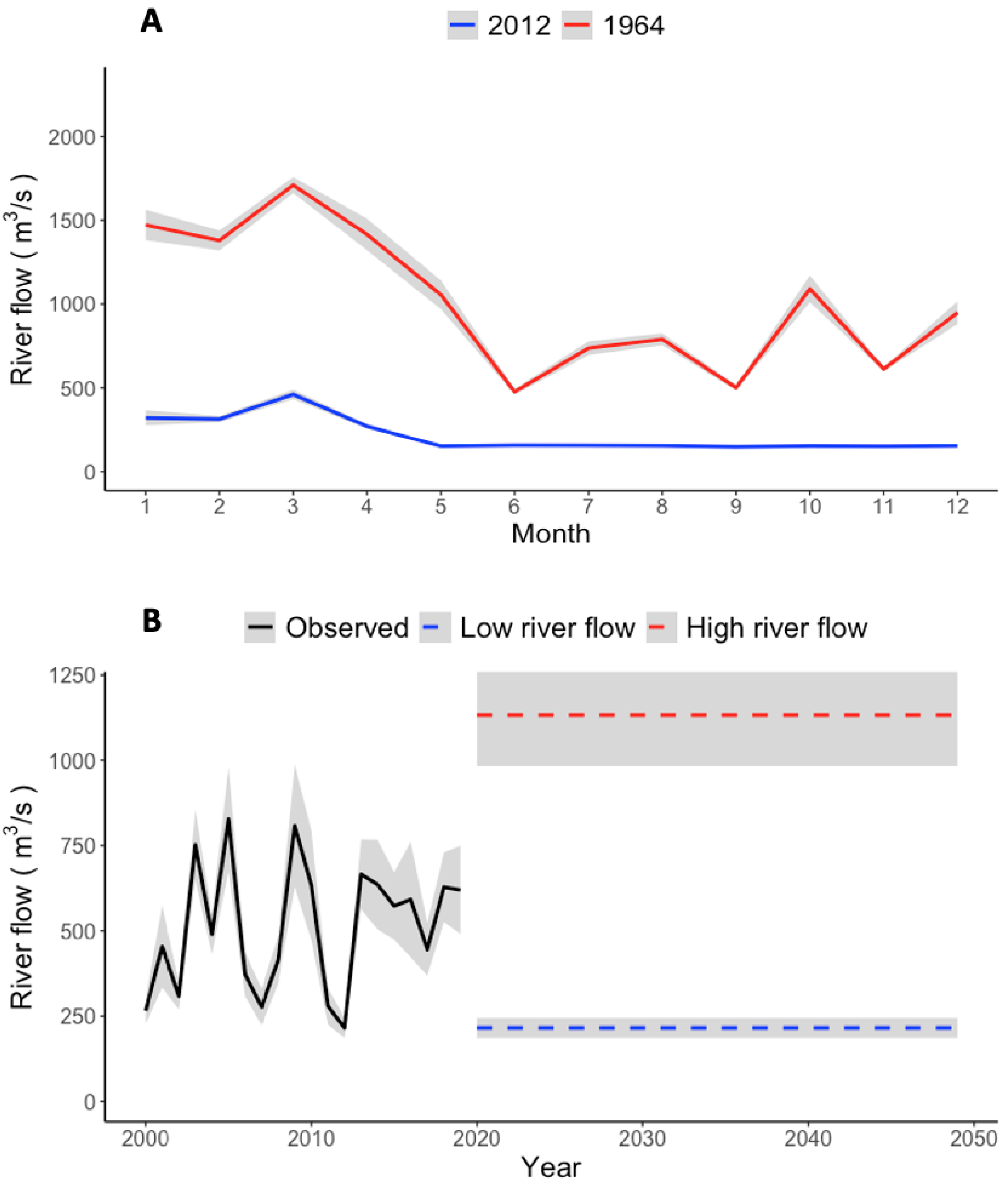


Figure 4: A) Monthly average Apalachicola River flow (with a 95% confidence interval) at historically low levels in 2012 and historically high levels in 1964. B) Observed annual average Apalachicola River flow (with a 95% confidence interval) from 2000 to 2019 with projected annual average river flow (with a 95% confidence interval) during future scenarios of low and high river flow conditions from 2020 to 2049. The monthly river flow variations in plot A were

used to simulate the future scenarios of low and high river flow through the hydrodynamic model by repeating the same monthly flow patterns across each year of the future scenarios.

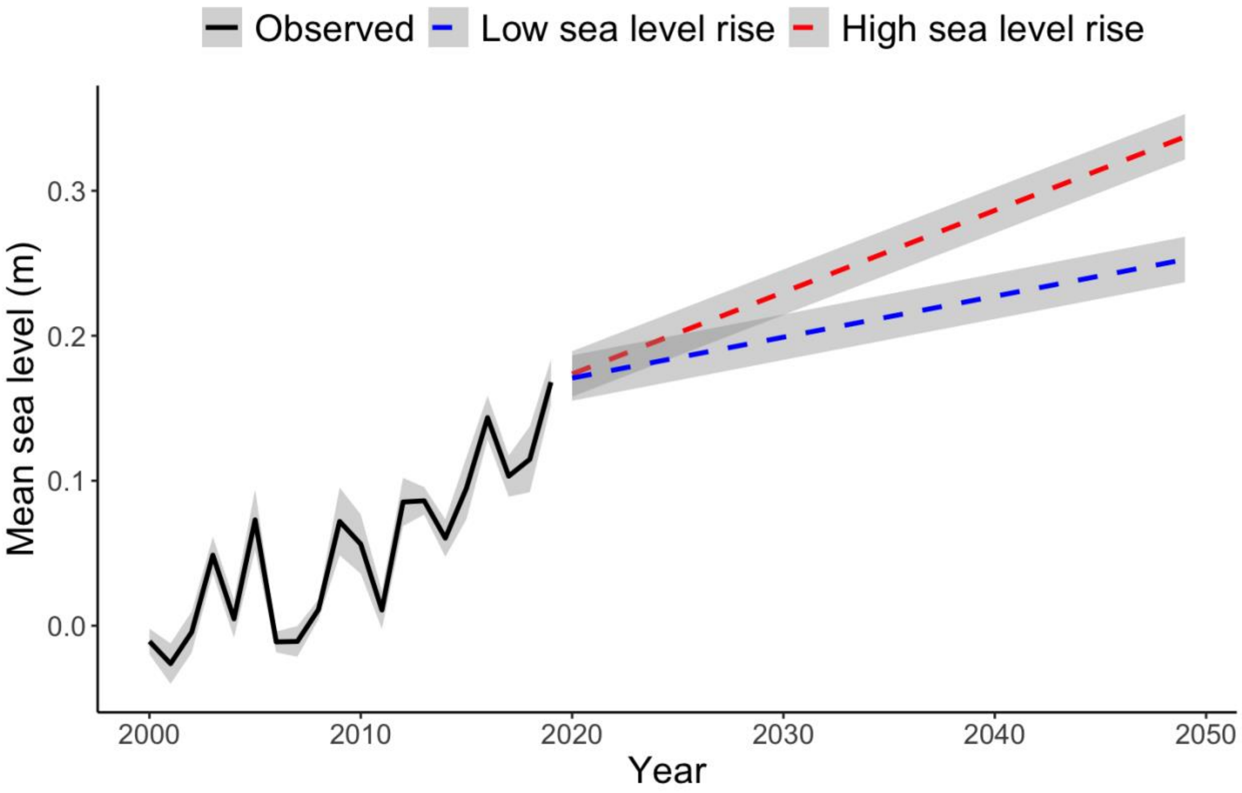


Figure 5: Observed annual average sea level (with a 95% confidence interval) from 2000 to 2019 and projected annual average sea level (with a 95% confidence interval) under low and high sea level rise conditions from 2020 until 2050 simulated through the hydrodynamic model for Apalachicola Bay.

2.5 Spatial-temporal food web model simulations using Ecospace

The Ecospace module of EwE was used to represent the combined temporal and spatial dynamics within the Apalachicola Bay system and will be the primary module evaluated in the results and discussion. Ecospace depicts spatial-temporal dynamics in the form of a georeferenced base map where the differential equations utilized in Ecosim are applied across each grid cell of the base map (Walters et al. 1997, Christensen et al. 2008). The domain of the

Apalachicola Bay Ecospace model encompasses the eight sampling sites visited as part of ANERR's trawl monitoring surveys (Figure 1) and consists of a network of 250 m^2 resolution grid cells. Cells with water within the model domain are considered active cells that can receive environmental input and be occupied by species and fishing groups. All other cells are considered inactive. An ASCII grid file representing depth across the model domain served as the foundation for the Ecospace model. This base map was derived from depth measurements output by the Delft3D model averaged over the year 2000. Additional ASCII grid files were used to delineate specific habitat types within Apalachicola Bay, which in the case of this model were oyster reefs and seagrass beds. The habitat type data were sourced from FWC's GIS mapping database (geodata.myfwc.com). Primary production data were represented by ASCII maps of chlorophyll *a* concentrations derived from the ANERR SWMP (NOAA National Estuarine Research Reserve System). Water temperature and salinity were represented by ASCII maps output by the Delft3D model. Measures of primary production, salinity and temperature were averaged over the first full year of available data (2000 for salinity and temperature, 2003 for primary production) to use as starting conditions in the Ecospace module.

Once the starting conditions were established, a series of ASCII grid files of primary production, salinity and temperature at monthly time steps were then loaded into Ecospace to drive changes over space and time. The series of monthly salinity and temperature grid files spanned all 20 years of the observed time period (2000 to 2019), and the primary production files began in April of 2002 (the first point at which chlorophyll *a* monitoring data were available). Measures of salinity and temperature across the model domain drove changes in species distributions according to each species' environmental tolerances. The species response curves used to represent environmental tolerances in Ecosim were transferred to Ecospace. The habitat capacity model (Christensen et al. 2014; described earlier in section 2.3) computes the suitability of each spatial grid cell for species inhabitance based on habitat and environmental conditions. Oysters and seagrass were the only species groups in the model restricted by habitat type (confined to oyster reefs and seagrass habitat respectively). All species groups with activated response curves responded to changes in water temperature and salinity. At each monthly time step, Ecospace displayed map images of biomass concentrations for each species group in the model in response to the environmental input. The Ecospace food web model simulations were first run over the observed time period (2000-2019, Observed scenario in Table 4) before simulating future conditions from 2020 through 2049.

To simulate the future scenarios of varying river flow and sea level rise conditions (Table 4), ASCII grid files of environmental parameters at monthly time steps representing the years 2020 through 2049 were appended to the series of files spanning the initial time period. Each scenario was run separately in Ecospace using the scenario outputs of salinity and temperature from the Delft3D model. Fishing effort was kept constant across the future scenarios by using the mean effort from 2000 to 2019. In 2020, a moratorium was instituted on the Apalachicola Bay oyster fishery up through 2025 (Elliott 2020), and this fishery closure was represented in the food web model simulations by restricting oysters from harvest during the established closure period. No other changes were made to fishing effort in the future simulations. Primary production levels were kept constant across all future scenarios by repeating the observed patterns from the initial time period. The resulting temporal and spatial changes in species biomasses in response to the environmental drivers were output as monthly ASCII maps of biomass for each year of the simulation.

2.6 Stakeholder survey

A survey of Apalachicola Bay stakeholders was developed to explore local ecological knowledge (LEK) of how river flow and sea level rise in the Apalachicola Bay area contribute to species and environmental changes (IRB approval in Appendix H). For the context of this study, a stakeholder was defined as anyone who lives in the Apalachicola Bay system or whose work pertains to the system. Survey questions were designed in collaboration with ANERR staff and scientists to determine stakeholders' relationships to Apalachicola Bay, resident fish and invertebrate species considered to be commercially or recreationally important, knowledge of changes in river flow and sea level in the system, how these changes impact important species and how these changes impact the stakeholders themselves (Appendix I).

The survey was programmed using ESRI ArcGIS Survey123 software and designed to solicit participation from scientific researchers, commercial and recreational fishers, seafood workers, charter boat captains, government employees or representatives, non-profit organization representatives and local community members. Participants were recruited by emailing known contacts of ANERR, in-person engagement of the local community, and sharing the survey on social media. The survey was left open to responses from November 2021 to June 2022. The stakeholder survey garnered a total of 37 responses from participants who were asked to identify themselves as either a scientific researcher, commercial fisher, seafood worker, recreational fisher, charter boat captain, government employee or representative, non-profit organization representative or a local community member (or some combination of these roles; Figure 6). Survey results were used to determine commercially and recreationally important species to direct the focus of the food web model analysis and assess the perceived impacts of climate change to the stakeholders, which includes the changing salinity regimes occurring in the system.

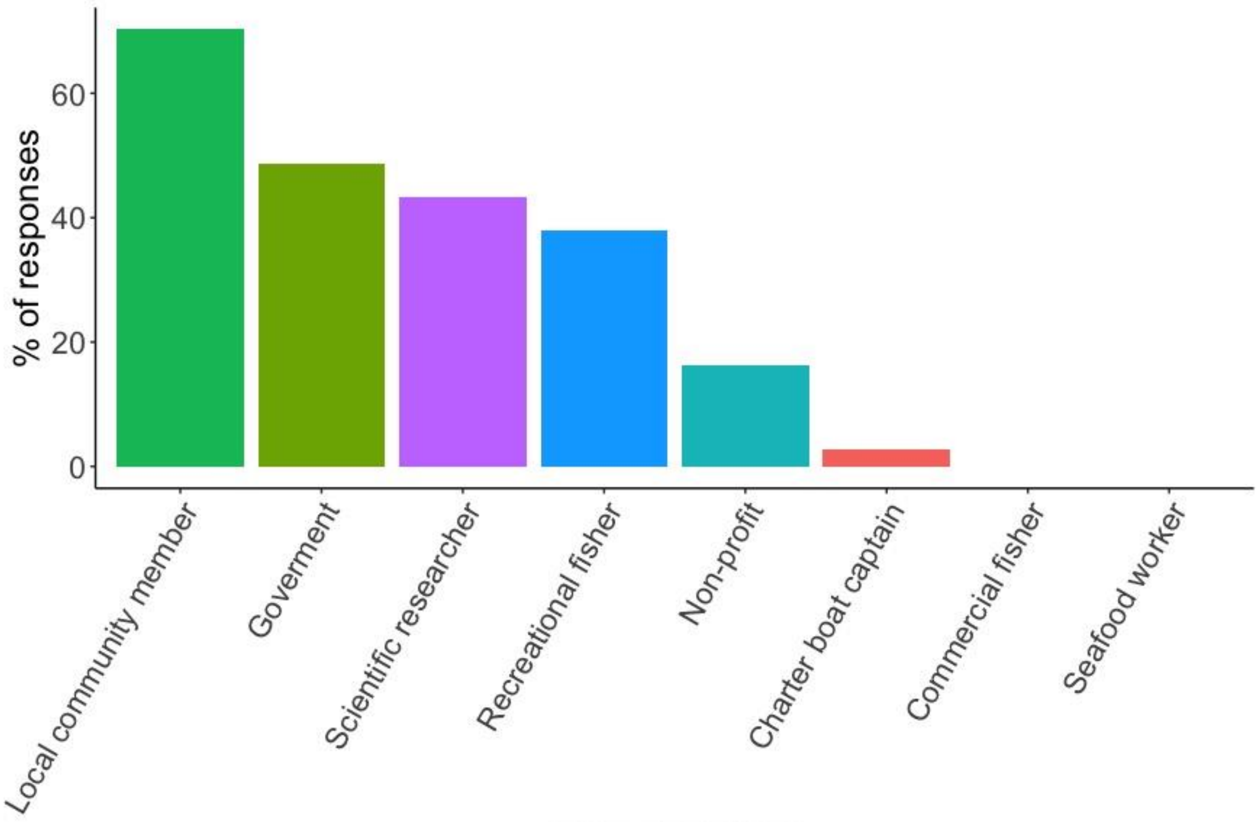


Figure 6: Stakeholder roles as defined in the stakeholder engagement survey and the percentage of survey participants who were identified in each role (n = 37).

3. RESULTS

Coupled hydrodynamic and food web model results were used to assess the impacts of changes in river flow and sea level rise on Apalachicola Bay environmental conditions (i.e., salinity and temperature), individual species' biomass and distribution, as well as total food web biomass and upper trophic level diversity. All model results compared the percent change in annual means of each variable (salinity, temperature, biomass, etc.) between 2019 and 2049 for each of the future scenarios of river flow and sea level rise, along with the spatial distributions of each given variable over time. Since the hydrodynamic and food web model outputs lack statistically independent samples, statistically significant differences in environmental or species variables were unable to be assessed. Rather, the model results serve as a visualization of the range of potential impacts changes in river and sea level rise may have on the abiotic and biotic characteristics of Apalachicola Bay.

Survey results were used to assess stakeholder perceptions about how future freshwater reduction and sea level rise may impact Apalachicola Bay environmental conditions, commercially and recreationally important fisheries species, and the human community (Franklin County economy, stakeholder profession, and personal interaction with the estuary) of the Apalachicola Bay system. The survey results served as a point of comparison to evaluate the agreement of the model simulation results with stakeholder perceptions of environmental and species population changes. This combined approach provides a novel method to understand how changes in an estuarine food web can potentially impact the human communities that rely on these systems.

Thus, the results presented below are organized to capture both the estuarine food web and human community impacts of sea level rise and changes in river flow. Given the complexity of the study, the results are organized around three general topics: 1) Impacts to environmental conditions (water temperature and salinity), 2) Impacts to species of commercial and recreational fishing importance and 3) Impacts to the broader food web (total biomass and upper trophic level diversity) and human community (Franklin County economy, stakeholder profession, and personal interaction with the estuary) of Apalachicola Bay. In each of these sections, the model results are presented first, followed by the results of the stakeholder survey.

3.1 Environmental conditions

3.1.1 Model results

Impacts to environmental conditions on the estuarine food web were assessed by examining the percent change in annual mean salinity and temperature between 2019 and 2049 for each of the future scenarios as output by the hydrodynamic model, along with changes in the spatial patterns of each variable over time. The hydrodynamic model output changes in Apalachicola Bay water temperature and salinity in response to each of the future river flow and sea level rise scenarios. Predicted mean temperature for year 2049 increased across all scenarios relative to the observed mean for 2019 (Figure 7A). The greatest increases in annual mean temperature occurred during low river flow scenarios (+13.24 % in the Low-Low scenario and +13.22% in the Low-High scenario; Figure 7A). Mean salinity for 2049 increased during the low river flow scenarios (+10.96% in the Low-Low scenario and +13.19% in the Low-High scenario;

Figure 7B) and decreased during the high river flow scenarios (-61.26% in the High-Low scenario and -59.65% in the High-High scenario; Figure 7B). Within the low or high river flow scenarios, there were little differences in 2049 mean temperature and salinity compared across different sea level rise conditions (Figures 7A, B).

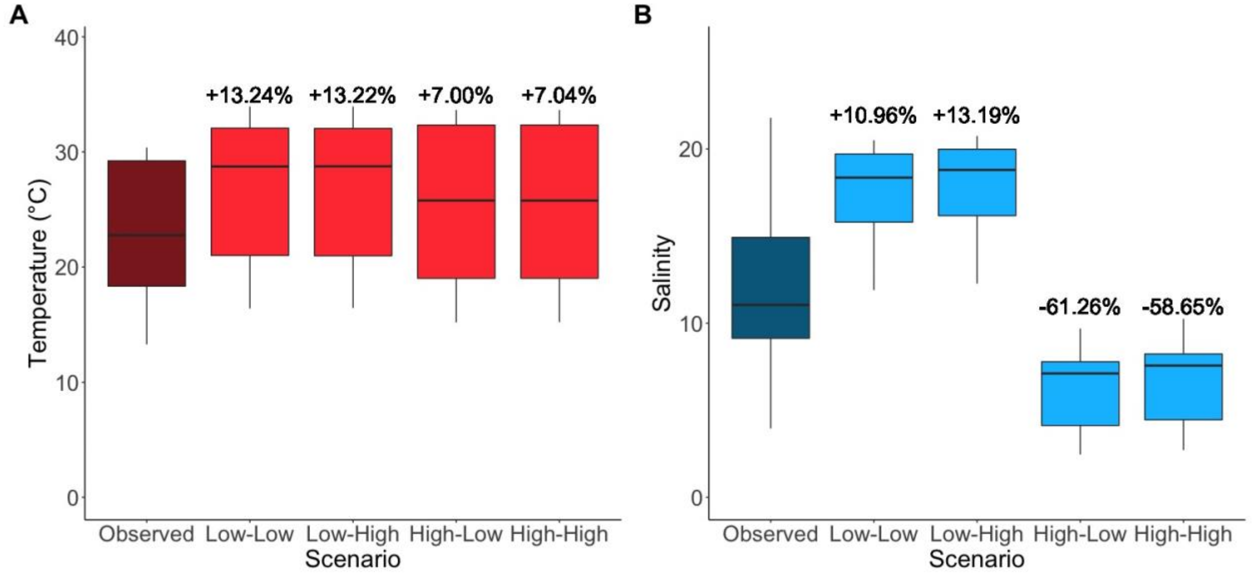


Figure 7: The annual range of Apalachicola Bay water temperature (° C) and salinity averaged over the entire study area between year 2019 (Observed) and year 2049 of each of the future scenarios. A) Pertains to water temperature and B) pertains to salinity. Scenario names define the river flow conditions first, followed by sea level rise conditions (e.g. Low-High indicates low river flow and high sea level rise; scenario parameters defined in Table 4). Percent changes indicate the difference between the 2049 annual mean of each scenario and the 2019 annual mean.

Apalachicola Bay water temperature and salinity spatially varied over time. Annual average water temperature showed greater spatial variation in 2049 compared to 2000 and 2019 (Figure 8). Across all future scenarios, annual average temperatures were highest in the southern region of Apalachicola Bay, with the warmest temperatures present during low river flow scenarios (Figure 8). During the observed years (2000 and 2019), annual average salinity was higher in the southern regions of the bay, while the northern region (closest to freshwater inflow) was less saline (Figure 8). A similar pattern occurred in 2049 for both the low river flow scenarios. Low salinity levels covered much of the southern region of the bay during high river flow scenarios (Figure 8).

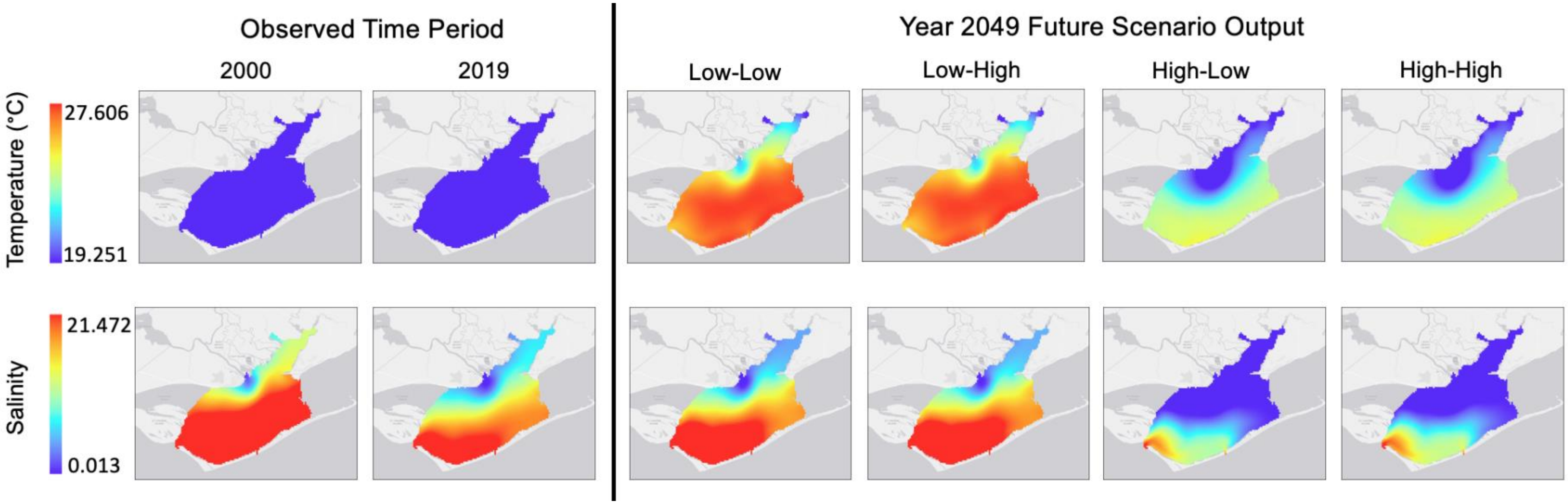


Figure 8: Spatial variation in annual average water temperature (° C) and salinity in Apalachicola Bay during the beginning (2000) and end (2019) of the observed time period and year 2049 of each of the future scenarios. Scenario names define the river flow conditions first, followed by sea level rise conditions (e.g. Low-High indicates low river flow and high sea level rise; scenario parameters defined in Table 4).

3.1.2 Survey results

Stakeholder survey questions were used to assess stakeholder perceptions about how a future reduction in river flow or increase in sea level would affect water temperature and salinity in Apalachicola Bay. The majority of survey participants (~43%) thought a future reduction in river flow would increase water temperature (Figure 9A). Survey results also indicated that most participants (~32%) assumed an increase in sea level would have little to no effect on water temperature, though a large proportion (~30%) said water temperature would increase (Figure 9B). Both a future reduction in river flow and increase in sea level were largely thought to result in an increase in salinity (~89% in Figure 9A, ~76% in Figure 9B).

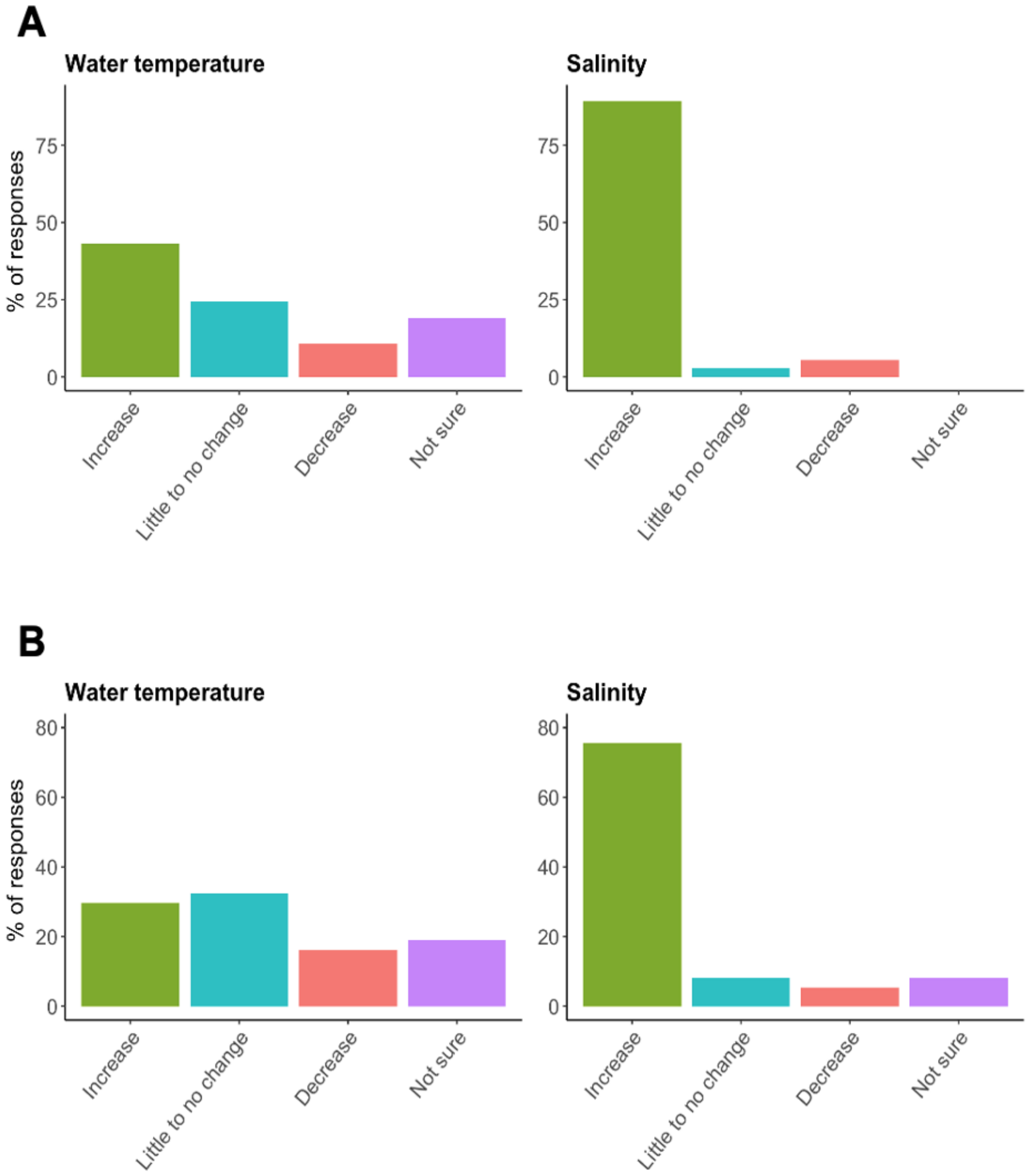


Figure 9: The percentage of survey responses indicating stakeholder perceptions regarding how potential future reductions in river flow and sea level rise would affect Apalachicola Bay water temperature and salinity. A) Pertains to river flow and B) pertains to sea level rise.

3.2 Impacts to important commercial and recreational fishery species

3.2.1 Model results

Food web model results were used to assess the response of commercially and recreationally important fishery species populations to the simulated scenarios of changes in river flow and sea level rise. Specific focal species were chosen based on those identified as the most commercially or recreationally important in the stakeholder survey (see section 3.2.2), which included white shrimp, blue crab, Gulf flounder and red drum. Since white shrimp is a multi-stanza group in the food web model, analysis focused on both the juvenile and adult populations of the species. Juvenile and adult white shrimp biomass increased between 2019 and 2049 during the low river flow scenarios and decreased during the high river flow scenarios (Figure 10A and B). Mean blue crab biomass increased between 2019 and 2049 for all scenarios, and the largest percent increase occurred during the Low-Low scenario (+69.93%, Figure 10C). Gulf Flounder mean biomass decreased between 2019 and 2049 for all scenarios, and the largest percent decrease occurred during the High-Low scenario (-78.33%, Figure 10D). Red Drum mean biomass decreased between 2019 and 2049 for the low river flow scenarios and increased during the high river flow scenarios (Figure 10E).

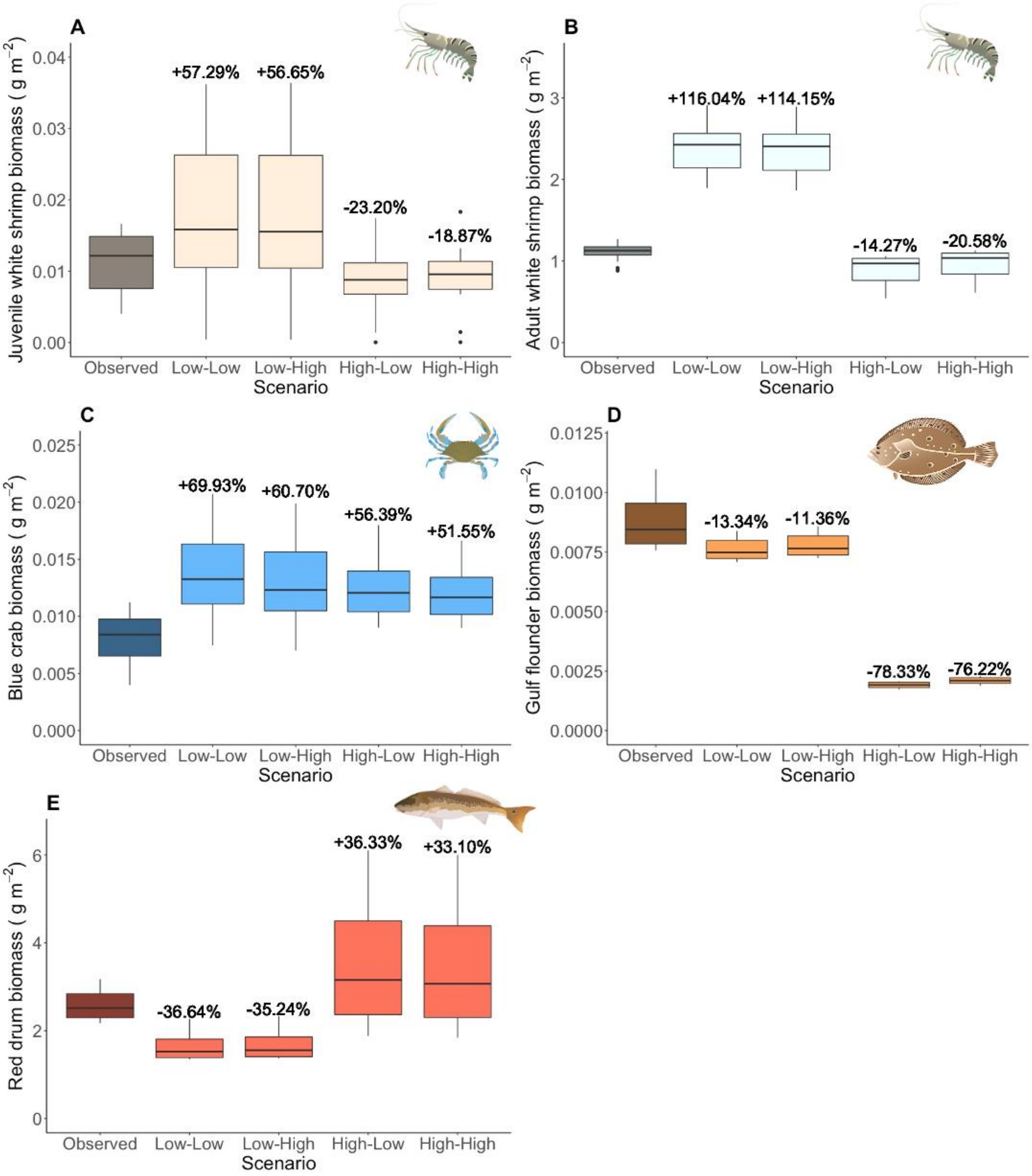

A
Juvenile white shrimp biomass (g m^{-2})
0.04
0.03
0.02
0.01
0.00
+57.29%
+56.65%
-23.20%
-18.87%
Observed
Low-Low
Low-High
High-Low
High-High
Scenario
B
Adult white shrimp biomass (g m^{-2})
3
2
1
0
+116.04%
+114.15%
-14.27%
-20.58%
Observed
Low-Low
Low-High
High-Low
High-High
Scenario
C
Blue crab biomass (g m^{-2})
0.025
0.020
0.015
0.010
0.005
0.000
+69.93%
+60.70%
+56.39%
+51.55%
Observed
Low-Low
Low-High
High-Low
High-High
Scenario
D
Gulf flounder biomass (g m^{-2})
0.0125
0.0100
0.0075
0.0050
0.0025
0.0000
-13.34%
-11.36%
-78.33%
-76.22%
Observed
Low-Low
Low-High
High-Low
High-High
Scenario
E
Red drum biomass (g m^{-2})
6
4
2
0
-36.64%
-35.24%
+36.33%
+33.10%
Observed
Low-Low
Low-High
High-Low
High-High
Scenario

Figure 10: The annual range of spatially-averaged biomass (g m^{-2}) for commercially and recreationally important species in Apalachicola Bay between year 2019 (Observed) and year 2049 of each of the future scenarios. A) Pertains to juvenile white shrimp, B) pertains to adult white shrimp, C) pertains to blue crab, D) pertains to Gulf flounder and E) pertains to red drum. Scenario names define the river flow conditions first, followed by sea level rise conditions (e.g. Low-High indicates low river flow and high sea level rise; scenario parameters defined in Table 4). Percent changes indicate the difference between the 2049 annual mean species biomass of each scenario and the 2019 annual mean.

The spatial distributions of white shrimp, blue crab, Gulf flounder and red drum changed across the observed time period and future scenarios. Species distribution patterns were more similar between future scenarios defined by the same river flow conditions rather than those defined by the same sea level rise conditions (e.g., there was a greater resemblance between the Low-Low and Low-High scenarios than between the Low-Low and High-Low scenarios; Figure 11). Biomasses of both juvenile and adult white shrimp were higher in the southern (particularly southwestern) portion of Apalachicola Bay across all years and scenarios (Figure 11). In the high river flow scenarios, white shrimp biomass for both juveniles and adults was low across the northern, middle and southeastern regions of the bay (Figure 11). Spatial variation in annual average blue crab biomass was greater during the future scenarios compared to the observed years (Figure 11). For all future scenarios, blue crab biomass was highest in the northern and middle regions of the bay (Figure 11). Gulf flounder biomass was generally higher in the southern region of Apalachicola Bay (Figure 11). For all future scenarios, Gulf flounder biomass was low across much of the bay, except for near two small passes connecting to the Gulf of Mexico (Figure 11). Spatial variation in red drum biomass was greatest during the high river flow scenarios and red drum biomass was highest in the northern region of Apalachicola Bay (Figure 11).

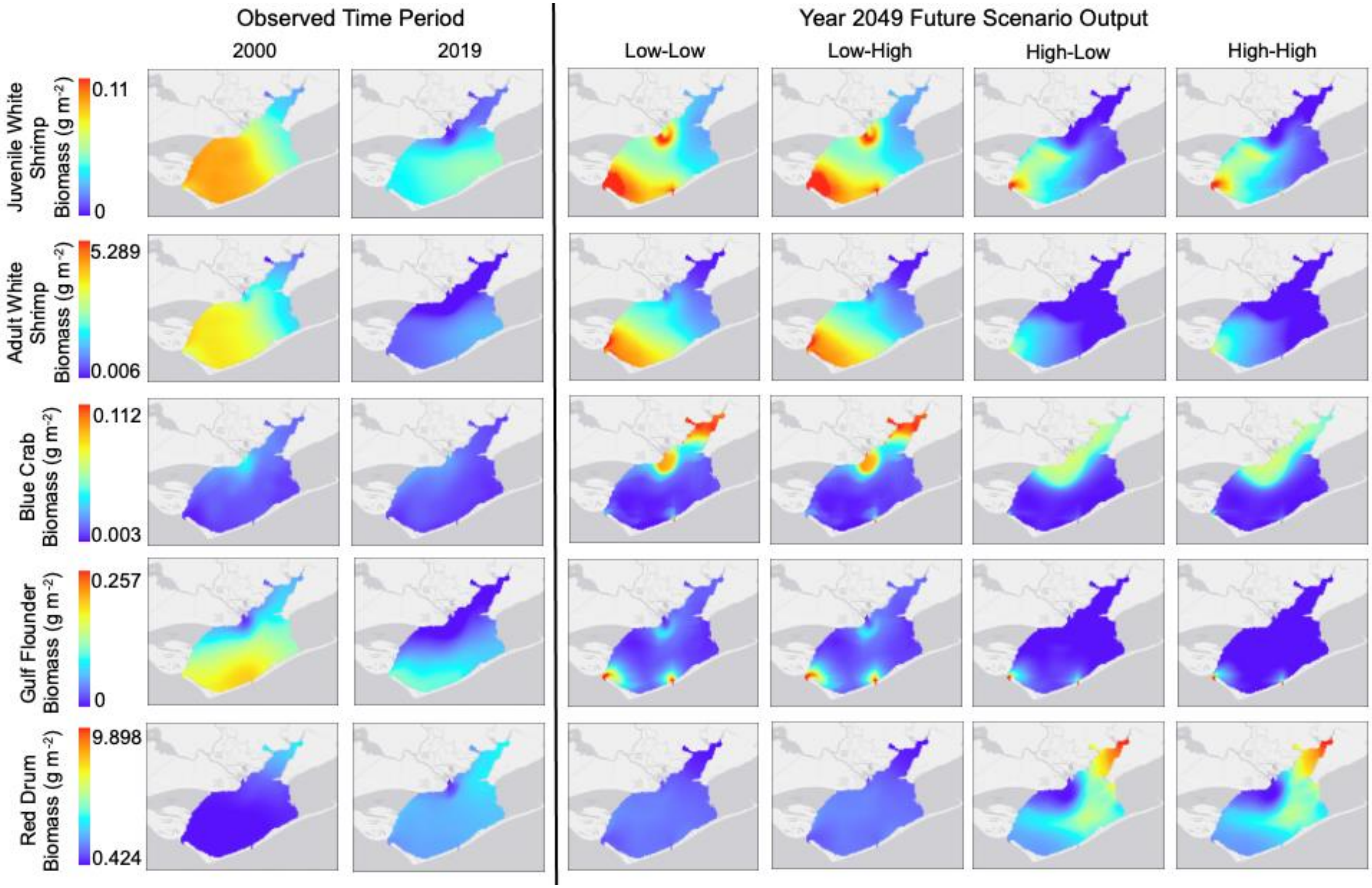


Figure 11: Spatial variation in annual average biomass (g m^{-2}) of juvenile and adult white shrimp, blue crab, Gulf Flounder and Red Drum in Apalachicola Bay during the beginning (2000) and end (2019) of the observed time period and year 2049 of each of the future scenarios. Scenario names define the river flow conditions first, followed by sea level rise conditions (e.g., Low-High indicates low river flow and high sea level rise; scenario parameters defined in Table 4).

3.2.2 Survey results

In order to evaluate the impacts of changes in river flow and sea level rise on important fishery species from a stakeholder perspective, results from the survey were first used to determine which Apalachicola Bay species were regarded as commercially and recreationally important. As part of the stakeholder survey, participants were given a pre-defined list of species and asked to select which species they considered to be the most commercially or recreationally important. The pre-defined list was based on fishery species that were well represented in the ANERR trawl survey data. Though oysters are known as a highly valued commercial fishery species in Apalachicola Bay, they were excluded from the survey list because the intent of the study was to give greater focus to nekton species. Survey participants were made aware that oysters were excluded from the list. Participants had the option to write in a different answer if a species they considered commercially or recreationally important was not included on the list. Most survey participants (~54%) selected commercial shrimp as the most commercially important species (outside of oysters) in Apalachicola Bay (Figure 12A). Approximately 14% of survey participants selected blue crab as the most commercially important and roughly 16% of participants declared they were not sure which species to consider the most commercially important (Figure 12A). For recreationally important species, the majority of survey participants selected flounders (~22%), followed by red drum as a write-in answer (~16%; Figure 12B).

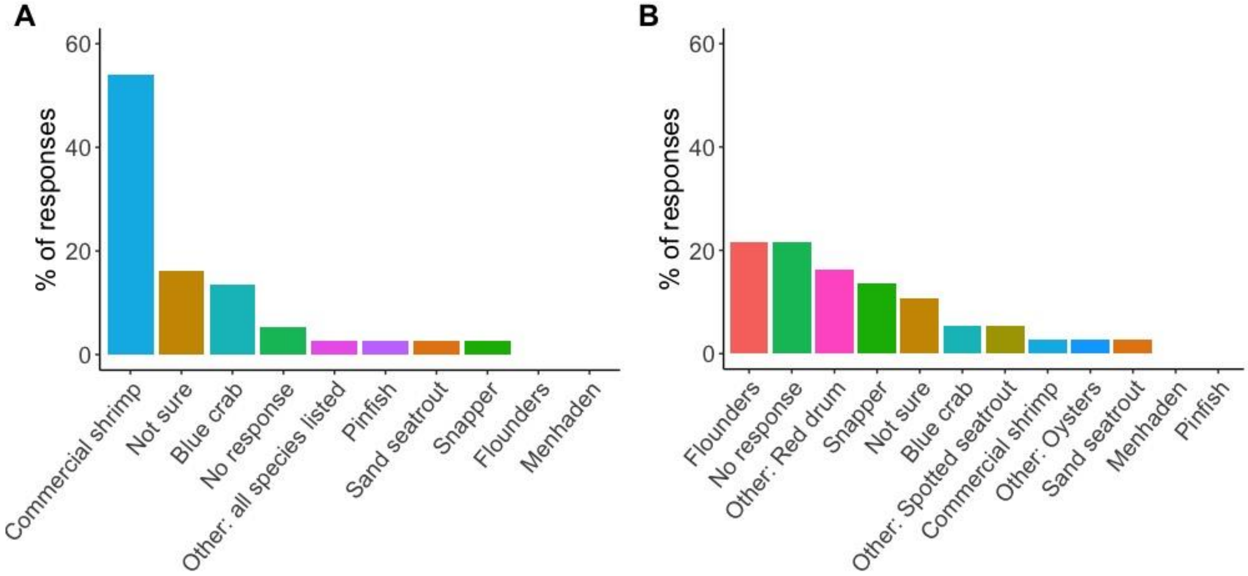


Figure 12: Stakeholder survey responses indicating which species were considered to be the most commercially or recreationally important in Apalachicola Bay. A) Pertains to commercially important species (outside of oysters) and B) pertains to recreationally important species.

Further analysis of the stakeholder survey, as well as analysis of the food web model results (see section 3.2.1), focused on the top two selections of commercially and recreationally important species reported by the survey (commercial shrimp, blue crab, flounders and red drum). After survey participants selected a commercially or recreationally important species, they were asked a subset of questions pertaining to how they thought a future reduction in river flow or increase in sea level would impact the selected species population in Apalachicola Bay. Survey responses indicated that the majority of participants who selected commercial shrimp, blue crab, or flounders thought a future reduction in river flow would result in a decrease in the populations of these species (Figure 13A). There was insufficient survey response data to assess the anticipated impact of reduced river flow on Red Drum. An anticipated increase in sea level was expected to have more variable impacts on species. For commercial shrimp, the majority of participants (~40%) thought the population would decrease in response to an increase in sea level, though a large proportion (~35%) were not sure of the possible effect (Figure 13B). There was an even split between participants who thought the blue crab population would either increase (~40%) or decrease (~40%; Figure 11B). For flounders, the majority of participants thought the population would decrease (~50%; Figure 13B). There was also insufficient survey response data to assess the anticipated impact of increased sea level on red drum.

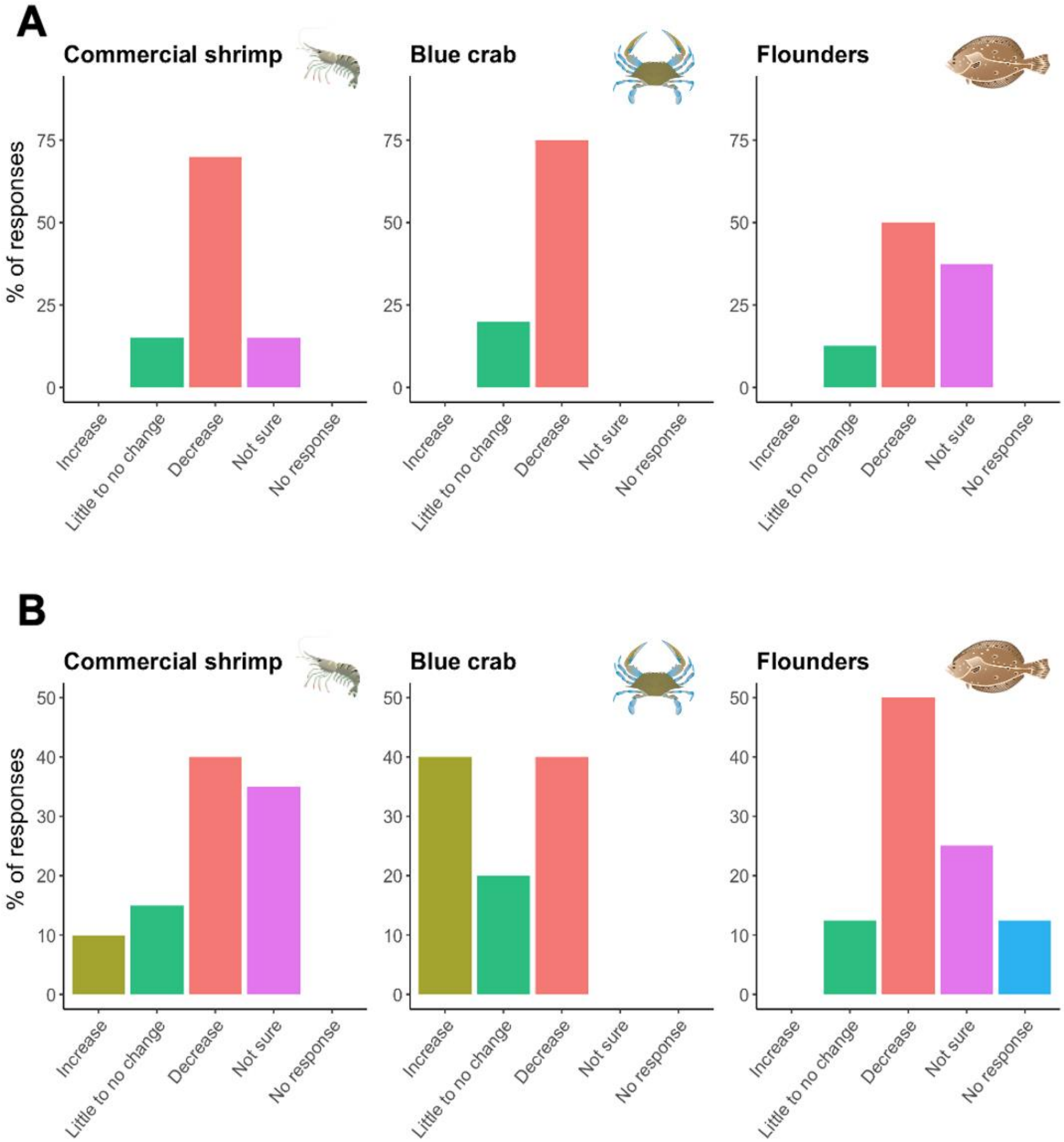


Figure 13: The percentage of survey responses indicating the anticipated impact of a future reduction in river flow or increase in sea level on populations of commercially important commercial shrimp (n = 20) and blue crab (n = 5) populations, and recreationally important flounder (n = 8) population in Apalachicola Bay. A) Pertains to river flow and B) pertains to sea level rise.

3.3 Impacts to the broader food web and human community

3.3.1 Model results

The impacts of future changes in river flow and sea level rise on the broader food web network of Apalachicola Bay were evaluated using the food web model outputs of total biomass (g m^{-2}) and Kempton’s Q index. Mean total biomass of the entire food web between year 2019 and year 2049 increased by similar percentages across all scenarios (Figure 14A). As calculated by EwE, Kempton's Q index is a measure of biomass diversity of organisms with trophic level ≥ 3 where the Q value is proportional to the inverse slope of the species-abundance curve (Ainsworth and Pitcher 2006). Kempton's Q index can be interpreted as a proxy for ecosystem biodiversity, with higher Q values corresponding to greater biodiversity (Ainsworth and Pitcher 2006). Mean Kempton’s Q index decreased between 2019 and 2049 for all scenarios, with the largest percent decrease occurring during the High-Low scenario (-16.87%; Figure 14B).

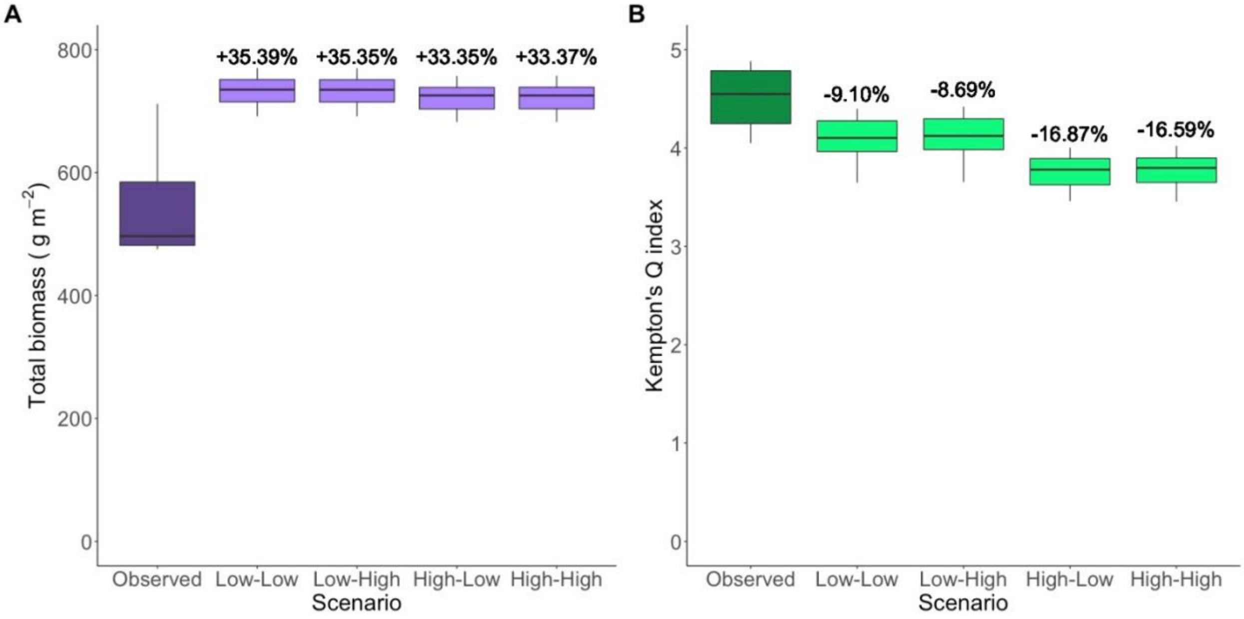


Figure 14: The annual range of spatially-averaged total biomass (g m^{-2}) and Kempton's Q index in Apalachicola Bay between year 2019 (Observed) and year 2049 of each of the future scenarios. A) Pertains to total biomass and B) pertains to Kempton's Q index. Scenario names define the river flow conditions first, followed by sea level rise conditions (ie. Low-High indicates low river flow and high sea level rise; scenario parameters defined in Table 4). Percent changes indicate the difference between the 2049 annual mean of each scenario and the 2019 annual mean.

Total biomass and Kempton's Q index also varied spatially across the observed time period and future scenarios. To better visualize spatial changes in total biomass across Apalachicola Bay, oyster and seagrass biomasses were excluded from the annual average total biomass maps (Figure 15) as these species were stationary in the spatial-temporal model framework and had high biomass values that obscured any spatial changes in the biomasses of mobile species in the model (spatial distribution of oyster and seagrass biomasses can be found in Appendix J). Annual average total biomass exhibited the greatest spatial variation in 2000 (Figure 15). In 2019, annual average total biomass was highest in the southwestern region of Apalachicola Bay and highest in the bay's northern region in 2049 (Figure 15). Annual average values of Kempton's Q index had greater spatial variation in 2000 and 2019, while the spatial patterns became more uniform across the future scenarios (Figure 15). Kempton's Q index values were generally higher in the southern region of Apalachicola Bay for all future scenarios (Figure 15).

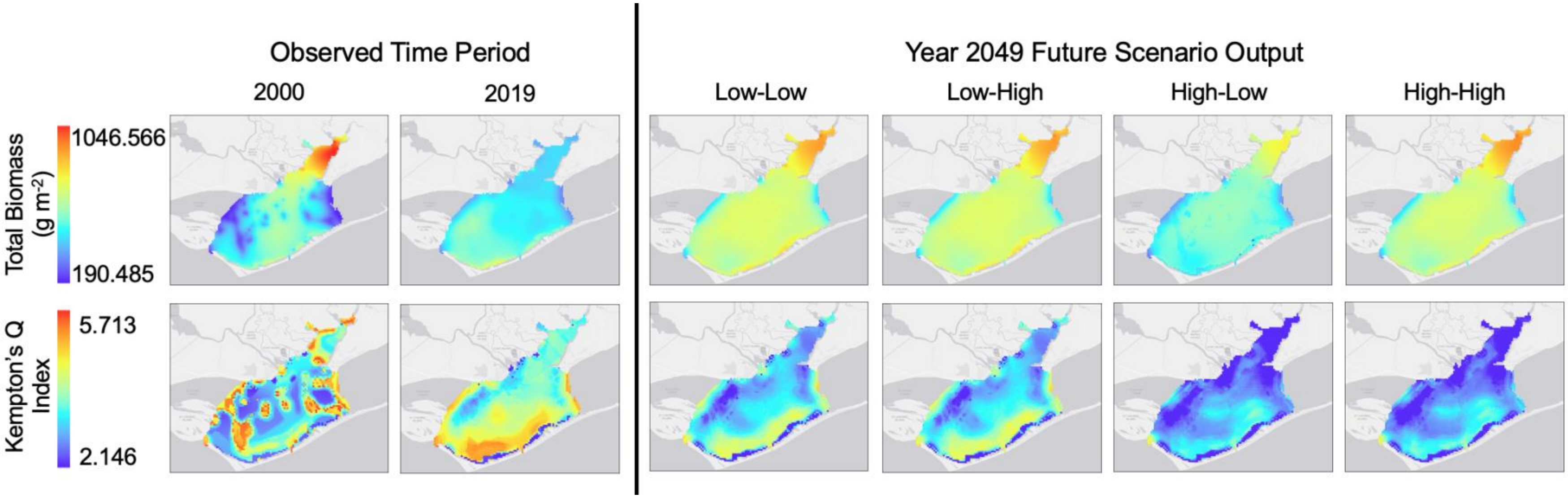


Figure 15: Spatial variation in total average biomass (g m^{-2}) of spatially mobile species and Kempton's Q index in Apalachicola Bay during the beginning (2000) and end (2019) of the observed time period and year 2049 of each of the future scenarios. Total biomass represents the biomass of all species in the food web model except the stationary oyster and seagrass groups. Scenario names define the river flow conditions first, followed by sea level rise conditions (e.g., Low-High indicates low river flow and high sea level rise; scenario parameters defined in Table 4).

3.3.2 Survey results

Effects of future changes in river flow and sea level rise on the human community of Apalachicola Bay were assessed using survey responses on impacts to the Franklin County economy (where Apalachicola Bay resides), each stakeholder's profession and each stakeholder's personal interaction with Apalachicola Bay. Personal interaction with Apalachicola Bay could include activities such as fishing, birding, hiking, boating or any engagement with the ecosystem outside of the participant’s profession. Most survey responses indicated the perception that both a future reduction in river flow (~84%, Figure 16A) and increase in sea level (~84%, Figure 16B) would have a negative impact on the Franklin County economy. Most survey participants also thought that these future environmental changes would have little to no impact on their professions (~65% Figures 16A, ~54% Figure 16B). In terms of participants’ personal interactions with Apalachicola Bay, the majority thought a future reduction in river flow would have a negative impact (~49%, Figure 16A) and a future increase in sea level would have little to no impact (~51%, Figure 16B).

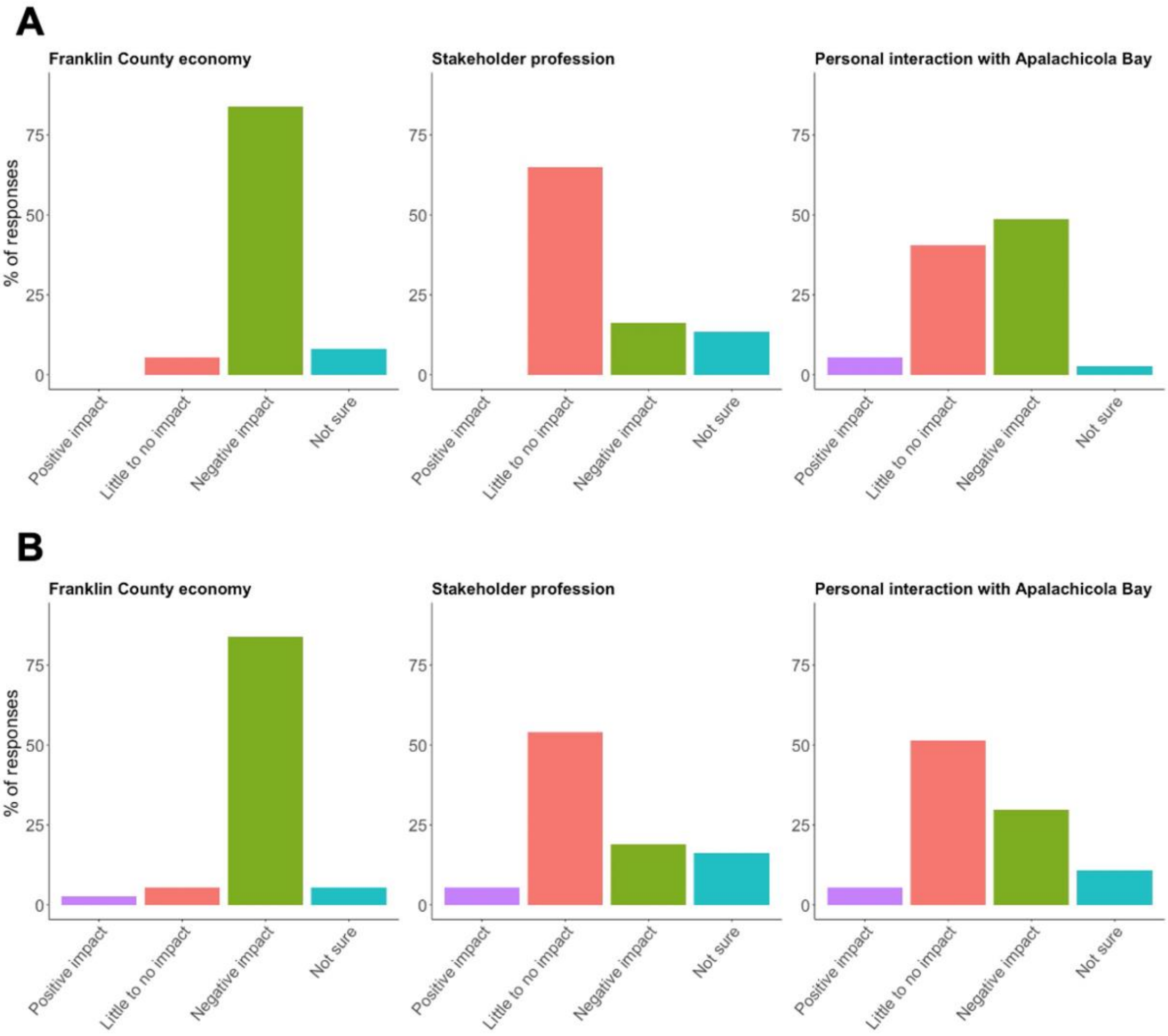


Figure 16: The percentage of survey responses indicating stakeholder perceptions regarding how potential future reductions in river flow and sea level rise would impact the Franklin County economy, the stakeholder's profession, and the stakeholder's personal interaction with Apalachicola Bay. A) Pertains to river flow and B) pertains to sea level rise.

4. DISCUSSION

Apalachicola Bay is likely to experience future changes in river inflow and sea level rise. This study used a coupled hydrodynamic and food web model, along with a survey of Apalachicola Bay stakeholders, to determine the potential impacts of 30-year future scenarios of low and high river flow and sea level rise on the Apalachicola Bay food web. Analysis of the results focused on impacts to environmental conditions and populations of commercially and recreationally important species in Apalachicola Bay, in addition to assessing impacts from a broader food web perspective. Changes in these biotic and abiotic factors were largely different between scenarios of low and high river flow, while there were little differences that occurred between the low and high sea level rise conditions within each river flow scenario. The hydrodynamic and food web model simulation outputs provide a point of comparison with stakeholder concerns regarding anticipated future changes in the abiotic and biotic characteristics of Apalachicola Bay. Results offer insight on the impacts of climate change and human-induced stressors to both the estuarine food web and human communities of Apalachicola Bay.

4.1 Environmental conditions

Different future river flow and sea level rise conditions are expected to result in an increase in Apalachicola Bay water temperature and increase or decrease in salinity. The majority of survey respondents thought a reduction in Apalachicola River flow would increase the bay’s water temperature and an increase in sea level would result in either little to no change or an increase in temperature. The modeled output of the environmental conditions generally agreed with the results of the survey. The projected increase in Apalachicola Bay water temperature output by the hydrodynamic model in our study is a continuation of the observed temperature trend from 2000 to 2019. These results also align with previous studies that suggest estuarine water temperatures may increase with air temperature as a result of climate change (Scavia et al. 2002). Future sea surface temperatures in the Gulf of Mexico are expected to increase (Muhling et al. 2011), therefore, the predicted sea level rise in the region would bring warmer, more saline waters into Apalachicola Bay, aligning with both stakeholder perceptions and the food web model outputs. The water temperature of river inflow may also increase as a result of reduced flow volume upstream (Mosley 2015). Spatial variation in Apalachicola Bay water temperature also increased between 2019 and 2049 for each simulated future scenario, which differs from previously observed trends of little spatial variability in temperature across Apalachicola Bay (Livingston et al. 1977, Garwood et al. *in review*).

While water temperature increased across all future scenarios, there were distinct differences in salinity changes between scenarios of low and high river flow. Most stakeholder survey participants thought a reduction in river flow and increase in sea level rise would increase Apalachicola Bay salinity, and the hydrodynamic model results largely supported this perception. Low Apalachicola River flow conditions led to an increase in salinity and high river flow conditions led to a decrease in salinity. Low and high sea level rise conditions coincided with an increase in salinity when coupled with low river flow, but not when coupled with high river flow. This is likely because Apalachicola River flow has been found to act as a more dominant influence on estuarine salinity compared to sea level (Sun and Koch 2001, Morey and Dukhovskoy 2012). Minimum river flow can result in above-average salinity in Apalachicola Bay and maximum river flow can decrease salinity to below-average levels, even when paired with sea level rise (Huang et al. 2015). The use of the hydrodynamic model to simulate changes in both river flow and sea level rise provides insight on the coupled effects of these stressors and more nuanced potential outcomes for the Apalachicola Bay system.

4.2 Fisheries species

The average biomass of commercially important white shrimp increased with low river flow conditions and decreased with high river flow conditions in Apalachicola Bay. Higher biomass values for both juvenile and adult white shrimp were concentrated in areas of higher salinity and intermediate to warm temperatures during both the observed time period and future scenarios. Within the low and high river flow scenarios, modeled outputs suggested little difference in biomass between low and high sea level conditions. Both the juvenile and adult groups of white shrimp modeled in this study exhibit broad salinity tolerances (approximate optimum range of 5 – 35 ppt, Appendix C). The salinity increase in the low river flow scenarios still falls within the white shrimp tolerance range, while the high river flow scenarios result in less optimal, very fresh water (< 5 ppt) covering much of the bay. The temperature response curve for juvenile white shrimp also indicates a preference for warmer temperatures (~ 25-30° C, Appendix D). White shrimp biomass was also driven by prey availability and predation in the model. Red drum is a major predator of both juvenile and adult white shrimp (Supplemental Table 1; Scharf and Schlicht 200) and exhibited an increase in biomass during the high river flow scenarios, which likely contributed to the decrease in white shrimp biomass during those scenarios. Juvenile and adult white shrimp in the model primarily consumed zoobenthos and zooplankton (macro and micro; Supplemental Table 1), which increased in biomass across all scenarios (Supplemental Table 3). The modeled trends in white shrimp biomass contrasted with the perceptions of stakeholders in the Apalachicola Bay region. Survey responses suggested a decrease in the Apalachicola Bay white shrimp population in response to reduced river flow and increased sea level. This perception may be based on historical trends in shrimp fishery landings, which have previously dropped by 90% after drought events in the Apalachicola Bay system (Livingston 2008). A wide range of factors such as altered habitat conditions, enhanced predation, competition and disease likely played a role in the historical shrimp population decline (Livingston 2008). While the food web model incorporated species environmental tolerances and trophic dynamics, other factors such as changes in habitat, disease prevalence and influxes of new species were not represented. The assessment of these additional factors may provide further insight regarding the differences in modeled trends versus those anticipated by stakeholders. The modeled response of white shrimp to high river flow did align with results of previous studies in other Gulf of Mexico estuaries. In Louisiana, increased river inflow has been associated with low white shrimp harvest (Childers et al. 1990). Higher estuarine salinities along the Gulf of Mexico have been linked to higher early life stage abundance of white shrimp (Diop et al. 2007) and faster growth rate (Rozas and Minello 2011). Juvenile white shrimp abundance in Gulf of Mexico estuaries also exhibits a positive relationship with temperature (Diop et al. 2007) and adult white shrimp landings exhibit a positive relationship with high sea level events (Morris et al. 1990). These previous study results, along with this study, indicate high river flow conditions coupled with sea level rise may pose more of a detriment to white shrimp than low river flow with sea level rise.

Blue crab, another commercially important species in Apalachicola Bay, increased in biomass across different modeled scenarios of river flow and sea level rise conditions. All future scenarios showed low blue crab biomass throughout the southern region of Apalachicola Bay, but blue crab biomass was high in the cooler and less saline northern region of the bay. The environmental response curves for blue crab applied in the food web model define a preference for lower salinity (~ 0-5 ppt, Appendix C) and warmer temperatures (~ 25-30° C, Appendix D), so salinity appears to have a larger influence on blue crab biomass distribution than temperature. An increase in blue crab prey (primarily zoobenthos; Supplemental Table 1) across all future scenarios (Supplemental Table 3) likely contributed to the increases in blue crab biomass, along with the fact that blue crab only made up a small proportion of predator diets in the food web model (Supplemental Table 1). The modeled results were in opposition to the anticipated decline in blue crab biomass many stakeholders thought would result from reduced river flow and increased sea level rise. However, there was an equal proportion of survey respondents who thought sea level rise would have a positive effect on blue crab biomass, indicating a greater amount of uncertainty among survey participants. Similar to white shrimp, the anticipated negative impacts of reduced river flow and increased sea level rise on blue crab populations may be based on a historical decline in blue crab landings during drought periods (Livingston 2008). In other estuarine habitats along the north-central Gulf of Mexico and southeastern U.S. juvenile blue crab abundance and growth has been negatively associated with an increase in salinity (Posey et al. 2005, Sanchez-Rubio et al. 2010). Blue crabs in higher salinity waters across Gulf of Mexico estuaries may also have greater infestation rates by the gill barnacle *Octolasmis mülleri*, which can result in mortality in cases of heavy infestation (Gannon et al. 2001). The food web model for this study was unable to account for parasitic infection. The modeled populations of blue crab in Apalachicola Bay did exhibit a preference for lower salinities, but the simulated spatial patterns in blue crab biomass indicate that even with an increase in annual mean salinity during the low river flow scenarios, there is still sufficient low-salinity habitat to support higher blue crab biomass. These results present an optimistic future for blue crab populations in Apalachicola Bay in response both low and high river flow and sea level rise conditions.

Gulf flounder, a species of recreational fishing interest, experienced a decrease in average biomass across all future river flow and sea level rise conditions. Gulf flounder prefer high salinity (25-30 ppt, Appendix C) and temperature (20-30° C, Appendix D) conditions. Gulf flounder prey (zoobenthos, and macro- and microzooplankton; Supplemental Table 1) biomasses increased across all scenarios (Supplemental Table 3), so it appears the environmental tolerances of Gulf flounder were more indicative of a decline in biomass than prey availability. Gulf flounder biomass values for all future scenarios were at or near 0 g m^{-2} throughout much of Apalachicola Bay, except near the southern passes connecting the bay to the Gulf of Mexico. Recent studies on Gulf flounder population dynamics are limited, but historically, juvenile Gulf flounder abundance has been highest at the mouths of Florida estuaries where salinity is the highest (Gilbert 1986). An earlier habitat suitability index for Gulf flounder determined their optimal salinity and temperature conditions to be 15-40 ppt and 15-35 ° C (Enge and Mulholland 1985). Due to their high salinity preference, Gulf flounder are highly susceptible to change via altered salinity structure in Gulf of Mexico estuaries (Christensen et al. 1997). Salinity and sea level may function as strong predictors of population variability over time (Fujiwara et al. 2019). Results from the Apalachicola Bay stakeholder survey indicated an anticipated decrease in flounder populations due to reduced river flow and increased sea level rise. The food web model results aligned with this prediction because the increase in salinity across the low river flow scenarios still fell short of the optimal range for Gulf flounder, resulting in a decrease in biomass across both future low and high river flow and sea level rise conditions in Apalachicola Bay.

Recreationally important red drum in Apalachicola Bay appeared to favor scenarios of high river flow conditions. Annual average biomass decreased during low river flow scenarios and increased during high river flow scenarios, with little difference between low and high sea level rise conditions. In the low river flow scenarios, red drum had low biomass across the entire bay and in the high river flow scenarios the highest biomass values were concentrated in the low salinity and relatively low temperature northernmost region of Apalachicola Bay. Other studies have found a positive relationship between river discharge and abundance of both juvenile and adult red drum in Florida estuaries (Purtlebaugh and Allen 2010, Whaley et al. 2015). Juvenile red drum have a greater metabolic capacity (and thus are more active) at temperatures greater than 19° C (Fontaine et al. 2007), while adults prefer temperatures less than 22° C (Hightower et al. 2022). While the salinity and temperature response curves for red drum applied in the model were fairly broad (~5-25 ppt and 5-30° C, Appendices C and D), the greater increase in temperature during the low river flow scenarios may have contributed to the decrease in red drum biomass during these scenarios. Temperature can function as a better predictor of adult red drum abundance than salinity along nearshore waters in the north-central Gulf of Mexico (Hightower et al. 2022). Several species that make up the diet of red drum, such as bay anchovy, menhaden and blue crab, prefer less saline waters (Scharf and Schlicht 2000) and exhibited an increase in biomass during the high river flow scenarios (Supplemental Table 3), so the predicted increase in red drum biomass in low salinity regions of Apalachicola Bay during these scenarios may be due in part to a greater abundance of prey species. Overall, an increase in Apalachicola

River flow appears to benefit red drum, while reduced river flow is detrimental to their population in Apalachicola Bay. There were insufficient survey data to assess the anticipated impacts of reduced river flow and increased sea level rise on red drum from the perspective of stakeholders.

Changes in river flow and sea level rise in Apalachicola Bay will have variable impacts on the commercial fisheries for the region. Oysters were historically known as the most important commercial fishery in Apalachicola Bay and experienced a population decline due to low river inflow during times of drought, particularly in 2007 and 2012 (Livingston 2008, Havens et al. 2013). Drought periods corresponded with a decline in landings of other commercially important species such as white shrimp and blue crab in Apalachicola Bay as well (Livingston 2008). Results of this study, on the other hand, indicate that low river flow conditions (in combination with either low or high sea level rise) have the potential to positively impact the commercial white shrimp and blue crab fisheries through increases in the biomass of these species. While blue crab biomass also increased during the high river flow scenarios, white shrimp biomass decreased, so these scenarios may be less ideal for overall commercial fishery landings. White shrimp and blue crab are two of the top ten commercially valued species in Franklin County, FL (Commercial Fisheries Landings Summaries database) so changes in their populations will have implications for the local economy. However, it must be noted that the model results are only a representation of potential outcomes, and changes in species biomasses are primarily driven by environmental tolerances and predation/prey availability in the current model version. Incorporating additional influences on species biomasses, such as habitat changes and disease prevalence, may provide additional insight on species responses to changes in river flow and sea level rise.

Recreational fishing occurs throughout Apalachicola Bay and will be impacted by changes in the populations of species such as Gulf flounder and red drum. In this study, low river flow scenarios (combined with both low and high sea level rise conditions) decreased the biomass of both Gulf flounder and red drum populations in Apalachicola Bay, while high river flow conditions lead to an increase in red drum biomass. During the high river flow scenarios, Gulf flounder biomass was highest in the southern passes of the bay and red drum biomass was highest in the northern region, meaning recreational fishers targeting these species would likely seek out these areas. With the potential for both increased future drought and precipitation events in the Apalachicola Bay watershed, the model simulation results of this study indicate mixed effects on fisheries species within the estuary. The simulations performed serve as an example of how the coupled hydrodynamic and food web modeling approach can be useful for assessing a range of future impacts of environmental changes to commercially and/or recreationally important species. Managers can examine any number of species or drivers of species biomasses in the food web model and utilize the results to develop species monitoring or mitigation plans.

4.3 Broader Apalachicola Bay food web and human community

The broader Apalachicola Bay food web, specifically total biomass and upper trophic level diversity, will be impacted by future changes in river flow and sea level rise. Across all simulated future scenarios of low and high river flow and sea level rise conditions, total biomass increased and upper trophic level diversity (measured by Kempton’s Q index) decreased.

Historically, fish species richness and trophic diversity in Apalachicola Bay have declined during times of drought and reduced river flow (Livingston 1997), but there has been no report of exceptionally high river flow having a similar effect. However, these trends in species abundance and diversity are not uncommon in other estuaries around the world. In South Africa, both increased salinity and river flooding conditions can result in reduced species diversity due to a change in the estuarine salinity regime (Whitfield 2005). High fish species biomass has generally coincided with increased freshwater inflow in Brazilian and Mexican estuarine habitats (Flores-Verdugo et al. 1990, Barletta et al. 2003). Sea level rise simulations result in a loss of estuarine microbenthic biomass in the United Kingdom, though greater abundance of more salt-tolerant species has the potential to compensate for this effect (Fujii and Rafaelli 2008). In this study, the increase in total biomass and decrease in diversity across scenarios could be due to an increase in abundance of individual species that prefer different salinity regimes (depending on the scenario) and decrease in abundance of species unable to tolerate the new environmental conditions. However, the results of this study are only representative of the limited species groups represented in the food web model and are not able to account for increased abundance of new species that were not present in the original monitoring data that might occur as a result of the future scenarios.

Future changes in river flow and sea level rise would also affect some aspects of the human community of Apalachicola Bay. Results of the stakeholder survey indicated an anticipated negative impact to the Franklin County economy due to reduced river flow and increasing sea level rise. Much of the Franklin County economy is based on commercial and recreational fishing (Edmiston 2008) and past drought events have resulted in reduced landings of several fishery species, such as oysters, shrimp and blue crab, due to a reduction in river inflow to Apalachicola Bay (Livingston 2008, Havens et al. 2013). Declines in fishery species populations can have lasting impacts, as has been the case with the Apalachicola Bay oyster fishery, which has failed to recover since its collapse in 2012 and was put under a five-year moratorium in 2020 (Hallerman 2021). Simulation results of this study indicate that reduced river flow in combination with sea level rise may not always have such negative impacts, as the biomass of commercially important white shrimp and blue crab populations were predicted to increase during scenarios of low river flow. Many stakeholders also anticipated a reduction in river flow negatively impacting their personal interaction with Apalachicola Bay. Some of the most common recreational activities in the Apalachicola Bay region that might constitute "personal interaction" are fishing, camping and hiking (Shrestha et al. 2007). While this study is not able to assess the terrestrial impacts of changes in river flow and sea level rise, the food web model results did indicate decreases in biomass of recreationally important fishery species that stakeholders might value in their personal interaction with Apalachicola Bay. A more optimistic result of the stakeholder survey was the largely anticipated little to no impact of a reduction in river flow and increase in sea level on the professions of survey participants. However, this is limited to the demographic of survey participants, many of which held government or scientific researcher professions that are less likely to be directly affected by environmental changes. Had a greater proportion of recreational or commercial fishers participated in the survey, the answers regarding river flow and sea level rise impacts on stakeholder profession may have changed.

4.4 Future directions

There are several future directions that would help expand upon the study at hand. Firstly, the model results presented in this study reflect annual average measures of environmental conditions, species biomasses and Kempton's Q index, and are not representative of seasonal changes that may occur in these variables. Analysis of seasonal trends would be useful for better understanding species recruitment dynamics in the estuary. The environmental conditions presented in this study were limited to salinity and temperature, but Apalachicola River is also a major nutrient source to the bay (Mortazavi et al. 2000), so changes in river flow would affect nutrient loads within the estuary. Higher nutrient loads and subsequently primary production have been associated with increased river inflow to Apalachicola Bay (Huang et al. 2010). Eutrophication is generally not an issue of concern for Apalachicola Bay due to its relatively short residence time (Huang and Spaulding 2002, Livingston 2008). This study was unable to incorporate changes in nutrient loads in response to river flow and sea level rise, so further simulations of these changes and their impact on the food web would add greater depth to the study results. The food web model simulations were also limited by the model domain, which did not encompass the more saline channels (St. Vincent Sound and St. George Sound) that connect the western and eastern regions of Apalachicola Bay to the Gulf of Mexico. Thus, the results were unable to portray potential shifts in species distributions to these areas in response to environmental changes. While the focus of this study was on the Apalachicola Bay region where long-term monitoring data were available, the incorporation of species data from St. Vincent and St. George Sounds would provide a more complete picture of changes in species abundance and distributions in response to river flow and sea level rise. Ecospace is also limited by the inability to calibrate spatial data. While species biomasses and environmental variables were able to be calibrated over time using Ecosim, the same functionality does not yet exist for Ecospace. Though the calibrated Ecosim model serves as the foundation for species dynamics in Ecospace, further study mapping observed species distributions over time would be valuable to compare with the food web model results to assess the goodness of fit of the simulated spatial dynamics of the food web.

The survey of Apalachicola Bay stakeholders provided insight on stakeholder concerns over changes in environmental conditions and species populations in the bay, though this analysis could likely be improved through a greater number and more professionally diverse group of participants. There were little to no survey participants who identified themselves as holding a fishing- or seafood-related profession (i.e. charter boat captain, commercial fisher or seafood worker). As these professions directly rely on fishery species populations in Apalachicola Bay, greater engagement of these stakeholders would add further value to the survey results. Survey questions regarding environmental impacts to specific species also relied on responses from a subset of the total number of survey participants. In some cases, the subset of responses was quite small (e.g., n=5 for questions assessing environmental impacts on blue crab), offering a very limited perspective of anticipated changes in species populations. A greater number of overall survey participants would provide a more reliable sample size for these questions.

The modeling approach utilized by this study offers a comprehensive assessment of the impacts of changes in river flow and sea level rise on the Apalachicola Bay food web that can be expanded upon to serve as a management and education tool. As ANERR accumulates a solid foundation of additional species monitoring data, such as zooplankton and phytoplankton surveys, it is their intent to incorporate these data into the food web model to further enhance the localized representation of the estuary (J. Garwood, personal communication, October 17, 2022). Jason Garwood, Research Coordinator at ANERR, anticipates the model being used to help direct ANERR's management plan for their research and monitoring programs and outline future areas of study (J. Garwood, personal communication, October 17, 2022). The model can also be used as an educational tool, whether for local school groups or Apalachicola Bay stakeholders, to teach about food web ecology and the interaction of environmental and biotic variables, as well as to quantify the impacts of environmental stressors on species in system (J. Garwood, personal communication, October 17, 2022).

The examination of both food web dynamics and human dimensions in this study serves as an example of the comparison of food web modeling analysis and stakeholder perceptions to better understand changes occurring in the system. In some cases, the model and stakeholder survey results were complementary (environmental conditions, Gulf flounder), while in others there were differences between the two (white shrimp, blue crab). Instances where discrepancies were present between model results and stakeholder perceptions provide areas of further investigation into the reasoning behind these differences. Sánchez-Jiménez et al. (2019) suggests that discrepancies between LEK and scientific knowledge may indicate sources of management problems to be addressed with further study. The comparison of stakeholder knowledge and perceptions with modeled simulations is an approach that can be adapted to assess other climate and human-induced impacts on estuarine systems. Utilizing multiple knowledge sources provides a more nuanced understanding of the system (Sánchez-Jiménez et al. 2019). More ecosystem modeling studies around the world have begun to involve stakeholders in the model development process and the framing of research questions (Fulton et al. 2015, Koenigstein et al. 2016, Miller et al. 2017, Belisle et al. 2018). This co-production of knowledge between researchers and local stakeholders is important for providing actionable science that can be of use to natural resource managers (Beier et al. 2017).

4.5 Conclusions

This study used a coupled hydrodynamic and food web model, along with a stakeholder engagement survey, to assess future impacts of changes in river flow and sea level rise on the environmental conditions, fishery populations and greater food web of the Apalachicola Bay estuary. Apalachicola Bay salinity was predicted to increase during scenarios of low river flow and decrease during high river flow, while water temperature was predicted to increase across all scenarios. Within the different low and high river flow scenarios, there was little difference in salinity and temperature between the different sea level rise conditions of each scenario. This trend held true for the changes in species biomasses and broader food web metrics (total biomass and upper trophic level diversity) that were examined across scenarios. Results from the stakeholder survey indicated that white shrimp, blue crab, Gulf flounder and red drum were some of the most commercially and recreationally important species in Apalachicola Bay (besides oysters). The food web model simulations were used to assess changes in the biomass of these species across the future scenarios of river flow and sea level rise. White shrimp (both juvenile and adult) biomass increased during scenarios of low river flow and increased during scenarios of high river flow. Red drum biomass decreased during low river scenarios and increased during high river flow scenarios. Blue crab biomass increased across all scenarios and Gulf flounder biomass decreased across all scenarios. Each species also exhibited distinct spatial distributions in response to the environmental changes. The food web model results portrayed more variable trends in species biomasses due to reduced river flow and increased sea level rise compared to the mostly negative anticipated outcomes reported by the stakeholder survey. The food web model simulations also indicated a transition to greater total food web biomass and less upper trophic level diversity across all future scenarios. Stakeholder survey results showed future reduced river flow and increased sea level rise as largely having an anticipated negative impact on the Franklin County economy and little to no impact on stakeholder profession. Reduced river flow was mostly expected to have a negative impact on stakeholders' personal interaction with Apalachicola Bay, while increased sea level rise was mostly expected to have little or no impact. The food web model for this study serves as the first synthesis of ANERR's environmental and species monitoring data into an adaptable tool for management and education. The model creates a comprehensive roadmap for evaluating changes in estuarine food web dynamics moving forward. This study also highlights the usefulness of incorporating both ecosystem modeling and stakeholder engagement in assessing the impacts of environmental perturbations on coastal systems. Analysis of both species dynamics and human dimensions are important for resource managers to consider when investigating climate and human-induced stressors on estuarine food webs.

APPENDIX A:
IACUC PROTOCOL APPROVAL

UCF

APPROVAL OF IACUC PROTOCOL SUBMISSION

May 27, 2021

Kristy Lewis
Kristy.Lewis@ucf.edu

Dear Kristy Lewis:

The IACUC reviewed the following submission:

Type of Review:	New Protocol Application
Title of Protocol:	Food web dynamics
Investigator:	Kristy Lewis
IACUC ID:	PROTO202100013

- The protocol was approved on 5/24/2021.
- Your next annual review is due before 5/24/2022.
- Your next triennial review is due 5/24/2024.

Please be advised that IACUC approvals are limited to one year maximum and must be renewed annually. Should there be any technical or administrative changes to the approved protocol, they must be submitted as an Amendment to the IACUC for approval. Changes should not be initiated until written IACUC approval is received. Adverse events should be reported to the IACUC as they occur.

If the protocol is over three years old, it must be re-submitted as a Triennial Review for IACUC review and approval. Annual Reviews must be submitted for approval at least three months prior to the Annual Review end date.

You may purchase and use animals according to the provisions outlined in the above referenced animal project.

This letter does not serve as Environmental Health and Safety (EHS) or Institutional Biosafety Committee (IBC) approval. EHS and IBC approval must be handled separately. You must contact EHS prior to initiating animal work to confirm if EHS or IBC approval is required for your project.

Should you have any questions, please do not hesitate to call the office of Animal Welfare at (407) 266-2235.

Please accept our best wishes for the success of your endeavors.

Sincerely,
UCF - Office of Animal Welfare

APPENDIX B:
SPECIES DIET SOURCES

Large coastal sharks
Aines et al. 2018
Plumlee and Wells 2016

Small coastal sharks
Bethea et al. 2007
Plumlee and Wells 2016

Dolphins
Manooch et al. 1984

Seabirds
Lamb et al. 2017

Atlantic stingray
FishBase
GoMexSI

Snapper
Wells et al. 2008

Red drum
Scharf and Schlicht 2000

Black drum
Rubio et al. 2018

Mullet
FishBase
GoMexSI

Juvenile sand seatrout
Sheridan 1978

Adult sand seatrout
Sheridan 1978

Juvenile silver perch
Waggy et al. 2007

Adult silver perch
FishBase
GoMexSI

Inshore lizardfish
Jeffers 2007

Fringed flounder
FishBase
GoMexSI

Gulf flounder
FishBase
GoMexSI

Juvenile spot
Taylor 2012

Adult spot
Sheridan 1978

Southern kingfish
Willis et al. 2015

Juvenile Atlantic croaker
Sheridan 1978

Adult Atlantic croaker
Sheridan 1978

Juvenile pinfish
Stoner and Livingston 1984

Adult pinfish
Stoner and Livingston 1984

Juvenile pigfish
Howe 2001

Adult pigfish
FishBase
GoMexSI

Juvenile hardhead catfish
FishBase
GoMexSI

Adult hardhead catfish
FishBase
GoMexSI

Gulf butterfish

FishBase
GoMexSI

Atlantic bumper
FishBase
GoMexSI

Menhaden
FishBase
GoMexSI

Mojarra
FishBase
GoMexSI

Brief squid
FishBase
GoMexSI

Juvenile bay anchovy
Sheridan 1978

Adult bay anchovy
Sheridan 1978

Juvenile striped anchovy
Modde and Ross 1983

Adult striped anchovy
Modde and Ross 1983

Sardines
FishBase
GoMexSI

Menidia silversides
Warkentine and Rachlin 1989

Hogchoker
FishBase
GoMexSI

Mantis shrimp
Pihl et al. 1992

Roughback shrimp

Based on diet of other shrimp species

Brown shrimp
FishBase
GoMexSI

Pink shrimp
SeaLifeBase
GoMexSI

Juvenile white shrimp
Pollack et al. 2008

Adult white shrimp
SeaLifeBase
GoMexSI

Arrow shrimp
Based on diet of other shrimp species

Blue crab
Laughlin 1982

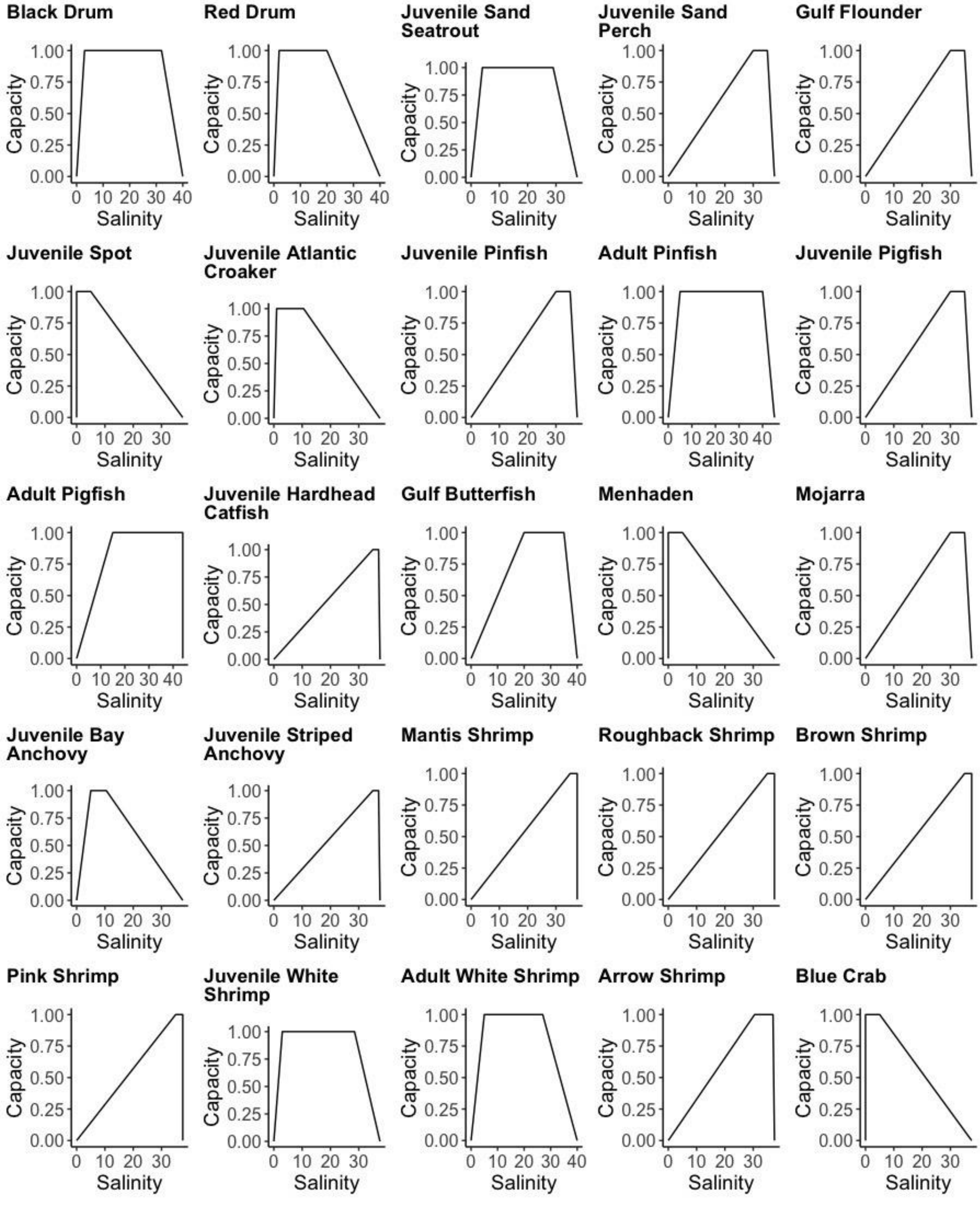
Oysters
FishBase
GoMexSI

Macrozooplankton
Turner 1986

Microzooplankton
Turner 1986

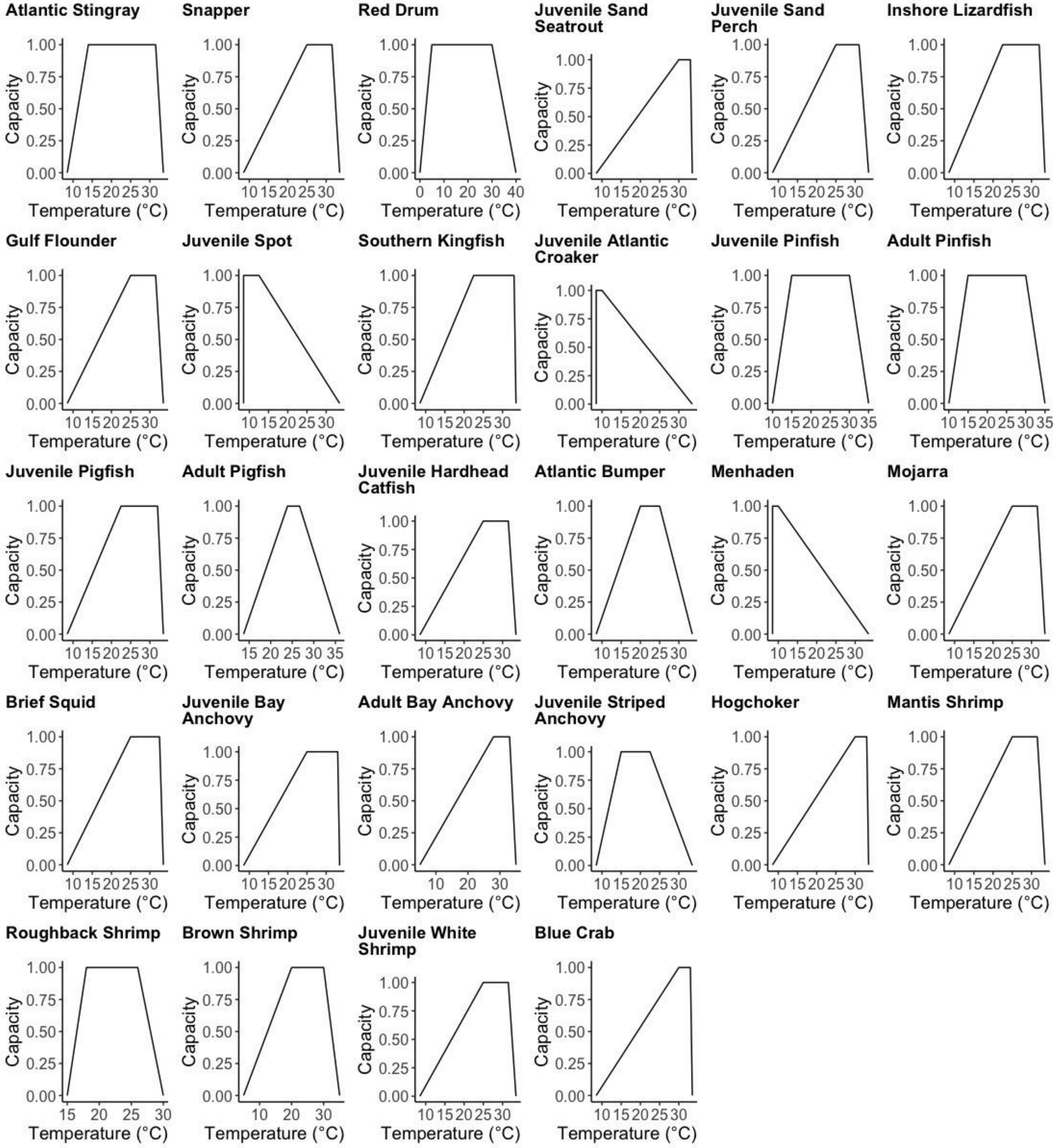
APPENDIX C:
SALINITY RESPONSE CURVES

Appendix C. Activated salinity response curves used in the Apalachicola Bay food web model to define the salinity tolerance ranges of different species.



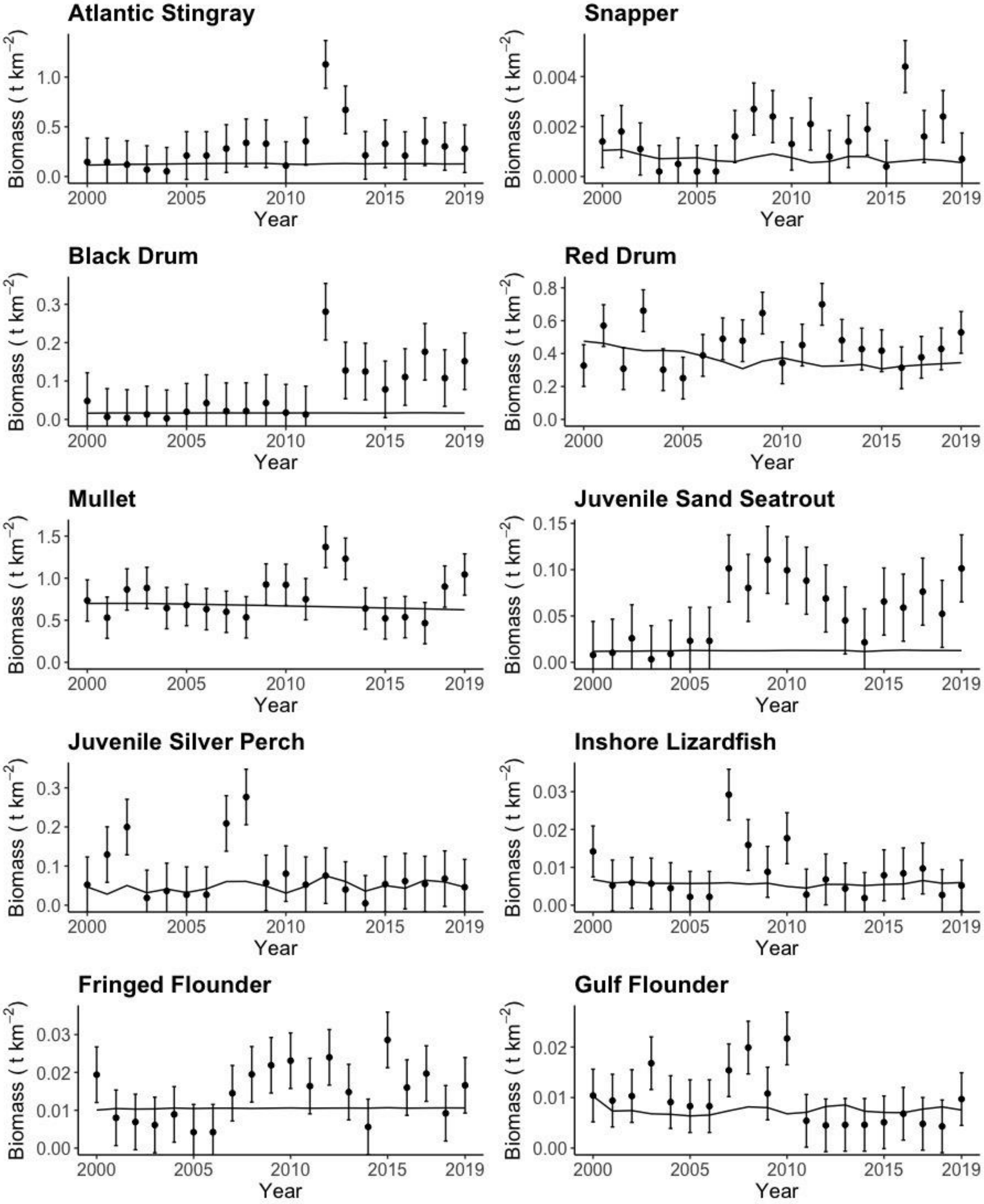
APPENDIX D:
TEMPERATURE RESPONSE CURVES

Appendix D. Activated temperature response curves used in the Apalachicola Bay food web model to define the water temperature tolerance ranges of different species.



APPENDIX E:
COMPARISON OF MODELED AND OBSERVED SPECIES BIOMASSES

Appendix E. Species biomass as modeled by Ecosim (lines) compared to annual observed biomass with standard deviation (dots). The plots shown pertain to species groups where monitoring data was available to provide observed measures of biomass.



Atlantic Stingray

Snapper

Black Drum

Red Drum

Mullet

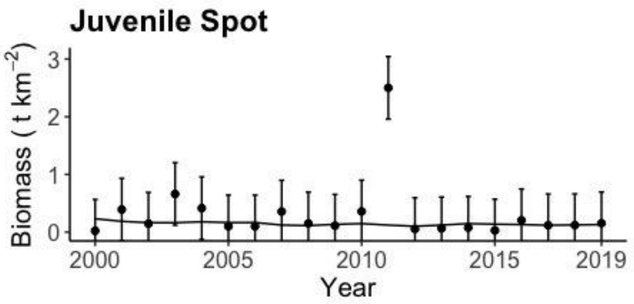
Juvenile Sand Seatrout

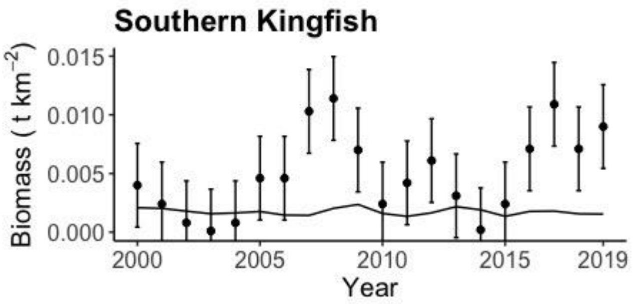
Juvenile Silver Perch

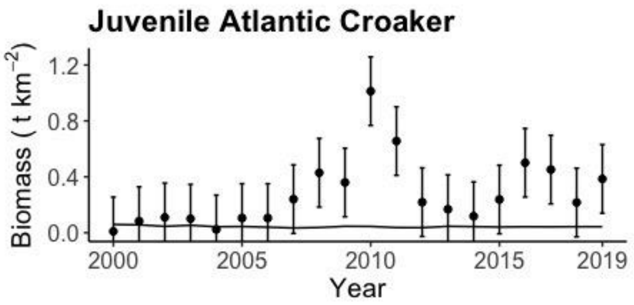
Inshore Lizardfish

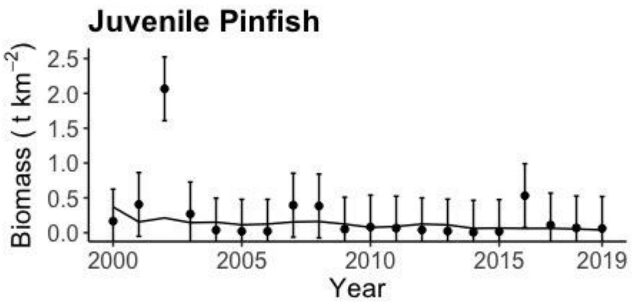
Fringed Flounder

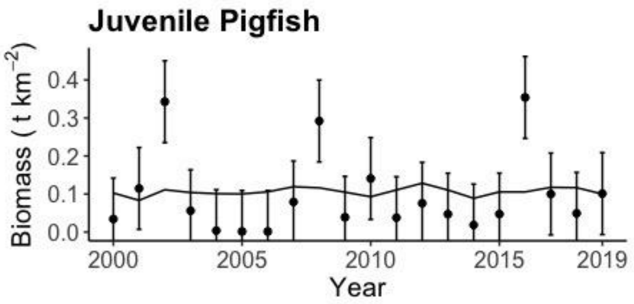
Gulf Flounder

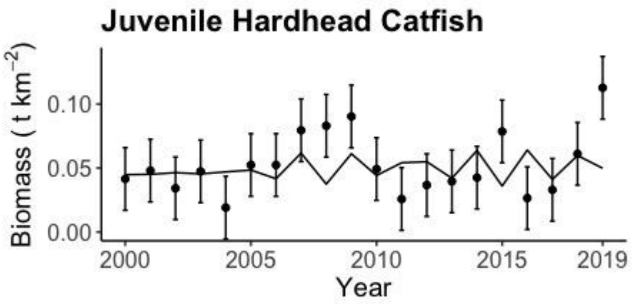

Juvenile Spot
Biomass (t km^{-2})
0
1
2
3
2000
2005
2010
2015
2019
Year

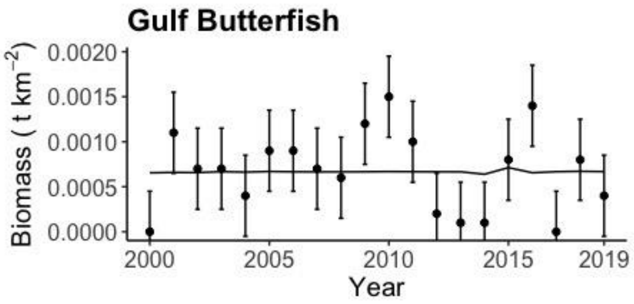

Southern Kingfish
Biomass (t km^{-2})
0.000
0.005
0.010
0.015
2000
2005
2010
2015
2019
Year

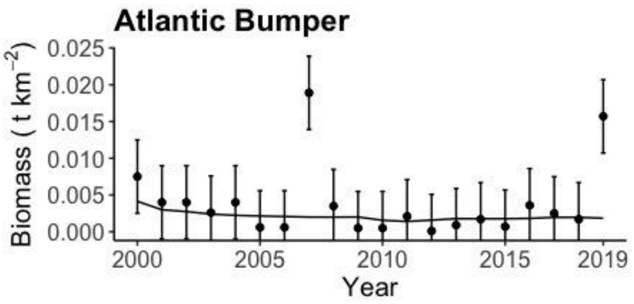

Juvenile Atlantic Croaker
Biomass (t km^{-2})
0.0
0.4
0.8
1.2
2000
2005
2010
2015
2019
Year

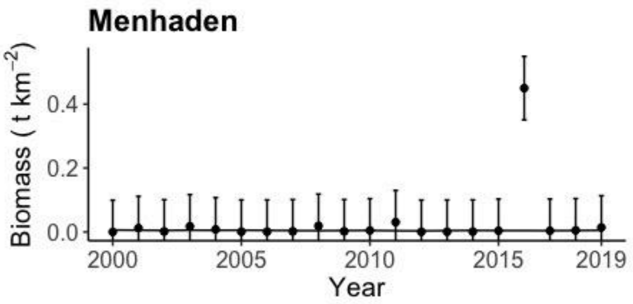

Juvenile Pinfish
Biomass (t km^{-2})
0.0
0.5
1.0
1.5
2.0
2.5
2000
2005
2010
2015
2019
Year

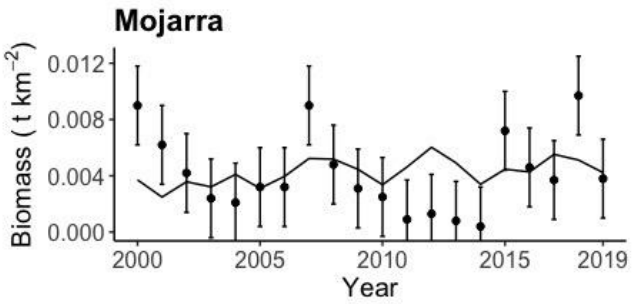

Juvenile Pigfish
Biomass (t km^{-2})
0.0
0.1
0.2
0.3
0.4
2000
2005
2010
2015
2019
Year

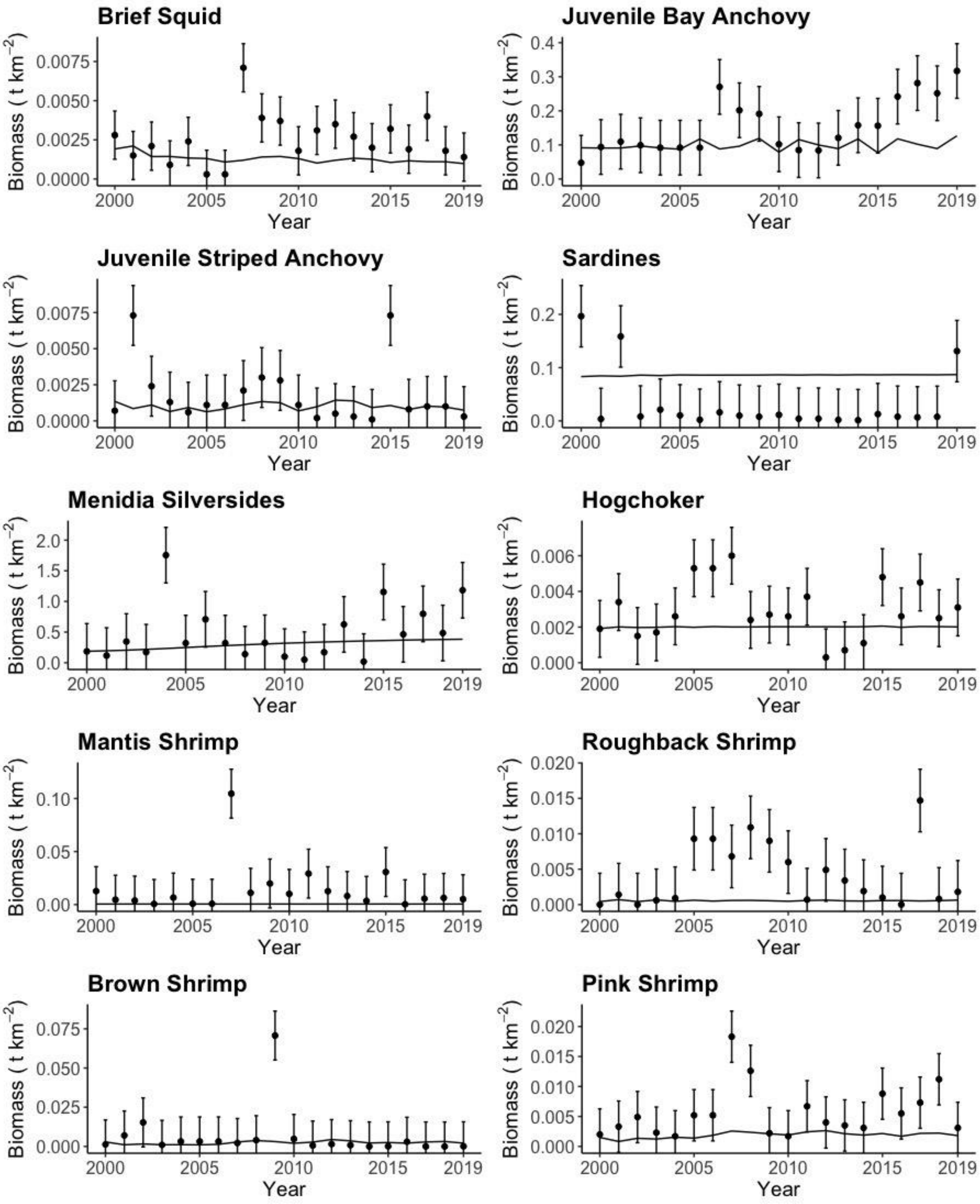

Juvenile Hardhead Catfish
Biomass (t km^{-2})
0.00
0.05
0.10
2000
2005
2010
2015
2019
Year

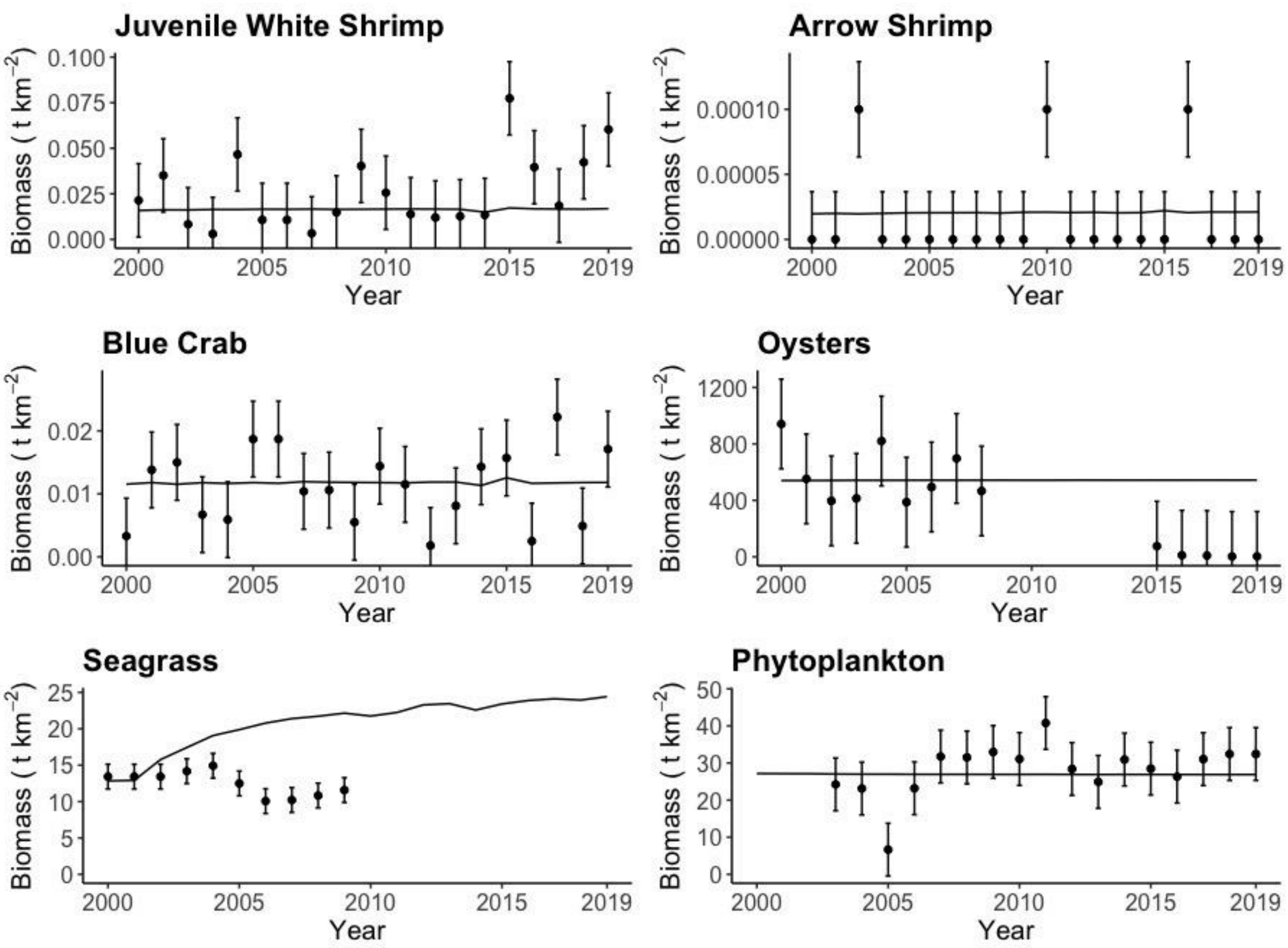

Gulf Butterfish
Biomass (t km^{-2})
0.0000
0.0005
0.0010
0.0015
0.0020
2000
2005
2010
2015
2019
Year


Atlantic Bumper
Biomass (t km^{-2})
0.000
0.005
0.010
0.015
0.020
0.025
2000
2005
2010
2015
2019
Year


Menhaden
Biomass (t km^{-2})
0.0
0.2
0.4
2000
2005
2010
2015
2019
Year

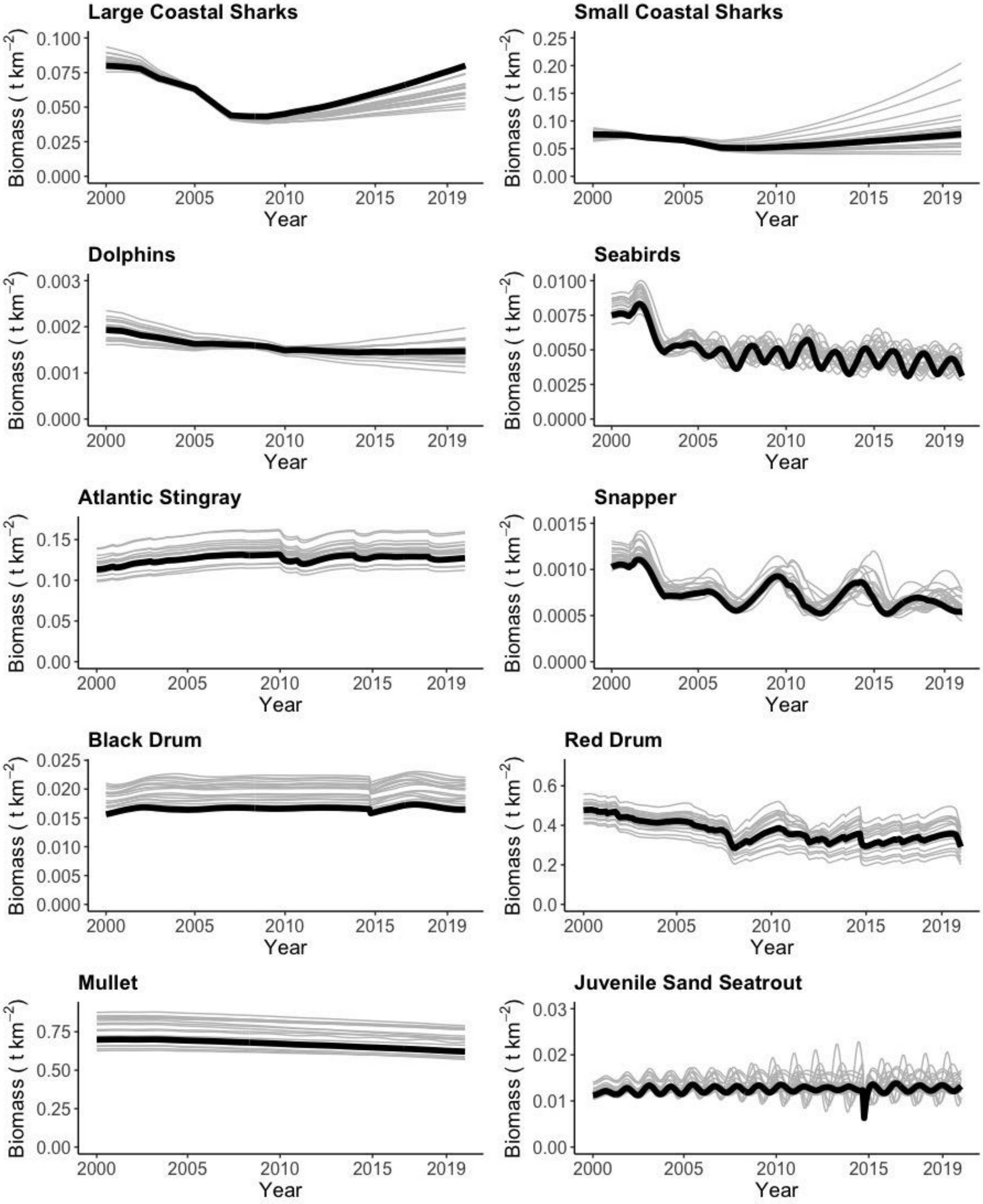

Mojarra
Biomass (t km^{-2})
0.000
0.004
0.008
0.012
2000
2005
2010
2015
2019
Year

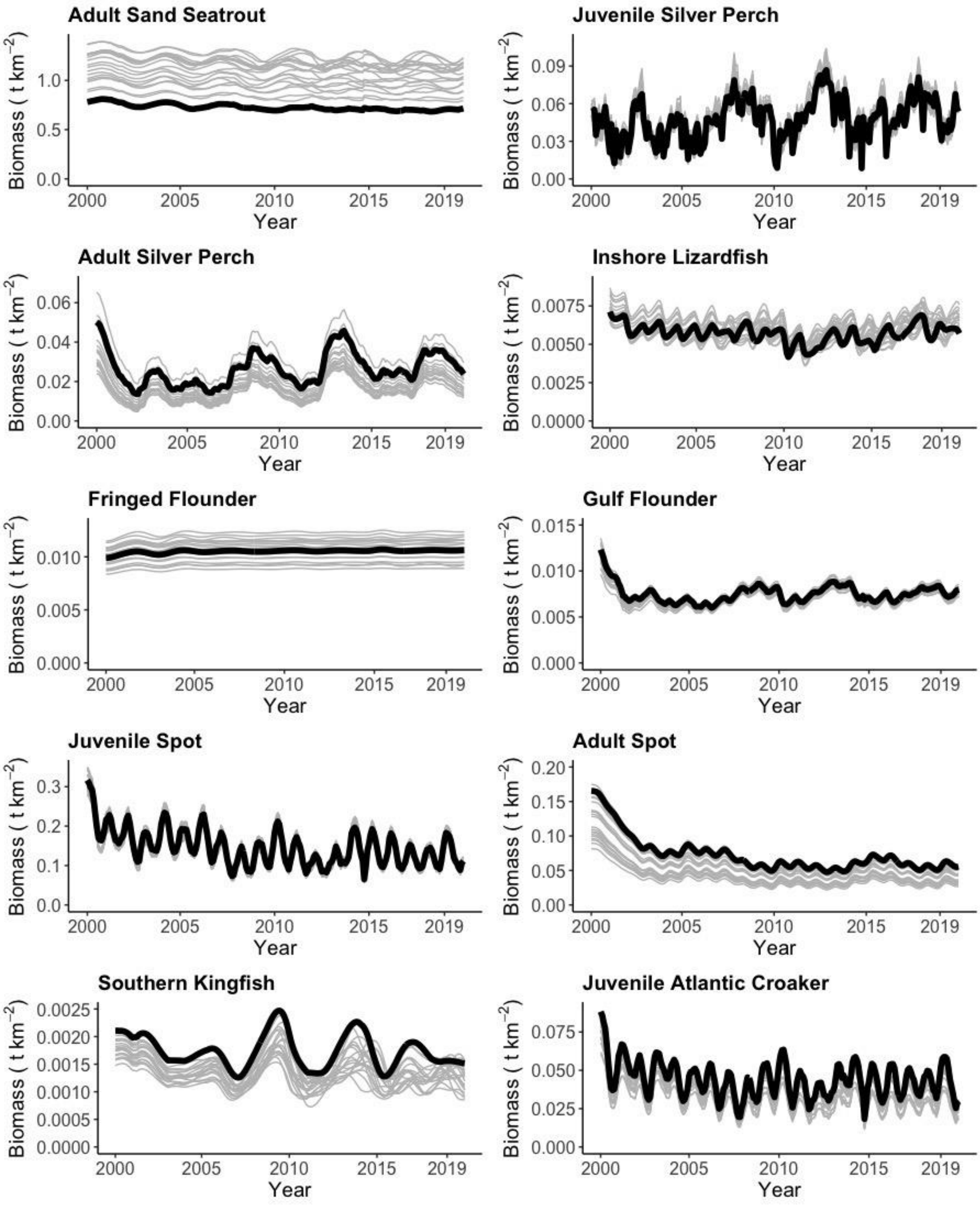

Brief Squid
Biomass (t km^{-2})
0.0000
0.0025
0.0050
0.0075
2000
2005
2010
2015
2019
Year
Juvenile Bay Anchovy
Biomass (t km^{-2})
0.0
0.1
0.2
0.3
0.4
2000
2005
2010
2015
2019
Year
Juvenile Striped Anchovy
Biomass (t km^{-2})
0.0000
0.0025
0.0050
0.0075
2000
2005
2010
2015
2019
Year
Sardines
Biomass (t km^{-2})
0.0
0.1
0.2
2000
2005
2010
2015
2019
Year
Menidia Silversides
Biomass (t km^{-2})
0.0
0.5
1.0
1.5
2.0
2000
2005
2010
2015
2019
Year
Hogchoker
Biomass (t km^{-2})
0.000
0.002
0.004
0.006
2000
2005
2010
2015
2019
Year
Mantis Shrimp
Biomass (t km^{-2})
0.00
0.05
0.10
2000
2005
2010
2015
2019
Year
Roughback Shrimp
Biomass (t km^{-2})
0.000
0.005
0.010
0.015
0.020
2000
2005
2010
2015
2019
Year
Brown Shrimp
Biomass (t km^{-2})
0.000
0.025
0.050
0.075
2000
2005
2010
2015
2019
Year
Pink Shrimp
Biomass (t km^{-2})
0.000
0.005
0.010
0.015
0.020
2000
2005
2010
2015
2019
Year

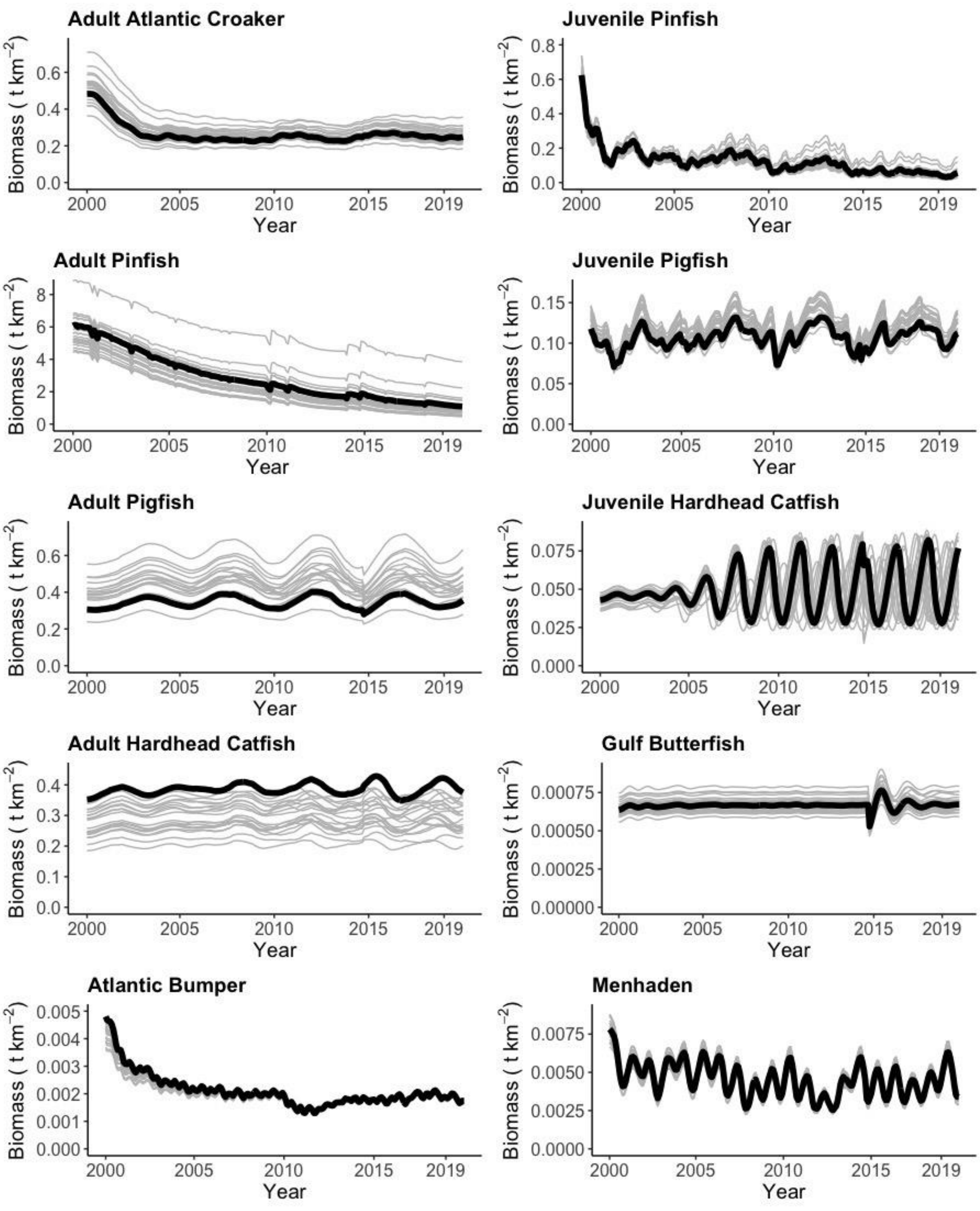

Juvenile White Shrimp
Arrow Shrimp
Blue Crab
Oysters
Seagrass
Phytoplankton
Biomass (t km^{-2})
Year
0.100
0.075
0.050
0.025
0.000
0.00010
0.00005
0.00000
0.02
0.01
0.00
1200
800
400
0
25
20
15
10
5
0
50
40
30
20
10
0
2000
2005
2010
2015
2019

APPENDIX F:
ECOSIM MONTE CARLO OUTPUT

Appendix F. Trends in species biomasses over time as evaluated by 20 iterations of the Monte Carlo routine in Ecosim. Grey lines indicate the biomass values produced by each iteration and the bolded black line indicates the iteration that yielded the lowest SS.




Adult Sand Seatrout
Juvenile Silver Perch
Adult Silver Perch
Inshore Lizardfish
Fringed Flounder
Gulf Flounder
Juvenile Spot
Adult Spot
Southern Kingfish
Juvenile Atlantic Croaker
Biomass (t km^{-2})
Year
2000
2005
2010
2015
2019
0.0
0.5
1.0
0.00
0.03
0.06
0.09
0.00
0.02
0.04
0.06
0.0000
0.0025
0.0050
0.0075
0.000
0.005
0.010
0.015
0.0
0.1
0.2
0.3
0.00
0.05
0.10
0.15
0.20
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.000
0.025
0.050
0.075



Adult Atlantic Croaker

Juvenile Pinfish

Adult Pinfish

Juvenile Pigfish

Adult Pigfish

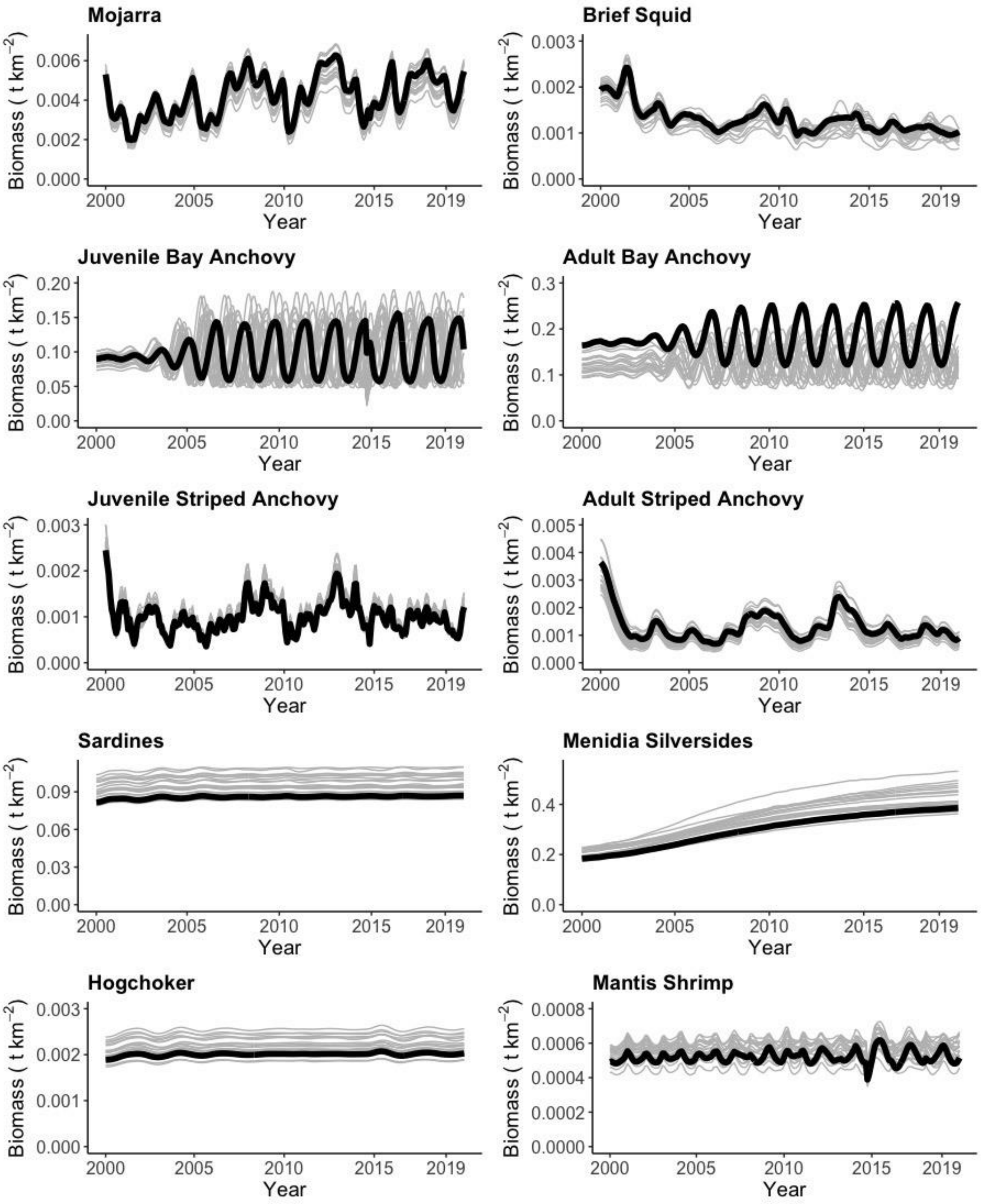
Juvenile Hardhead Catfish

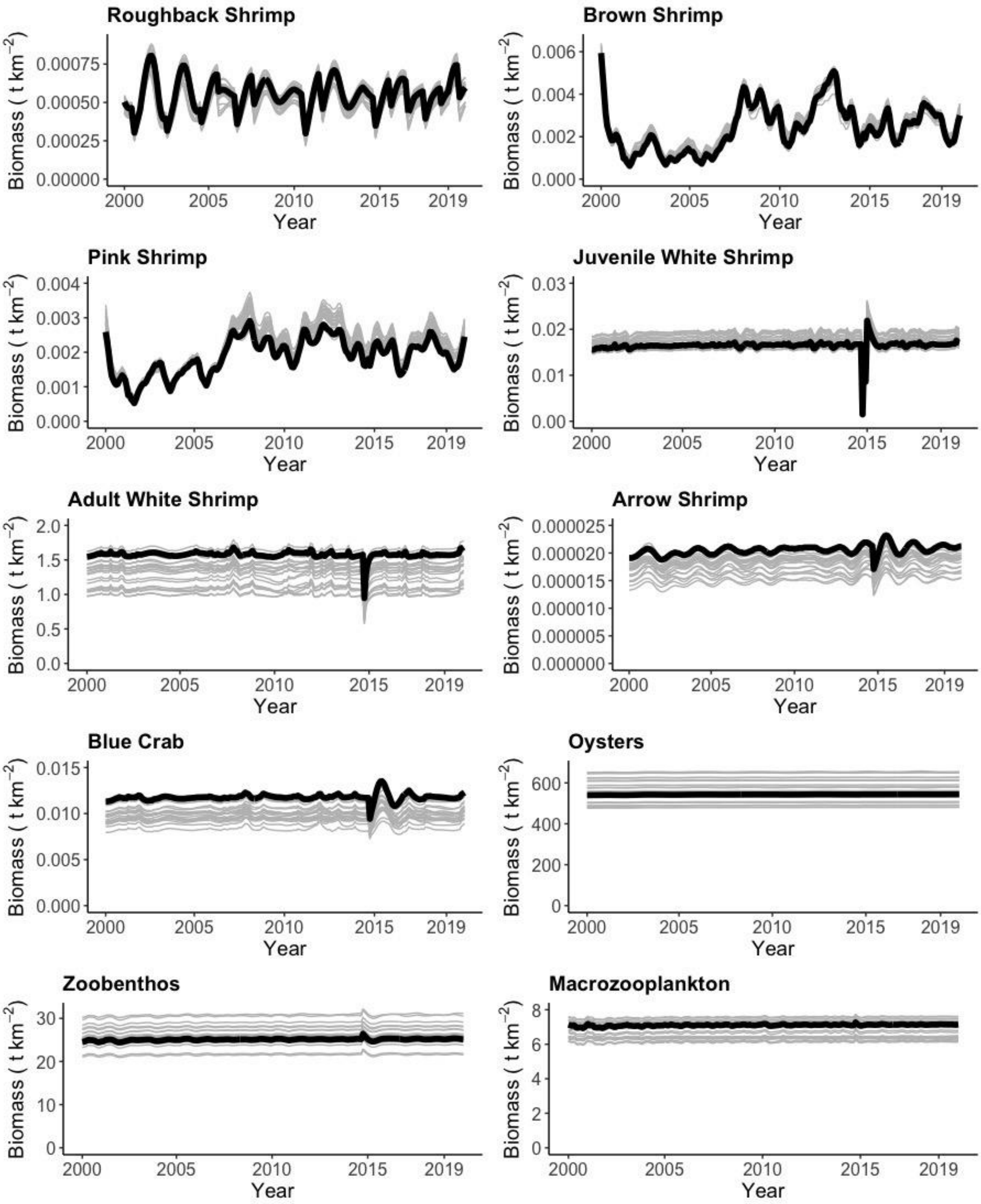
Adult Hardhead Catfish

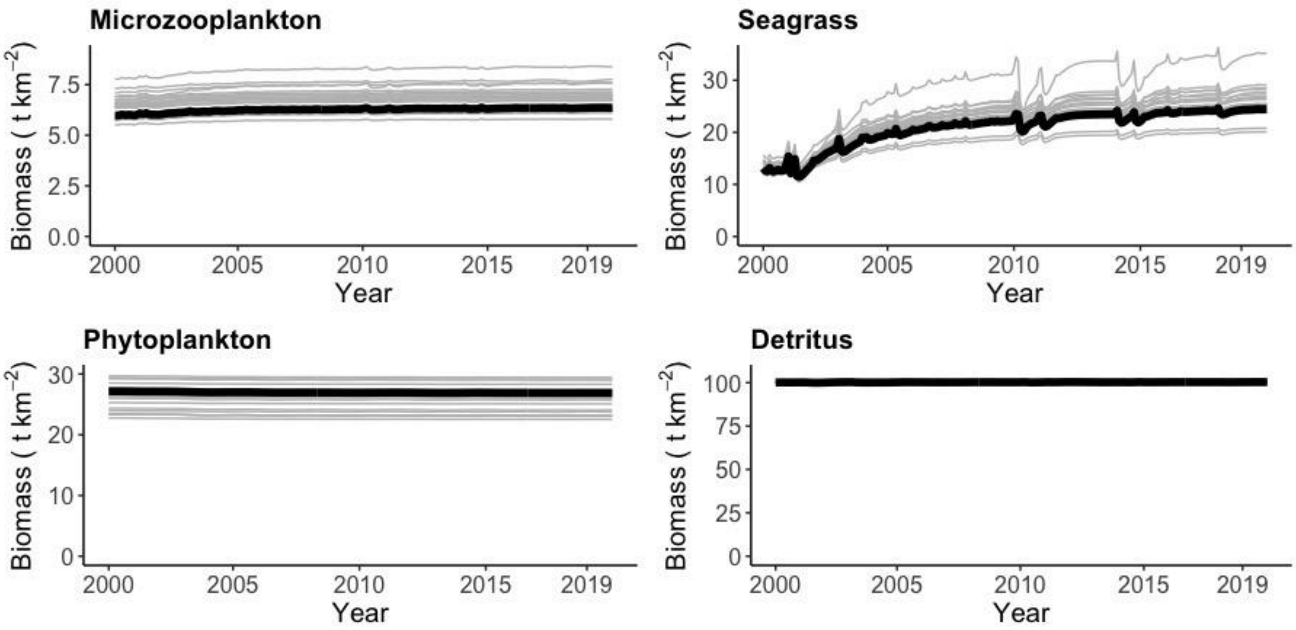
Gulf Butterfish

Atlantic Bumper

Menhaden


Mojarra
Brief Squid
Juvenile Bay Anchovy
Adult Bay Anchovy
Juvenile Striped Anchovy
Adult Striped Anchovy
Sardines
Menidia Silversides
Hogchoker
Mantis Shrimp
Biomass (t km^{-2})
Year
2000
2005
2010
2015
2019
0.000
0.002
0.004
0.006
0.001
0.003
0.00
0.05
0.10
0.15
0.20
0.0
0.1
0.2
0.3
0.005
0.03
0.06
0.09
0.4
0.0000
0.0002
0.0004
0.0006
0.0008


Roughback Shrimp
Brown Shrimp
Pink Shrimp
Juvenile White Shrimp
Adult White Shrimp
Arrow Shrimp
Blue Crab
Oysters
Zoobenthos
Macrozooplankton
Biomass (t km^{-2})
Year
2000
2005
2010
2015
2019
0.00000
0.00025
0.00050
0.00075
0.000
0.002
0.004
0.006
0.000
0.001
0.002
0.003
0.004
0.00
0.01
0.02
0.03
0.0
0.5
1.0
1.5
2.0
0.000000
0.000005
0.000010
0.000015
0.000020
0.000025
0.000
0.005
0.010
0.015
0
200
400
600
0
10
20
30
0
2
4
6
8


Microzooplankton
Biomass (t km^{-2})
0.0
2.5
5.0
7.5
2000
2005
2010
2015
2019
Year
Seagrass
Biomass (t km^{-2})
0
10
20
30
2000
2005
2010
2015
2019
Year
Phytoplankton
Biomass (t km^{-2})
0
10
20
30
2000
2005
2010
2015
2019
Year
Detritus
Biomass (t km^{-2})
0
25
50
75
100
2000
2005
2010
2015
2019
Year

APPENDIX G:
HYDRODYNAMIC MODEL-DATA COMPARISONS

Appendix G. Hydrodynamic model-data comparisons of water level, salinity and temperature data collected at NOAA tidal and SWMP stations in Apalachicola Bay during 2019 (model calibration) and 2000 to 2018 (model validation).

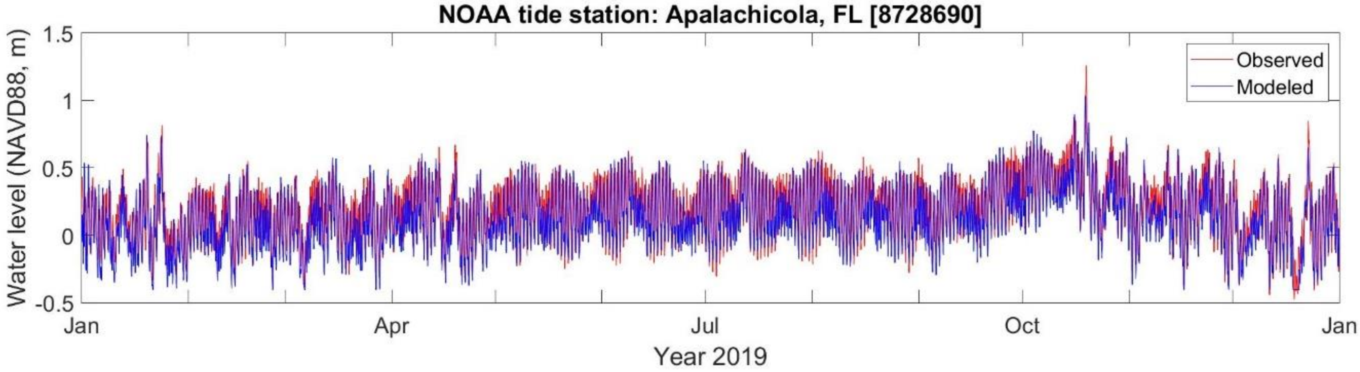


Figure G1. Comparison of 2019 hourly modeled and measured water level (m, NAVD88) at NOAA tide station 8728690 (Apalachicola, FL).

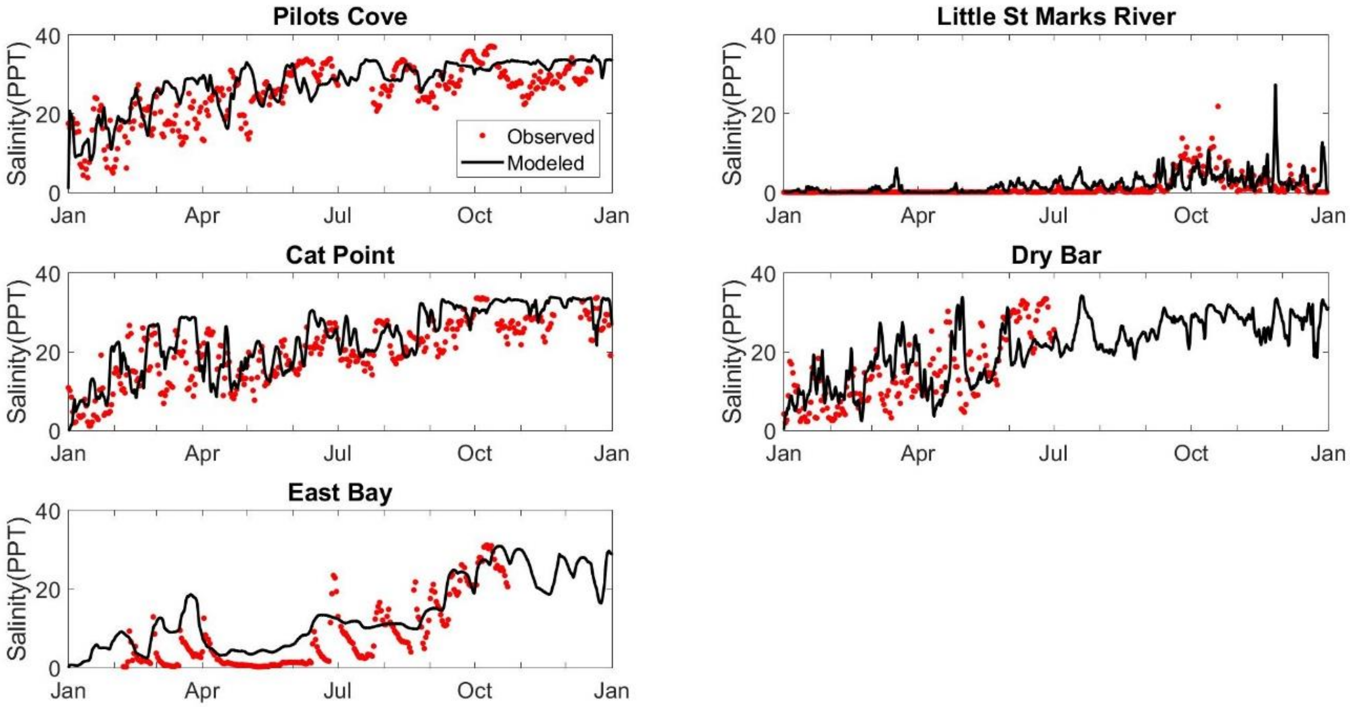


Figure G2. Comparison of 2019 daily modeled and measured salinity (ppt) at five SWMP stations.

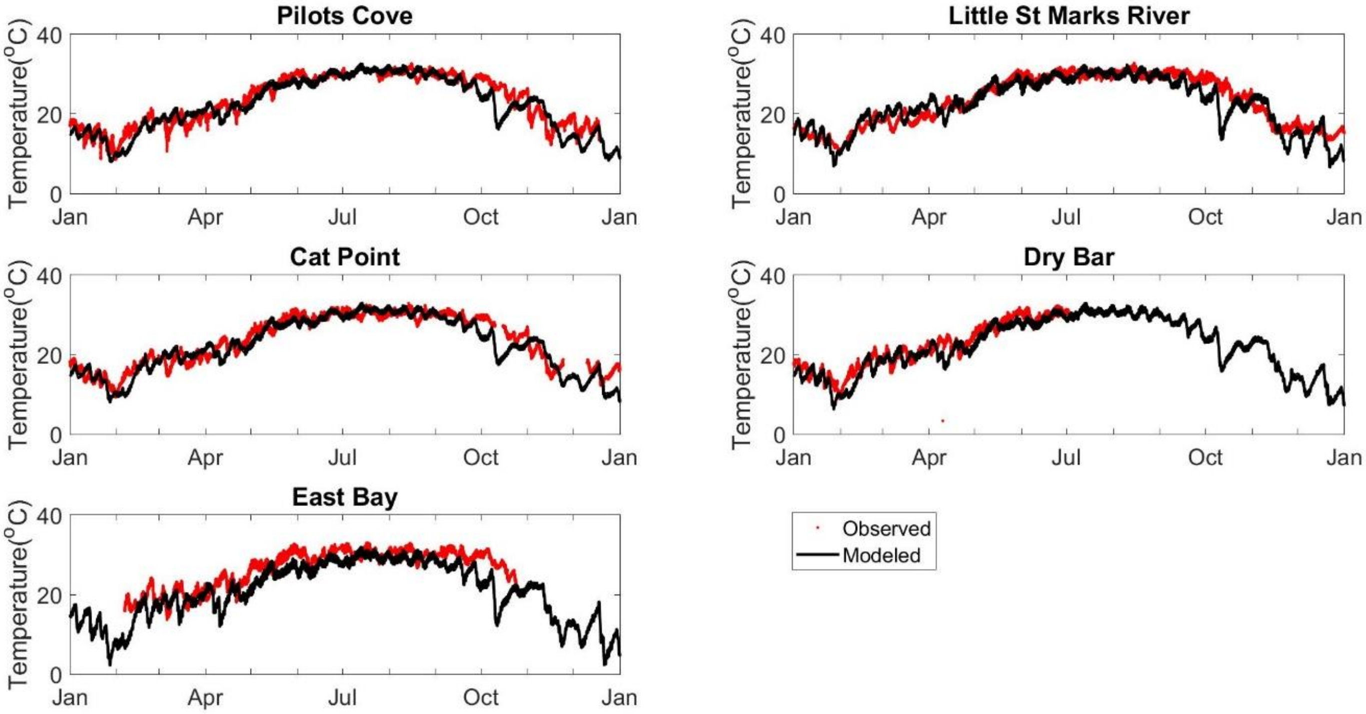


Figure G3. Comparison of 2019 daily modeled and measured temperature (°C) at five SWMP stations.

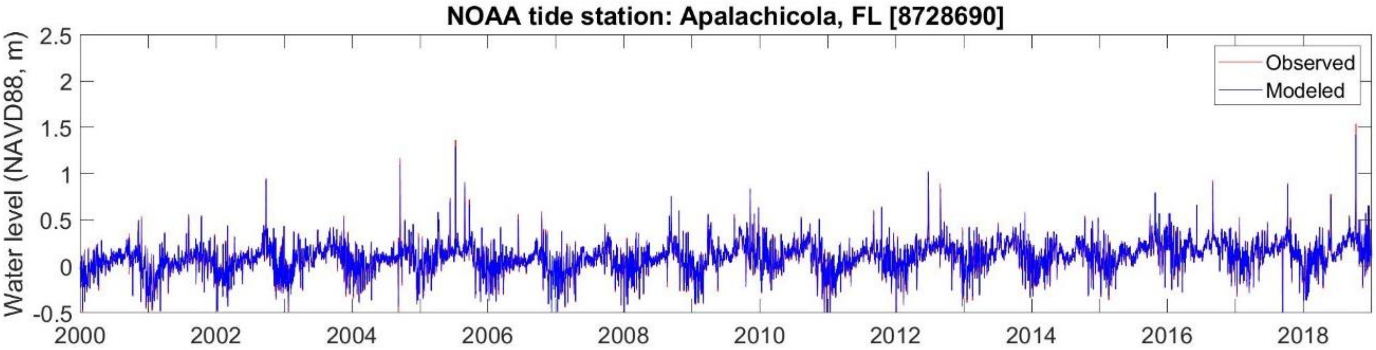


Figure G4. Comparison of daily modeled and measured water level (m, NAVD88) at NOAA tide station 8728690 (Apalachicola, FL) for years 2000-2018.

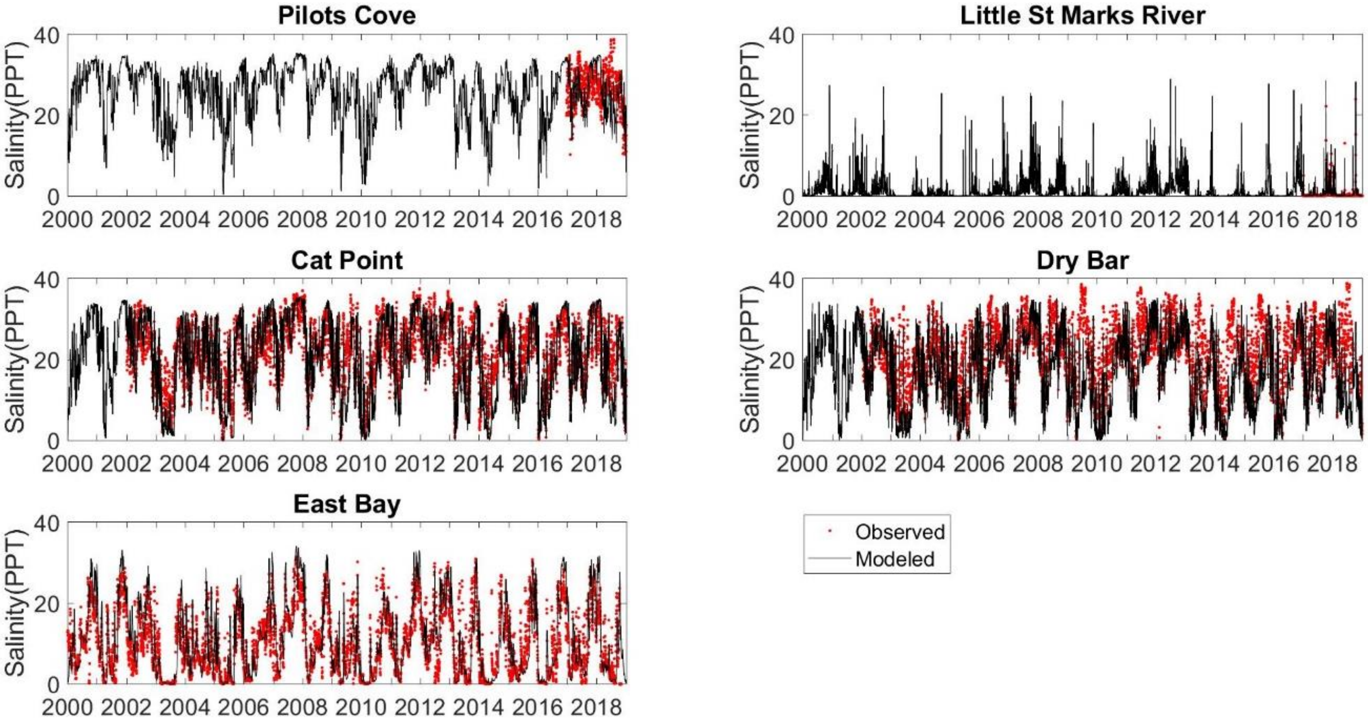


Figure G5. Comparison of daily modeled and measured salinity (ppt) at five SWMP stations for years 2000-2018.

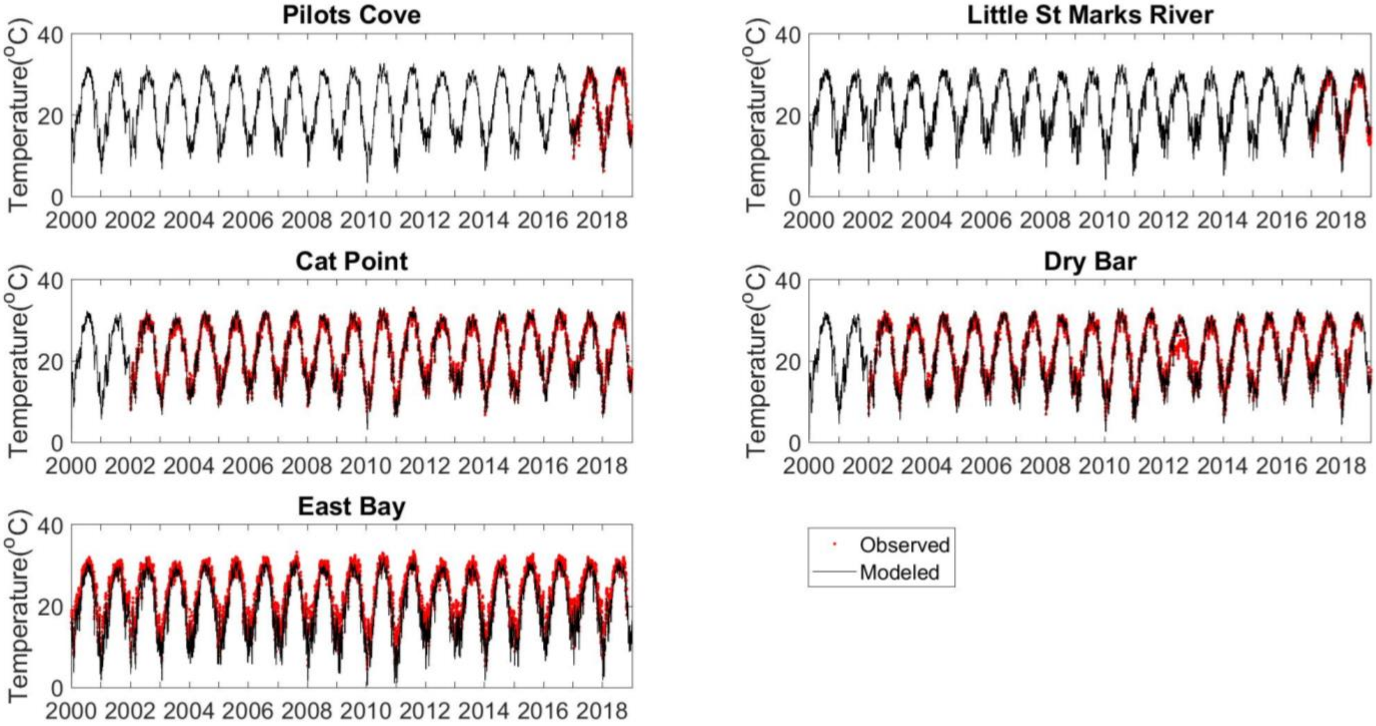


Figure G6. Comparison of daily modeled and measured temperature (°C) at five SWMP stations for years 2000-2018.

APPENDIX H:
IRB STAKEHOLDER SURVEY APPROVAL

UCF
UNIVERSITY OF CENTRAL FLORIDA

Institutional Review Board
FWA00000351
IRB00001138, IRB00012110
Office of Research
12201 Research Parkway
Orlando, FL 32826-3246

EXEMPTION DETERMINATION

October 18, 2021

Dear Kira Allen:

On 10/18/2021, the IRB determined the following submission to be human subjects research that is exempt from regulation:

Type of Review:	Initial Study
Title:	Effects of changing salinity regimes on Apalachicola Bay food web dynamics
Investigator:	Kira Allen
IRB ID:	STUDY00002991
Funding:	Name: Natl Oceanic Atmospheric Admin (NOAA), Funding Source ID: NA20NOS4200126
Grant ID:	N/A
Documents Reviewed:	• HRP-251- FORM - Faculty Advisor Scientific-Scholarly Review fillable form.pdf, Category: Faculty Research Approval; • HRP-254_update, Category: Consent Form; • HRP-255_update, Category: IRB Protocol; • IRB Allen 2991 Apalachicola Bay Stakeholders Survey transcript_update.docx, Category: Survey / Questionnaire; • stakeholder survey recruitment_update1.docx, Category: Recruitment Materials;

This determination applies only to the activities described in the IRB submission and does not apply should any changes be made. If changes are made, and there are questions about whether these changes affect the exempt status of the human research, please submit a modification request to the IRB. Guidance on submitting Modifications and Administrative Check-in are detailed in the Investigator Manual (HRP-103), which can be found by navigating to the IRB Library within the IRB system. When you have completed your research, please submit a Study Closure request so that IRB records will be accurate.

If you have any questions, please contact the UCF IRB at 407-823-2901 or irb@ucf.edu. Please include your project title and IRB number in all correspondence with this office.

Sincerely,

Kamille C. Birkbeck

Kamille Birkbeck
Designated Reviewer

APPENDIX I:
APALACHICOLA BAY STAKEHOLDER SURVEY QUESTIONS

Appendix H. Questions used to survey Apalachicola Bay stakeholders about their knowledge and perceptions of species and environmental changes in Apalachicola Bay. The survey was conducted electronically using ArcGIS Survey123 software.

Apalachicola Bay Stakeholders Survey

This document serves as a transcript of all survey questions. The online survey form that will be distributed to participants can be found here.

This survey is being conduct to assess knowledge and perceptions of environmental changes, species populations and future outlook of Apalachicola Bay.

Survey of Apalachicola Bay stakeholders

You are being invited to take part in a research study. Whether you take part is up to you.

Researchers at University of Central Florida and Apalachicola National Estuarine Research Reserve are partnering with stakeholders for the Apalachicola Bay region to learn about your knowledge and perceptions of environmental changes, species populations and future outlook of Apalachicola Bay.

The questionnaire will take 10-20 minutes to complete.

Your participation in this study is voluntary. You are free to withdraw your consent and discontinue participation in this study at any time without prejudice or penalty. Your name and identifying information will not be linked to your responses. Your identity will not be included in any reports, papers, and presentations.

You will also be asked to provide your contact information if you would like to receive a free mug by mail and/or would like to be contacted for a follow-up or the final results of this study. If you choose to disclose your identifiable information, it will be stored in a separate ESRI Survey123 form. Only the investigators associated with this study will have access to the data.

You must be 18 years of age or older to take part in this research study.

Study contact for questions about the study or to report a problem: If you have questions, concerns, or complaints: Kira Allen, Graduate Student, Department of Biology, College of Sciences, (503)-784-5265. Faculty advisor: Dr. Kristy Lewis, Department of Biology, College of Sciences, (407)-823-2906.

IRB contact about your rights in this study or to report a complaint: If you have questions about your rights as a research participant, or have concerns about the conduct of this study, please contact Institutional Review Board (IRB), University of Central Florida, Office of Research, 12201 Research Parkway, Suite 501, Orlando, FL 32826-3246 or by telephone at (407) 823-2901, or email irb@ucf.edu.

By continuing on to the survey, you consent to take part in this research.

Please confirm that you are 18 years of age or older and willing to participate.*

- ○ I am over 18 and willing to participate.
- ○ I am under 18.
- ○ I am unwilling to participate.

In what county or parish do you live?

____

In what state do you live?

____

Q1. Do you consider yourself a Scientific Researcher?
Pertaining to Apalachicola Bay.

- ○ Yes
- ○ No

If yes,
Q1a. What is your area of expertise?

____

Q2. Do you consider yourself a Commercial Fisher?
Pertaining to Apalachicola Bay.

- ○ Yes
- ○ No

If yes,
Q2a. What species do you target for commercial fishing?

____

Q2b. Which gear(s) do you use?

____

Q2c. Which area do you frequently fish in?
To identify where you fish for your target species, circle an area on the map. Click on the squiggly line icon in the right side of the window to begin drawing. Zoom in or out as necessary. Please draw a circle with a perimeter of ~20 miles (~30 km) or less (perimeter is calculated in the gray bar below the map). If you would like to circle more than one area, you can do so by adding a new map using the “+” symbol below.

Q3. Do you consider yourself a Seafood Worker?
Working with seafood may include processing, food preparation or other roles involved in converting raw seafood into a consumable product.

- ○ Yes
- ○ No

If yes,
Q3a. What kind of seafood do you work with?

_____

Q3b. Which describe(s) your role as a Seafood Worker?
Check all that apply.

- ▪ Processing (initial steps taken to convert raw fish or other species into a sellable product, i.e.. sorting, evisceration, cleaning, filleting, etc.)
- ▪ Food preparation (cooking or preparing seafood so it may be consumed)
- ▪ Other:______

Q4. Do you consider yourself a Recreational Fisher?
Pertaining to Apalachicola Bay.

- ○ Yes

○ No

If yes,

Q4a. What do you fish for?

____

Q4b. Which gear(s) do you use?

____

Q4c.

Which area(s) do you frequently fish in?

To identify where you frequently fish, circle an area on the map. Click on the squiggly line icon in the right side of the window to begin drawing. Zoom in or out as necessary. Please draw a circle with a perimeter of ~20 miles (~30 km) or less (perimeter is calculated in the gray bar below the map). If you would like to circle more than one area, you can do so by adding a new map using the “+” symbol below.

Q5. Do you consider yourself a Fishing Charter Boat Captain?

Pertaining to Apalachicola Bay.

○ Yes
○ No

If yes,

Q5a. Which area(s) do you frequently visit as part of charters?

To identify which areas you frequently visit for fishing charters, circle an area on the map. Click on the squiggly line icon in the right side of the window to begin drawing. Zoom in or out as necessary. Please draw a circle with a perimeter of ~20 miles (~30 km) or less (perimeter is calculated in the gray bar below the map). If you would like to circle more than one area, you can do so by adding a new map using the “+” symbol below.

Q6. Do you consider yourself a Local, State, or Federal Government Employee or Representative?

Pertaining to Apalachicola Bay.

○ Yes
○ No

If yes,

Q6a. Which branch(es) of government are you employed by or represent?

Check all that apply.

▪ Local
▪ State
▪ Federal

Q7. Do you consider yourself a Non-Profit Organization Representative?

Pertaining to Apalachicola Bay.

○ Yes
○ No

Q8. Do you consider yourself a Local Community Member?

Live within ~25 miles of Apalachicola Bay.

○ Yes
○ No

If yes,
Q8a. How long have you lived within ~25 miles of Apalachicola Bay?
- Less than 5 years
- 5 – 10 years
- 10 – 20 years
- More than 20 years

Q9. Do you work within the Apalachicola Bay watershed (as contained within the red border on the map image)?

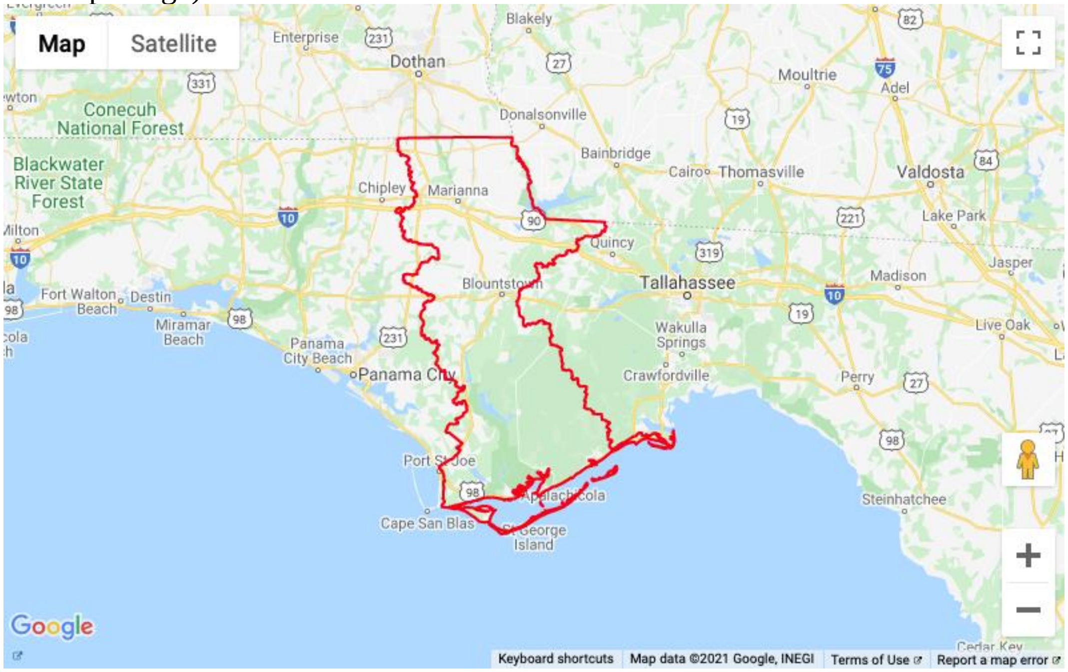


Image courtesy of Northwest Florida Water Management District.

- Yes
- No

If yes,
Q9a. How long have you been doing this work?
- Less than 5 years
- 5 – 10 years
- 10 – 20 years
- More than 20 years

Q10. Based on your knowledge, over approximately the past 10 years (since the 2011-2012 major drought), the WATER FLOW from Apalachicola River into Apalachicola Bay has:
- Increased
- Decreased
- Remained the same
- Not sure

Q11. Based on your knowledge, over approximately the past 10 years (since the 2011-2012 major drought), the HIGH TIDE LEVEL in Apalachicola Bay has:
- Increased

- ○ Decreased
- ○ Remained the same
- ○ Not sure

Q12. Oysters are known to be a highly important commercial species for Apalachicola Bay. Besides oysters, which species do you consider to be the most COMMERCIALLY IMPORTANT (holds commercial value) in Apalachicola Bay?

- Fringed Flounder, Gulf Flounder (Etropus crossotus, Paralichthys albiguttata)
- Menhaden (Brevoortia spp.)
- Blue crab (Callinectes sapidus)
- Pinfish (Lagodon rhomboides)
- Sand Seatrout (Cynoscion arenarius)
- Gray Snapper, Lane Snapper (Lutjanus griseus, Lutjanus synagris)
- White, brown, pink shrimp (Litopenaeus setiferus, Farfantepenaeus aztecus, Farfantepenaeus duorarum)
- None of these
- Not sure
- Other:_______

If anything other than "None of these or Not sure",

Q12a. Based on your knowledge, over the past 10 years (since the 2011-2012 major drought), the population of the previously selected COMMERCIALLY IMPORTANT species in Apalachicola Bay has:

- ○ Increased
- ○ Decreased
- ○ Remained the same
- ○ Not sure

Q12b. Apalachicola Bay is expected to experience a REDUCTION IN RIVER INFLOW over the next few decades. Based on your knowledge, how do you think a CONTINUAL REDUCTION IN RIVER FLOW will impact the population of the previously selected COMMERCIALLY IMPORTANT species?

- ○ Strong increase in population abundance
- ○ Moderate increase in population abundance
- ○ Little to no change in population abundance
- ○ Moderate decrease in population abundance
- ○ Strong decrease in population abundance
- ○ Not sure

Q12c. Apalachicola Bay is expected to experience an INCREASE IN SEA LEVEL over the next few decades, which would increase salinity levels. Based on your knowledge, how do you think an INCREASE IN SEA LEVEL will impact the population of the previously selected COMMERCIALLY IMPORTANT species?

- ○ Strong increase in population abundance
- ○ Moderate increase in population abundance
- ○ Little to no change in population abundance
- ○ Moderate decrease in population abundance
- ○ Strong decrease in population abundance
- ○ Not sure

Q13. Based on your knowledge, please rank the following species in order form most (#1) to least COMMERCIALLY IMPORTANT in Apalachicola Bay.

Drag and drop species to adjust the order. Most important (#1) is listed at the top and least important at the bottom.

- Fringed Flounder, Gulf Flounder (Etropus crossotus, Paralichthys albiguttata)
- Menhaden (Brevoortia spp.)
- Blue crab (Callinectes sapidus)
- Pinfish (Lagodon rhomboides)
- Sand Seatrout (Cynoscion arenarius)
- Gray Snapper, Lane Snapper (Lutjanus griseus, Lutjanus synagris)
- White, brown, pink shrimp (Litopenaeus setiferus, Farfantepenaeus aztecus, Farfantepenaeus duorarum)
- Oysters (Crassostrea virginica)
- Other: _____

Q14. Select a species you consider to be the most RECREATIONALLY IMPORTANT (sought after for recreational fishing) in Apalachicola Bay.

- Fringed Flounder, Gulf Flounder (Etropus crossotus, Paralichthys albiguttata)
- Menhaden (Brevoortia spp.)
- Blue crab (Callinectes sapidus)
- Pinfish (Lagodon rhomboides)
- Sand Seatrout (Cynoscion arenarius)
- Gray Snapper, Lane Snapper (Lutjanus griseus, Lutjanus synagris)
- White, brown, pink shrimp (Litopenaeus setiferus, Farfantepenaeus aztecus, Farfantepenaeus duorarum)
- None of these
- Not sure
- Other:______

If anything other than "None of these" or "Not sure",

Q14a. Based on your knowledge, over the past 10 years (since the 2011-2012 major drought), the population of the previously selected RECREATIONALLY IMPORTANT species in Apalachicola Bay has:

- ○ Increased
- ○ Decreased
- ○ Remained the same
- ○ Not sure

Q14b. Apalachicola Bay is expected to experience a REDUCTION IN RIVER INFLOW over the next few decades. How do you think a CONTINUAL REDUCTION IN RIVER FLOW will impact populations of the previously selected RECREATIONALLY IMPORTANT species?

- ○ Strong increase in population abundance
- ○ Moderate increase in population abundance
- ○ Little to no change in population abundance
- ○ Moderate decrease in population abundance
- ○ Strong decrease in population abundance
- ○ Not sure

Q14c. Apalachicola Bay is expected to experience an INCREASE IN SEA LEVEL over the next few decades, which would increase salinity levels. How do you think an INCREASE IN SEA LEVEL will impact the population of the previously selected RECREATIONALLY IMPORTANT species?

- ○ Strong increase in population abundance
- ○ Moderate increase in population abundance
- ○ Little to no change in population abundance
- ○ Moderate decrease in population abundance
- ○ Strong decrease in population abundance
- ○ Not sure

Q15. Based on your knowledge, please rank the following species in order form most (#1) to least RECREATIONALLY IMPORTANT in Apalachicola Bay.
Drag and drop species to adjust the order. Most important (#1) is listed at the top and least important at the bottom.

- Fringed Flounder, Gulf Flounder (Etropus crossotus, Paralichthys albiguttata)
- Menhaden (Brevoortia spp.)
- Blue crab (Callinectes sapidus)
- Pinfish (Lagodon rhomboides)
- Sand Seatrout (Cynoscion arenarius)
- Gray Snapper, Lane Snapper (Lutjanus griseus, Lutjanus synagris)
- White, brown, pink shrimp (Litopenaeus setiferus, Farfantepenaeus aztecus, Farfantepenaeus duorarum)
- Oysters (Crassostrea virginica)
- Other:______

Apalachicola Bay is expected to experience a REDUCTION IN RIVER INFLOW over the next few decades, which will likely increase salinity levels.

Q16. How do you think a CONTINUAL REDUCTION IN RIVER FLOW will impact the water temperature of Apalachicola Bay?

- ○ Strong increase
- ○ Moderate increase
- ○ Little to no change
- ○ Moderate decrease
- ○ Strong decrease
- ○ Not sure

Q17. How do you think a CONTINUAL REDUCTION IN RIVER FLOW will impact the salinity of Apalachicola Bay?

- ○ Strong increase
- ○ Moderate increase
- ○ Little to no change
- ○ Moderate decrease
- ○ Strong decrease
- ○ Not sure

Q18. How do you think a CONTINUAL REDUCTION IN RIVER FLOW will impact the turbidity (cloudiness of the water) of Apalachicola Bay?

- Strong increase
- Moderate increase
- Little to no change
- Moderate decrease
- Strong decrease
- Not sure

Q19. How do you think a CONTINUAL REDUCTION IN RIVER FLOW will impact the Franklin County economy?

- Strong positive impact
- Moderate positive impact
- Little to no impact
- Moderate negative impact
- Strong negative impact
- Not sure

Q20. How do you think a CONTINUAL REDUCTION IN RIVER FLOW will impact your profession?

- Strong positive impact
- Moderate positive impact
- Little to no impact
- Moderate negative impact
- Strong negative impact
- Not sure

Q21. How do you think a CONTINUAL REDUCTION IN RIVER FLOW will impact you personal interaction with the Apalachicola Bay ecosystem?

Personal interaction with the ecosystem might include activities such as fishing, birding, hiking, boating or any engagement with the ecosystem outside of your profession.

- Strong positive impact
- Moderate positive impact
- Little to no impact
- Moderate negative impact
- Strong negative impact
- Not sure

Apalachicola Bay is expected to experience an INCREASE IN SEA LEVEL over the next few decades, which would increase salinity levels.

Q22. How do you think an INCREASE IN SEA LEVEL will impact the water temperature of Apalachicola Bay?

- Strong increase
- Moderate increase
- Little to no change
- Moderate decrease

- Strong decrease
- Not sure

Q23. How do you think an INCREASE IN SEA LEVEL will impact the salinity of Apalachicola Bay?

- Strong increase
- Moderate increase
- Little to no change
- Moderate decrease
- Strong decrease
- Not sure

Q24. How do you think an INCREASE IN SEA LEVEL will impact the turbidity (cloudiness of the water) of Apalachicola Bay?

- Strong increase
- Moderate increase
- Little to no change
- Moderate decrease
- Strong decrease
- Not sure

Q25. How do you think an INCREASE IN SEA LEVEL will impact the Franklin County economy?

- Strong positive impact
- Moderate positive impact
- Little to no impact
- Moderate negative impact
- Strong negative impact
- Not sure

Q26. How do you think an INCREASE IN SEA LEVEL will impact your profession?

- Strong positive impact
- Moderate positive impact
- Little to no impact
- Moderate negative impact
- Strong negative impact
- Not sure

Q21. How do you think an INCREASE IN SEA LEVEL will impact you personal interaction with the Apalachicola Bay ecosystem?

Personal interaction with the ecosystem might include activities such as fishing, birding, hiking, boating or any engagement with the ecosystem outside of your profession.

- Strong positive impact
- Moderate positive impact
- Little to no impact
- Moderate negative impact
- Strong negative impact

○ Not sure

This marks the end of the survey questions. Thank you for taking the time to complete this survey.

If you are willing to be contacted for further questions, interested in survey results and/or would like to receive your FREE MUG, please click the link to the separate form below.
Click here to fill out the form.

The following text and questions are contained in the separate survey form to collect contact information:

If you are willing to be contacted for further questions, interested in the survey results and. Or would like to receive your free travel mug, please answer the questions below.

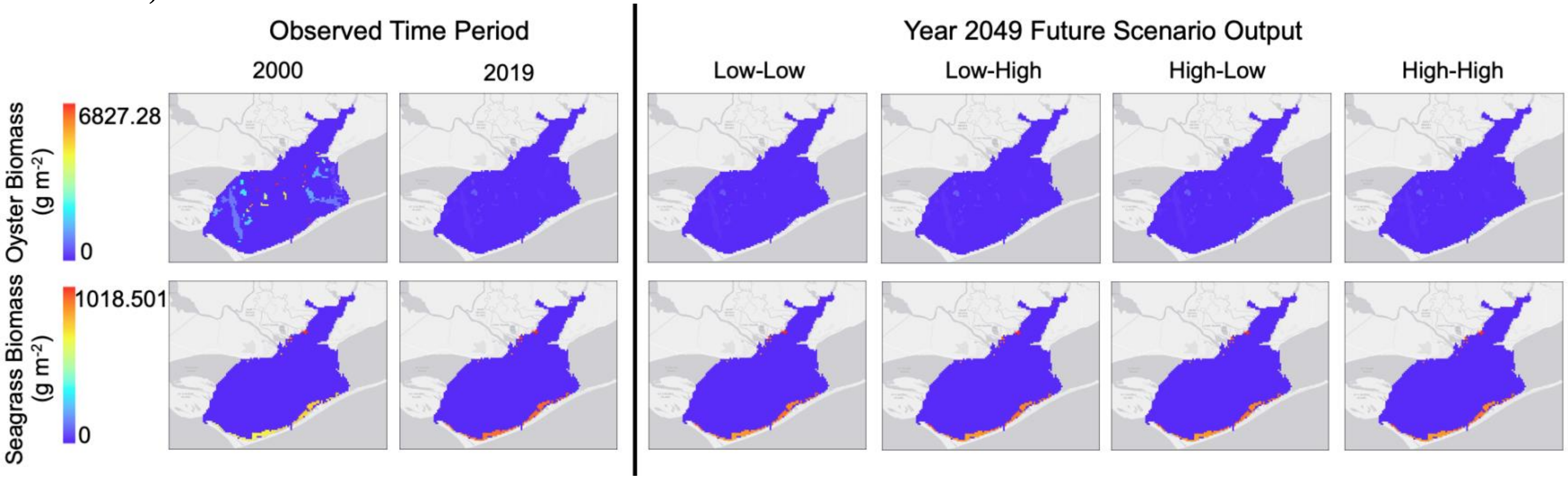
Are you willing to be contacted for further question if needed?
○ Yes
○ No
If yes,
The best way to contact you for further questions is:
____

Are you interested in hearing about the survey and final project results when they become available?
○ Yes
○ No
If yes,
The best way to contact you about the results is:
____

Would you like to receive a free Apalachicola National Estuarine Research Reserve travel mug for participating in this survey?
○ Yes
○ No
If yes,
Please provide a mailing address where we may send your free mug:
____

APPENDIX J:
SPATIAL VARIATION IN OYSTER AND SEAGRASS BIOMASSES

Appendix J. Spatial variation in annual average biomass (g m^{-2}) of oysters and seagrass in Apalachicola Bay during the beginning (2000) and end (2019) of the observed time period and year 2049 of each of the future scenarios. Scenario names define the river flow conditions first, followed by sea level rise conditions (e.g., Low-High indicates low river flow and high sea level rise).



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