Linking Land Use, Climate, and Coastal Ecosystems: A Watershed Perspective for a Changing South Carolina Coast

K. Lloyd Hill[1,2] | Master of Science Thesis Defense | August 6th, 2020

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COLLEGE of CHARLESTON
GRADUATE PROGRAM IN ENVIRONMENTAL STUDIES

Sea Grant
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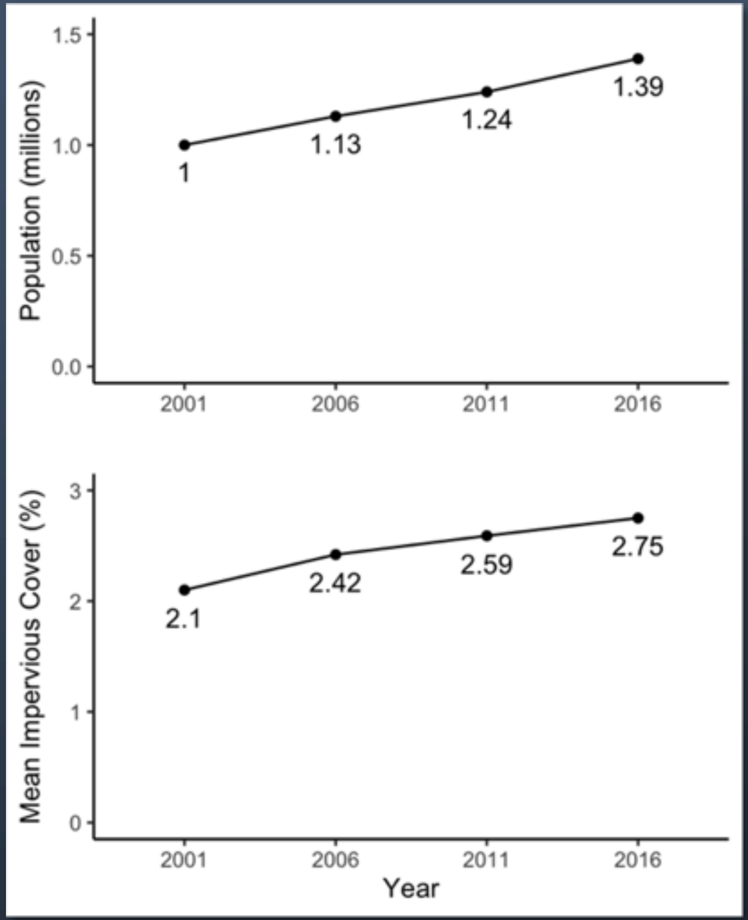
South Carolina’s Estuarine Environment

- Vast estuaries and tidal wetlands – nearly half a million acres of salt marsh
- Highly productive and diverse ecosystems
- Provide services such as nursery habitat for fishery species, shoreline protection, and added sociocultural value
- Estuaries and coastal wetlands threatened around the globe, SC is no exception

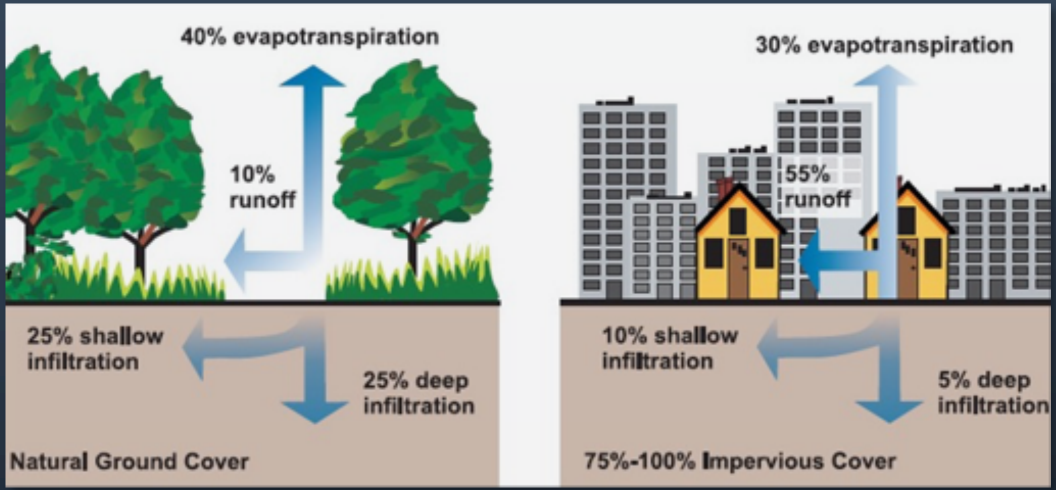
A Changing Landscape



- South Carolina is one of the fastest growing states in the nation
- Much of this growth is occurring in coastal counties
- Widespread shifts in landcover to accommodate rapidly growing population

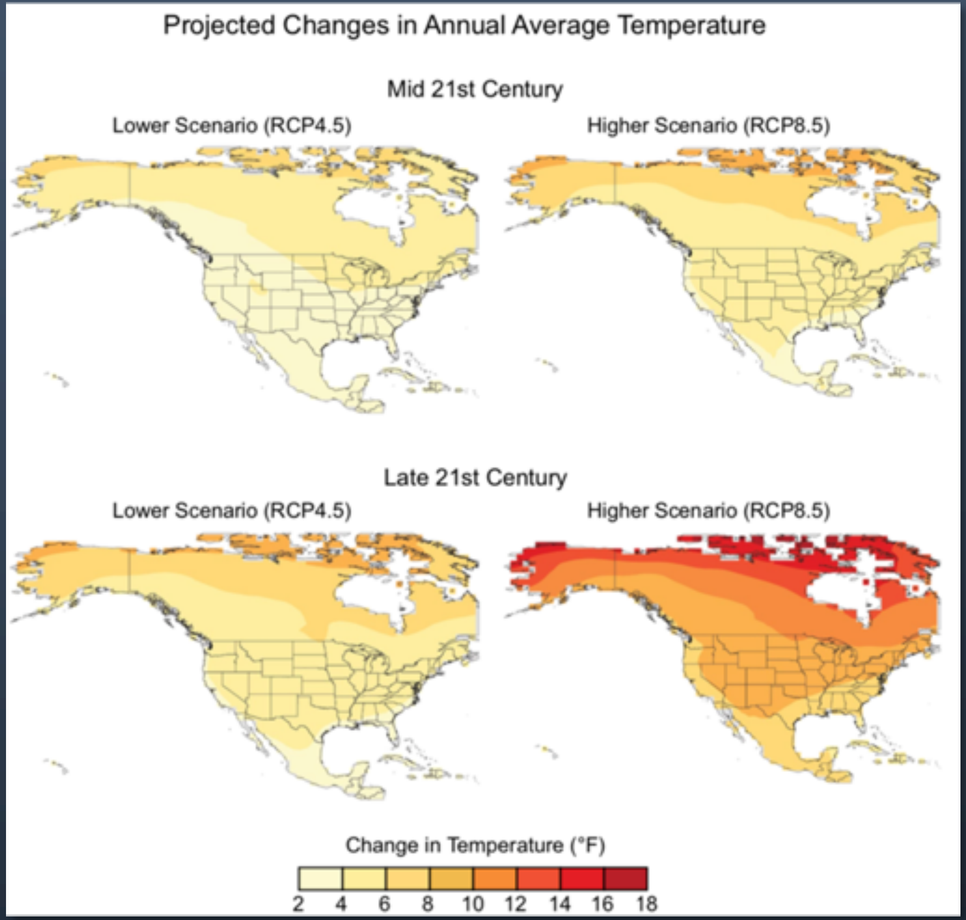
A Changing Landscape

- Increased impervious cover intensifies stormwater runoff
- Exacerbates coastal flooding
- Contributes to non-point source pollution of downstream, estuarine systems



A Changing Climate

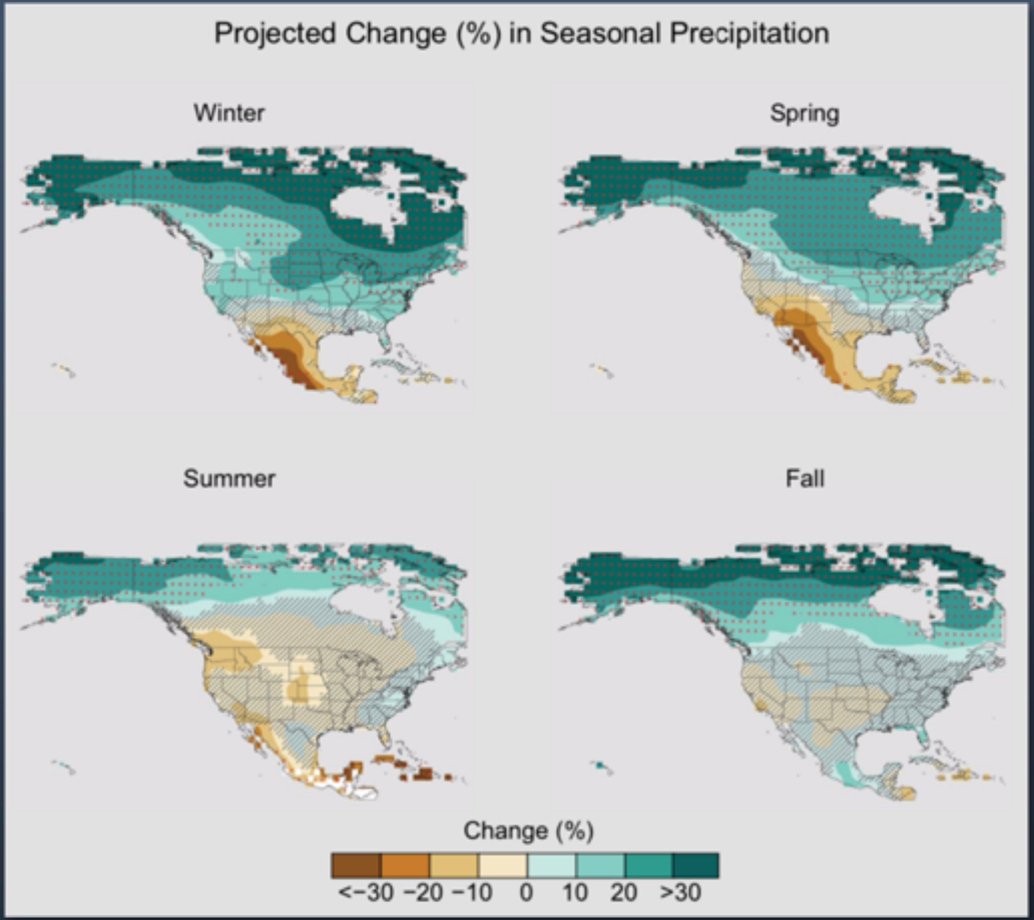
- Increase in annual average temperature
- **+3.4°F** in lower emissions, mid-century projection
- **+7.7°F** in higher emissions, late-century projection



USGCRP, 2017: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp., doi: 10.7930/J0J964J6.

A Changing Climate

- Increased precipitation expected, with regional and seasonal variability
- **+0-10%** increase in spring, summer, and fall
- **+10-20%** increase in winter



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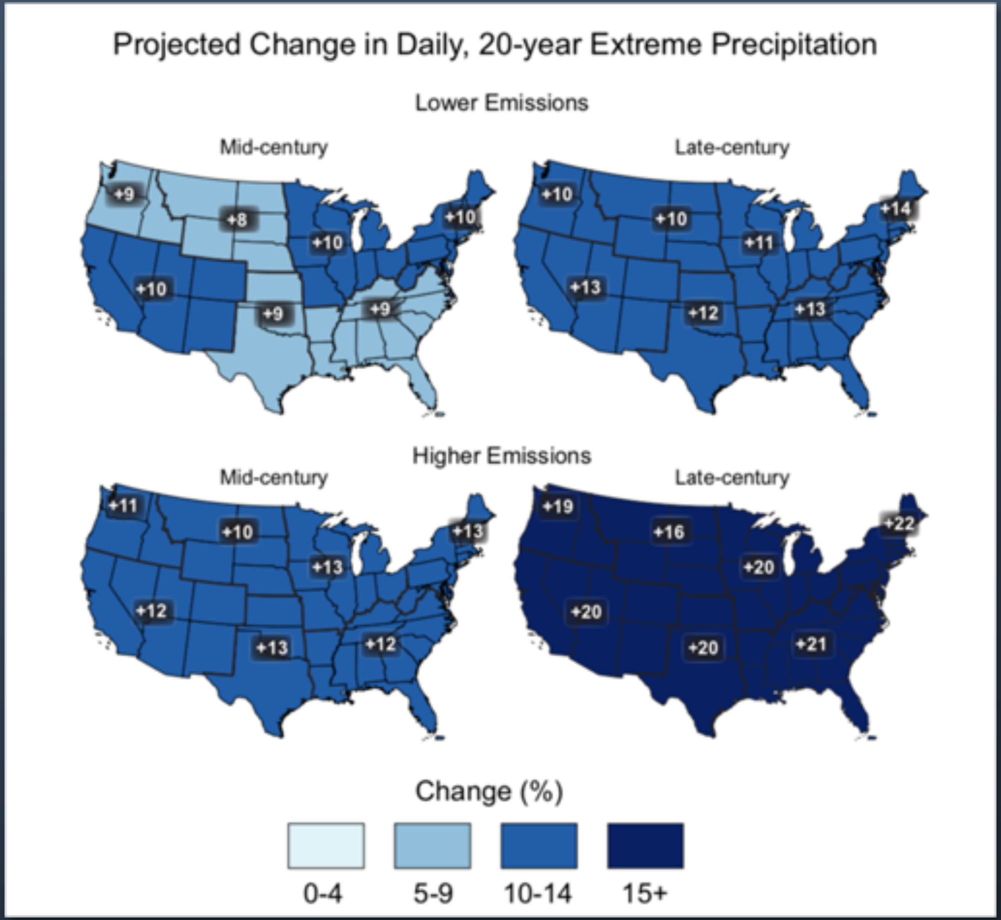
A Changing Climate

- More frequent, extreme rainfall events
- **+9%** in low emissions, mid-century scenario
- **+21%** in high emissions, late-century scenario



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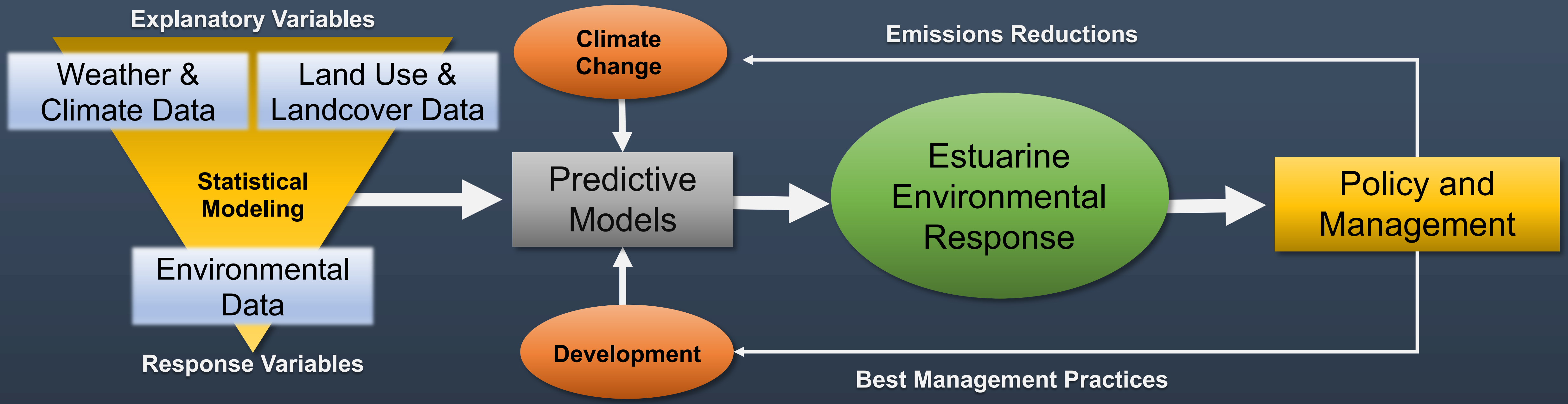
Previous Research and Motivation

- Previous studies in coastal SC have linked upland development to downstream, degraded estuarine habitats
  - Higher levels of sediment contamination, higher concentrations of bacteria, and decreased abundances of resident biological communities
- The goal of this project was to expand the scope of these earlier studies while adding in an additional theme of climate change
- **How will the estuarine environment respond to a changing climate and physical landscape?**

Research Hypotheses

- *H_1*: Degraded metrics of environmental quality in estuarine systems will relate to increasing development intensity within connected upland watersheds. Environmental impacts may include higher levels of sediment contamination, lower nekton diversity and abundance, fewer stress-sensitive benthic invertebrate taxa, and higher frequencies of bacterial contamination
- *H_2*: Weather patterns associated with climate change (e.g., higher temperatures, extreme rainfall events) will be associated with degraded metrics of environmental quality in estuarine systems (as listed in *H_1*)

A Data Synthesis Approach



Methods

Data **Collection**

⬇

Data **Processing**

⬇

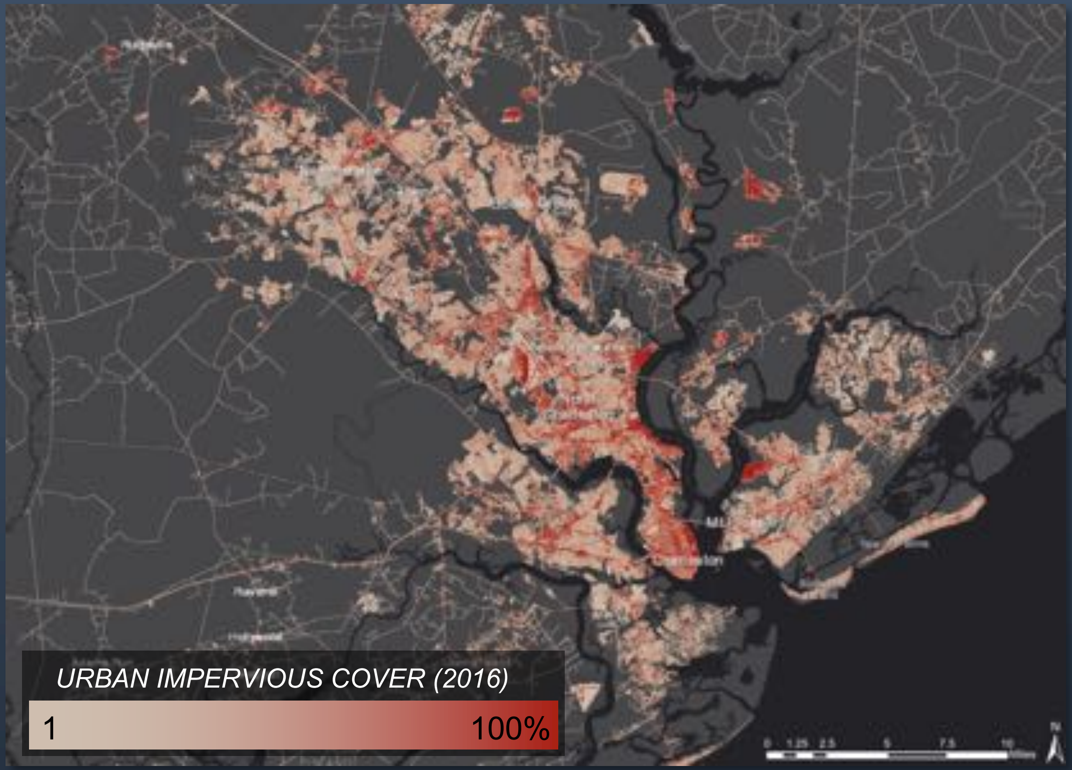
Data **Integration**

⬇

Data **Analysis**

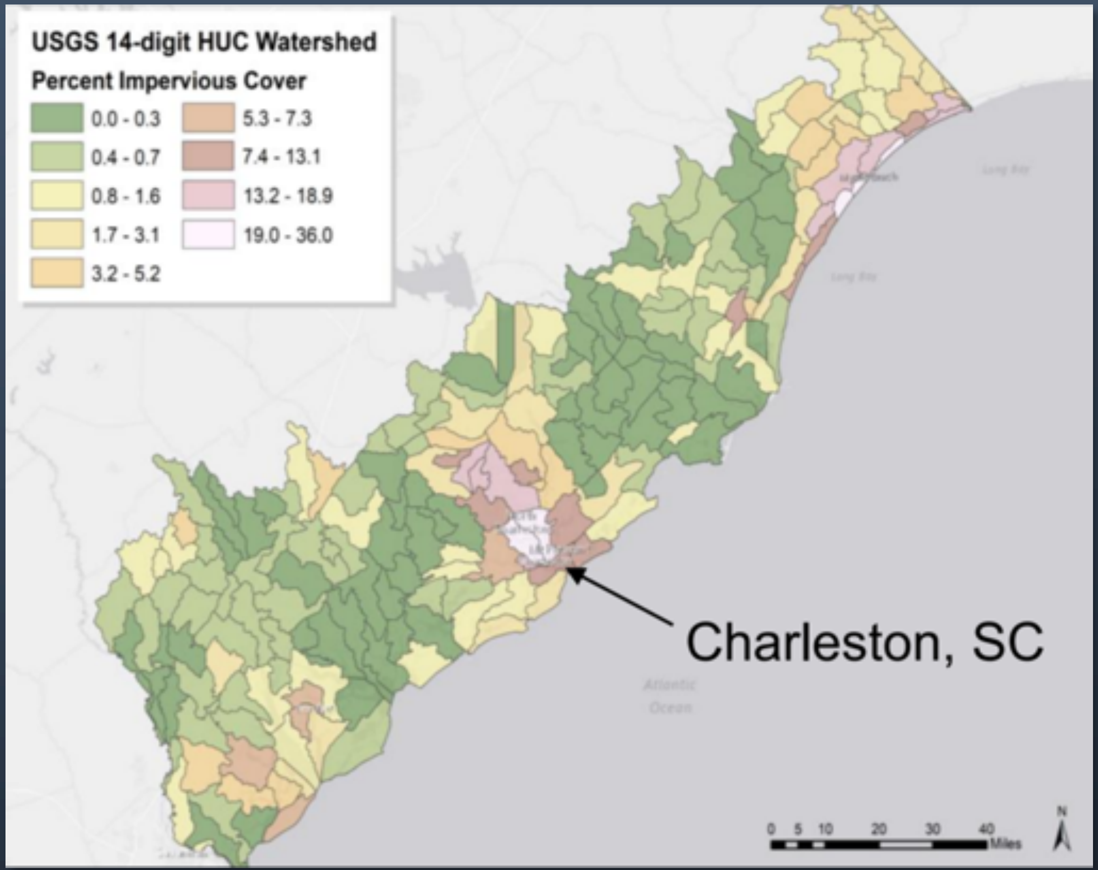
Data Collection: Physiographic Data

- National Land Cover Database (NLCD)
  - 16-landcover classes at 30m resolution
  - Urban Impervious Cover
- 2010 Census Population
- USDA Hydrologic Soil Groups
- SCDNR Stormwater Pond Inventory

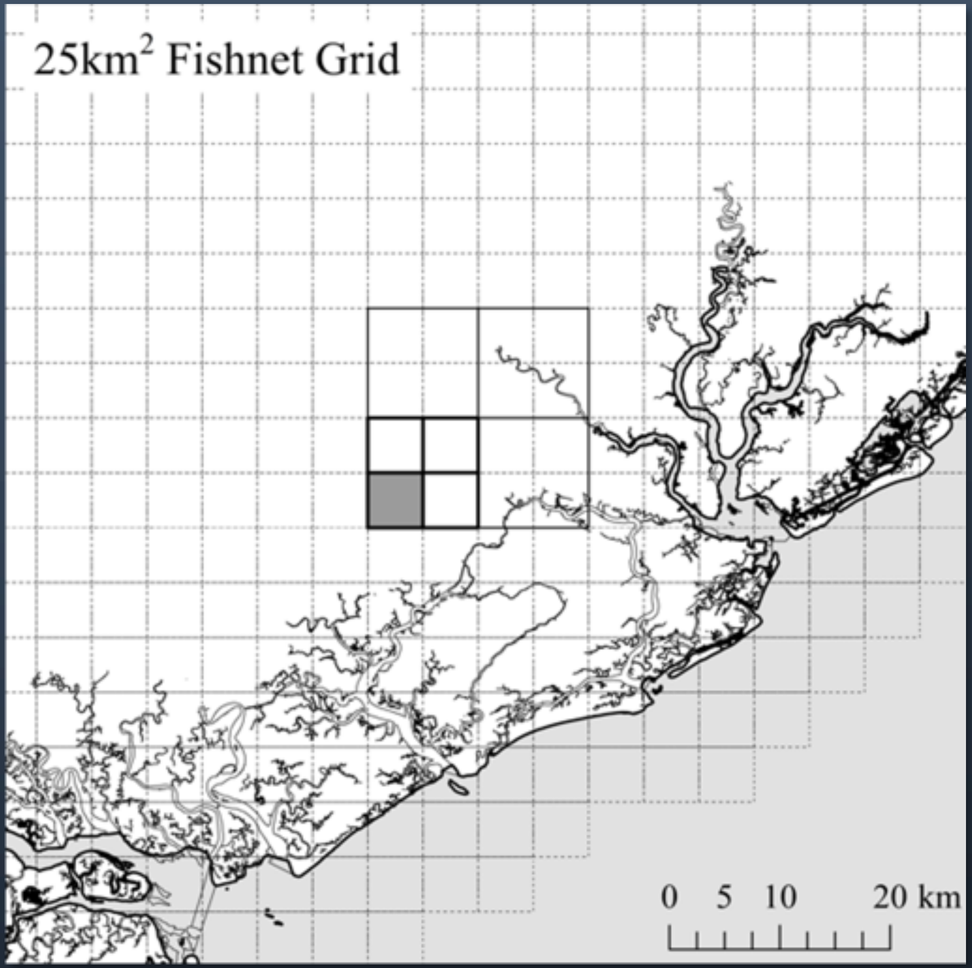


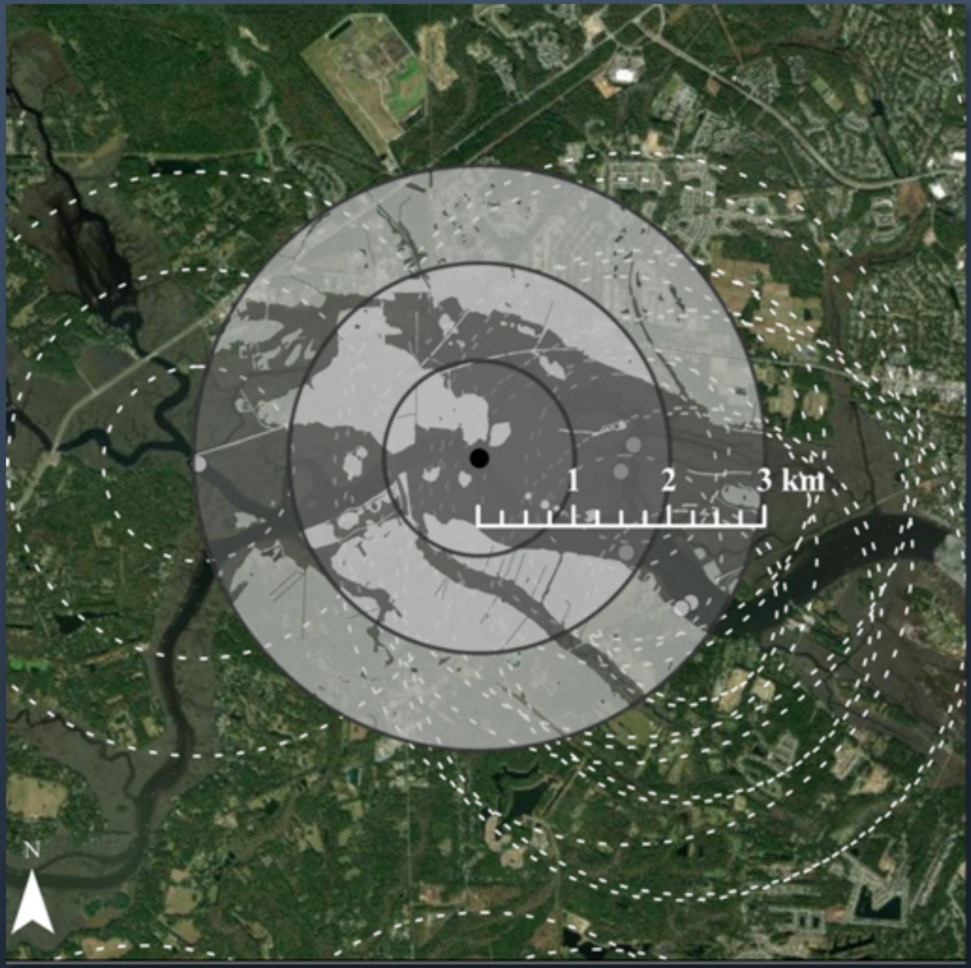
Data Processing: Physiographic Data

- Physiographic data analyzed in GIS by different spatial groupings
  - HUC Watersheds (8, 10, 12, 14-digits)
  - Grid cells (25, 100, 400, 1600 km^2)
  - Circular buffers (1, 2, 3 km)
- NLCD landcover composition (%), mean upland impervious cover (%), population density (persons/ha), stormwater pond count, etc.



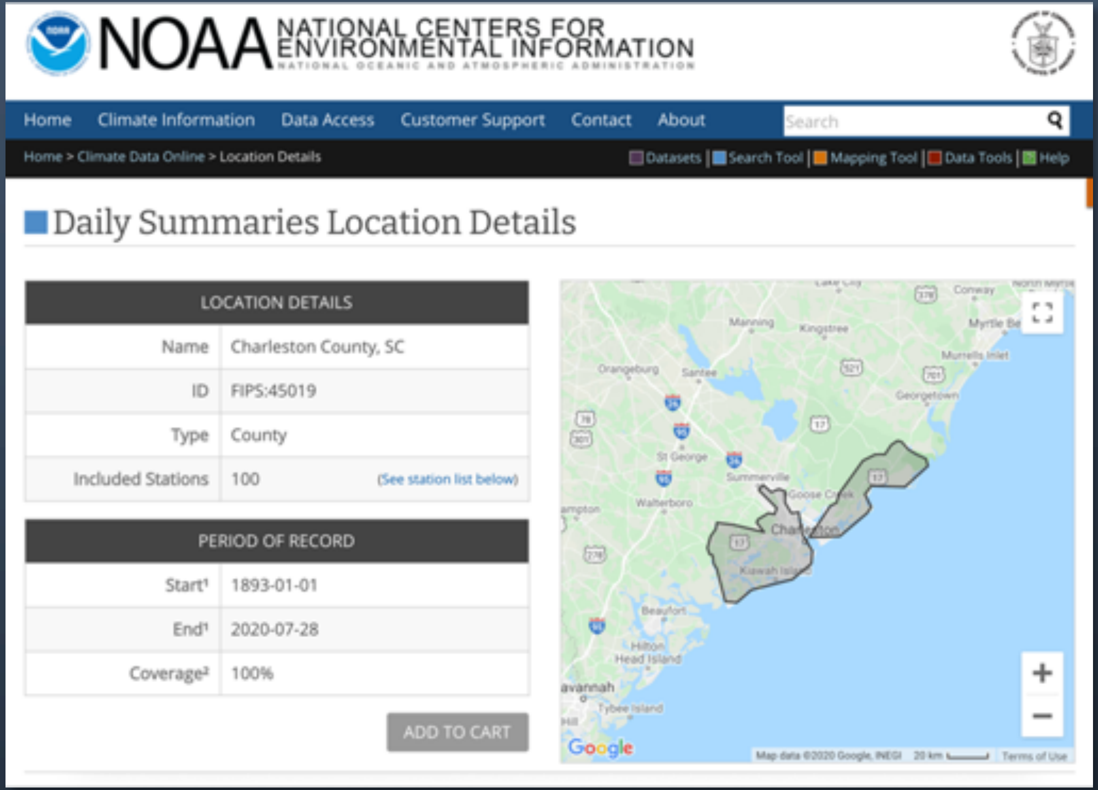
Data Processing: Physiographic Data





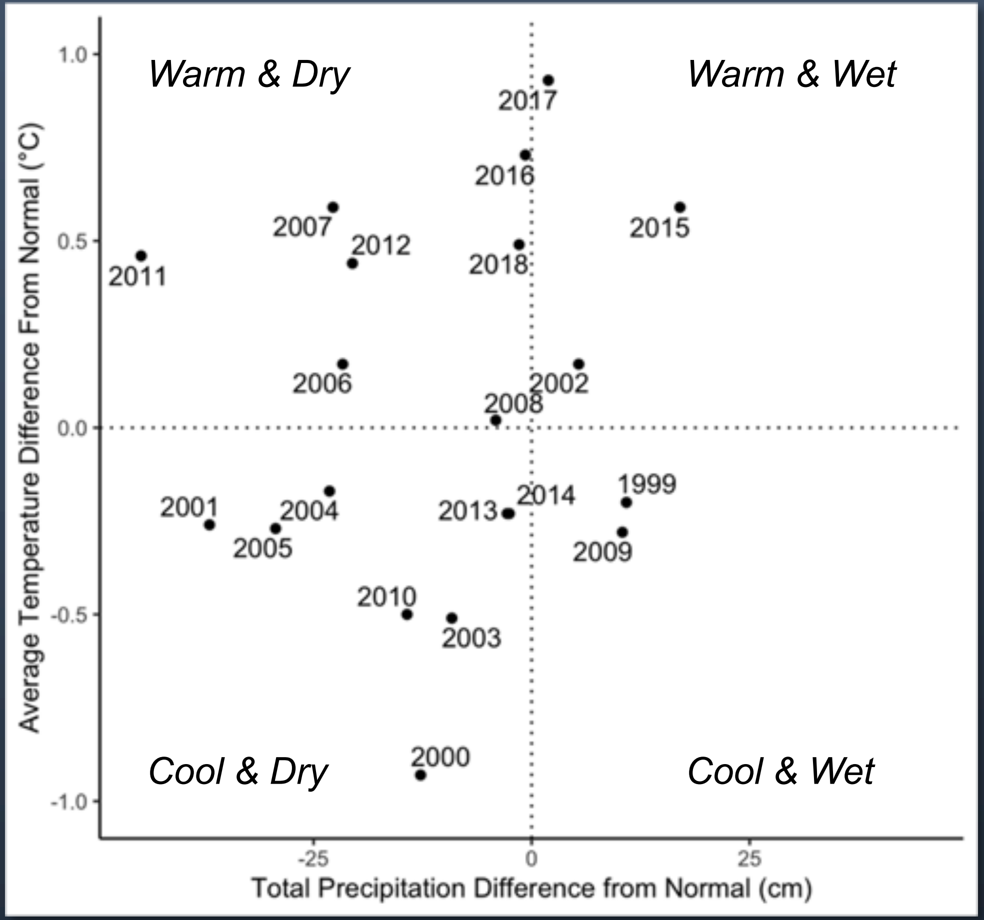
Data Collection: Weather & Climate Data

- Daily weather station data (temperature and precipitation)
- 30-year climate normals (1980-2010)
- DAYMET gridded weather dataset
- Drought Indices (PDSI, SPI,…)
- Climate Teleconnections (El Niño, NAO,...)



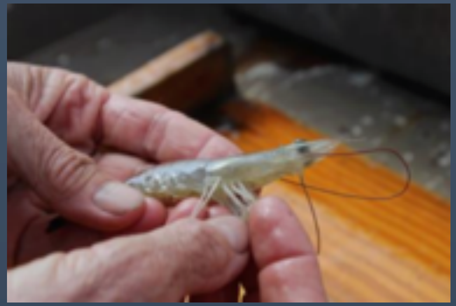
Data Processing: Weather & Climate Data

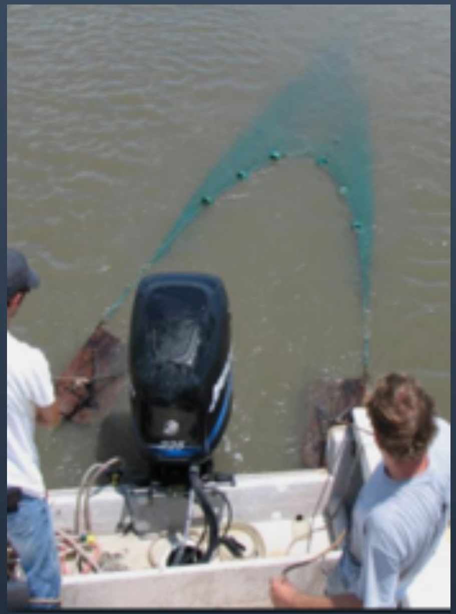
- Calculated multi-day running averages and totals of temperature and precipitation
- Summarized weather data by season and year to compare with 30-year climate normals



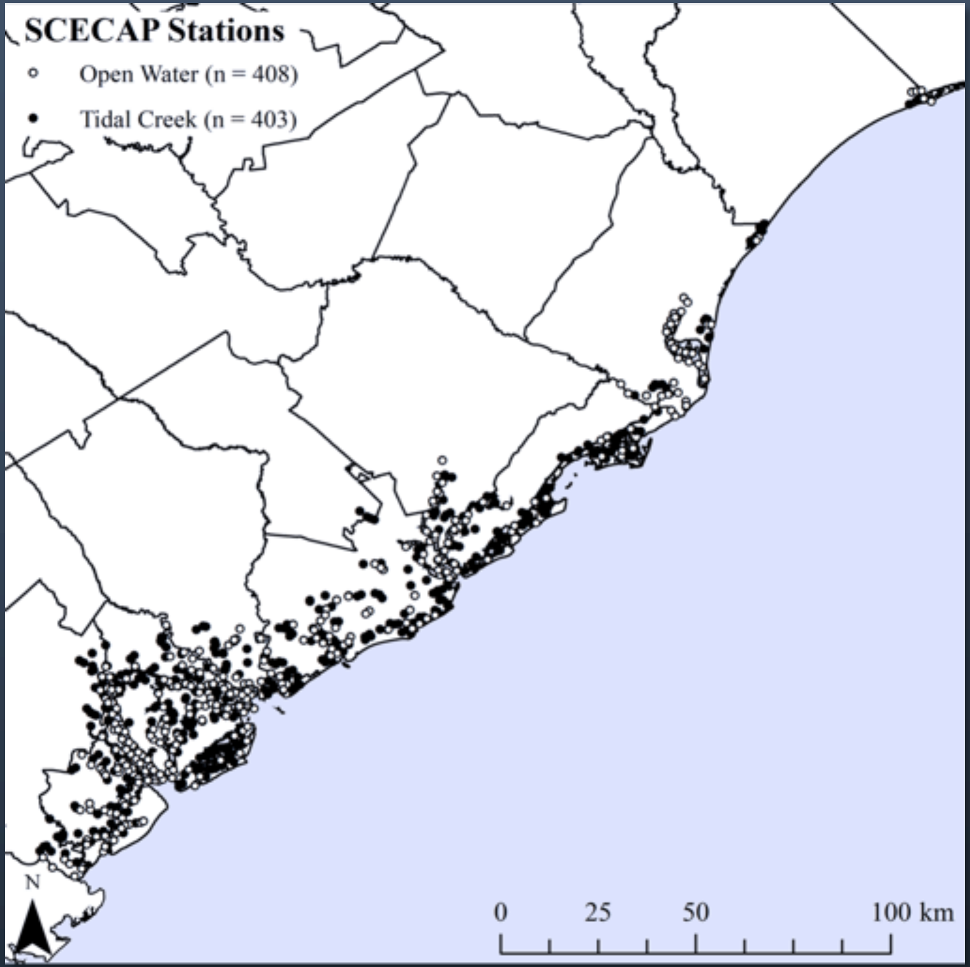
Data Collection: Environmental Data

- SCECAP (SC Estuarine and Coastal Assessment Program)
- DNR-run environmental monitoring program started in 1999
- Water Quality (bacteria, DO, salinity,...)
- Sediment Quality (TOC, metals, organic pollutants,...)
- Biological Condition (fish and large invertebrates, benthic invertebrate infauna)



Data Collection: Environmental Data



Data Processing: Environmental Data

- Converted raw sediment contaminant data into Effects Range Median Quotients (ERMQ)
- Calculated species richness and total abundance from trawl and benthic data
- Summarized benthic invertebrate community data with indices
  - Benthic Index of Biotic Integrity (BIBI)
  - Multivariate AZTI's Marine Biotic Index (MAMBI)

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Data Integration

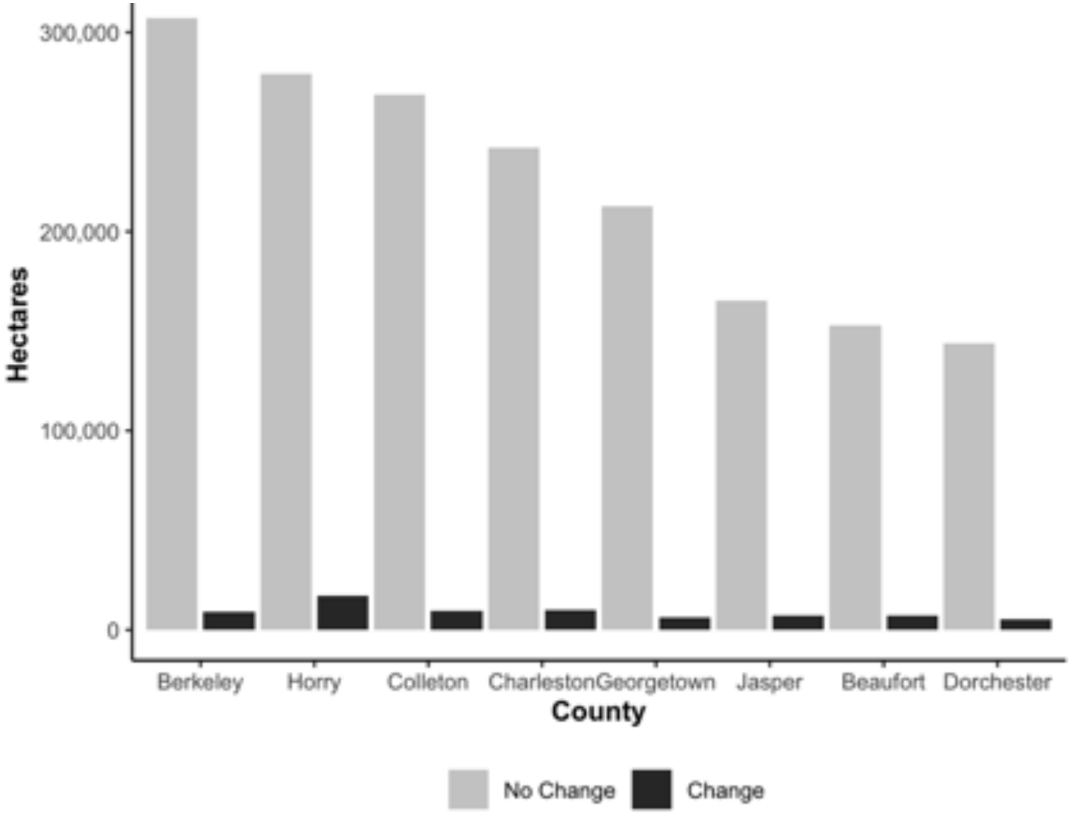
- Integrated weather, landcover, and environmental data across space and time
- Joined SCECAP stations to spatial units (e.g., HUC watershed) and paired with matching year of landcover data
- Linked each SCECAP station to nearest weather station with available data
- Combined all data into relational Access database for easy querying, filtering, and analysis

Data Analysis

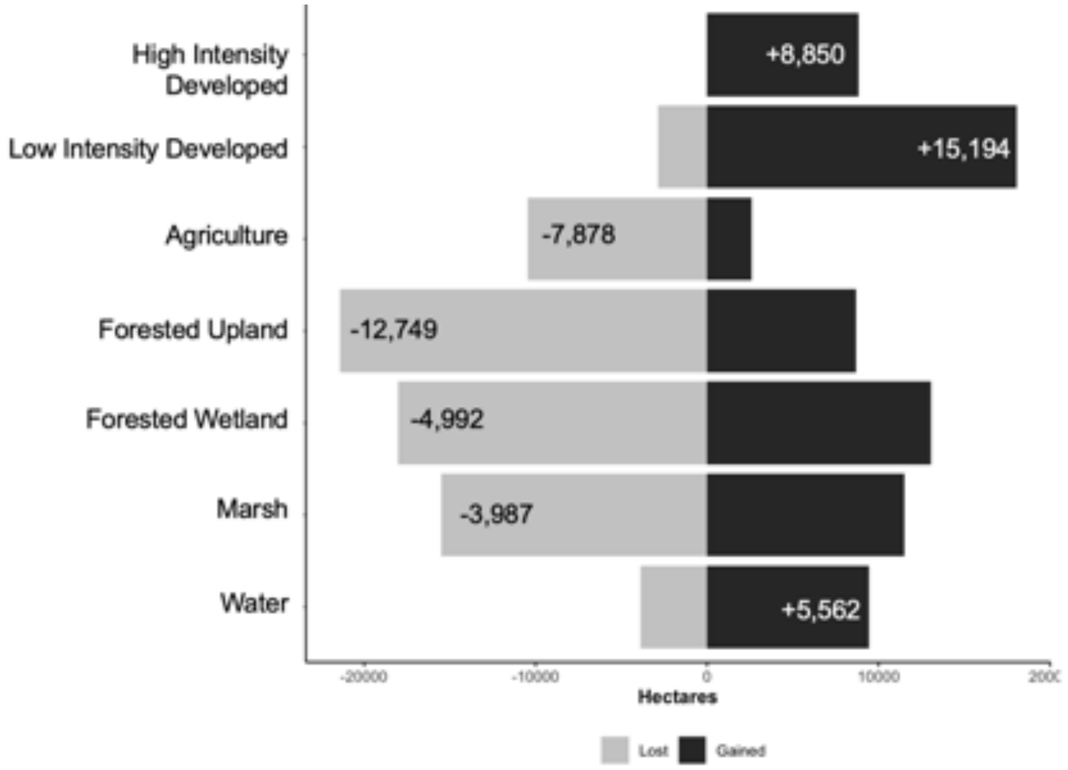
- Exploratory Data Analysis
  - How are these data changing over space and time?
- Linear Modeling
  - What variables are responsible for these changes?
  - How might the estuarine environment respond to climate change, increased development?

Landcover Change Analysis

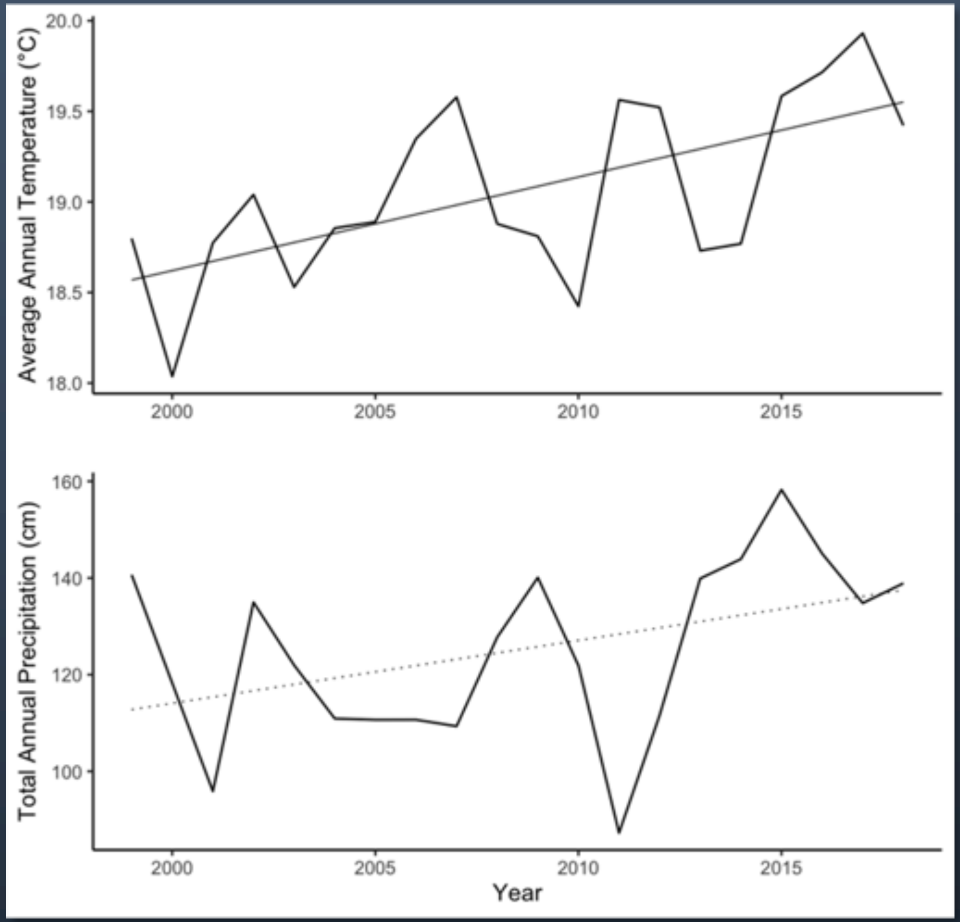
Change in Landcover by County (2001-2016)



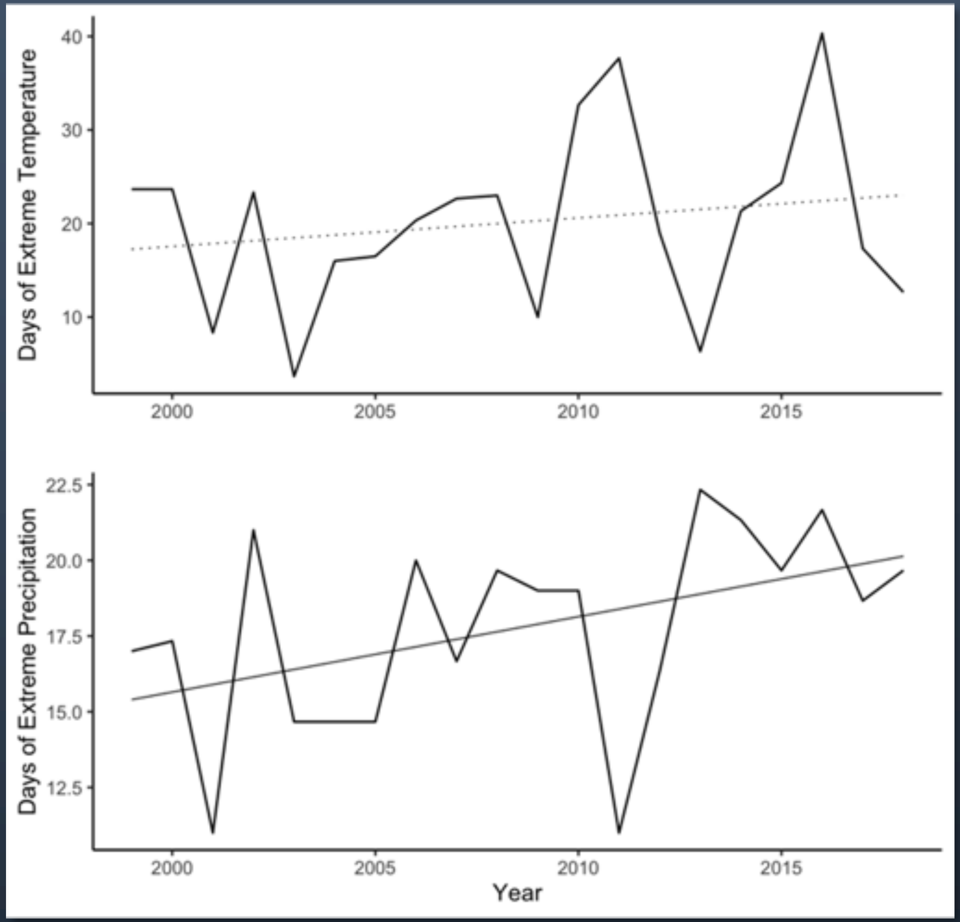
Change in Coastal SC Landcover (2001-2016)



Weather Data Time Series Analysis



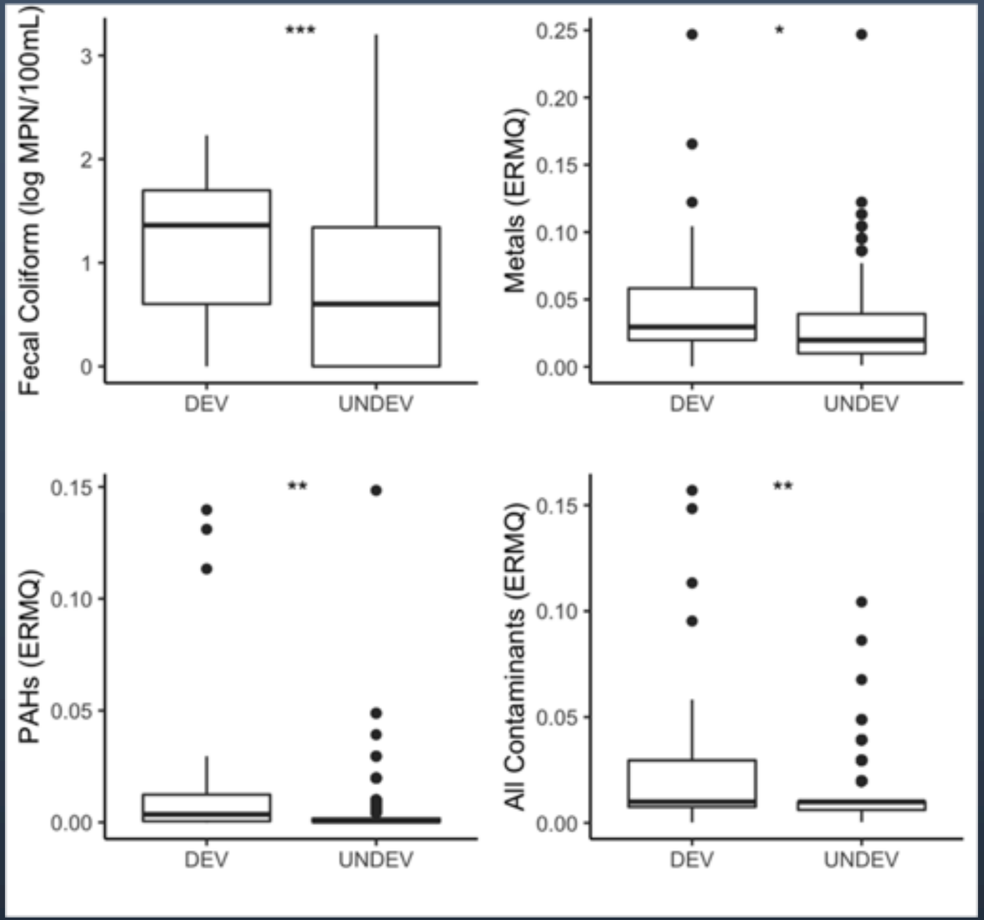
—— $p \leq 0.05$ ·········· $p > 0.05$



—— $p \leq 0.05$ ·········· $p > 0.05$

Environmental Data *t*-tests

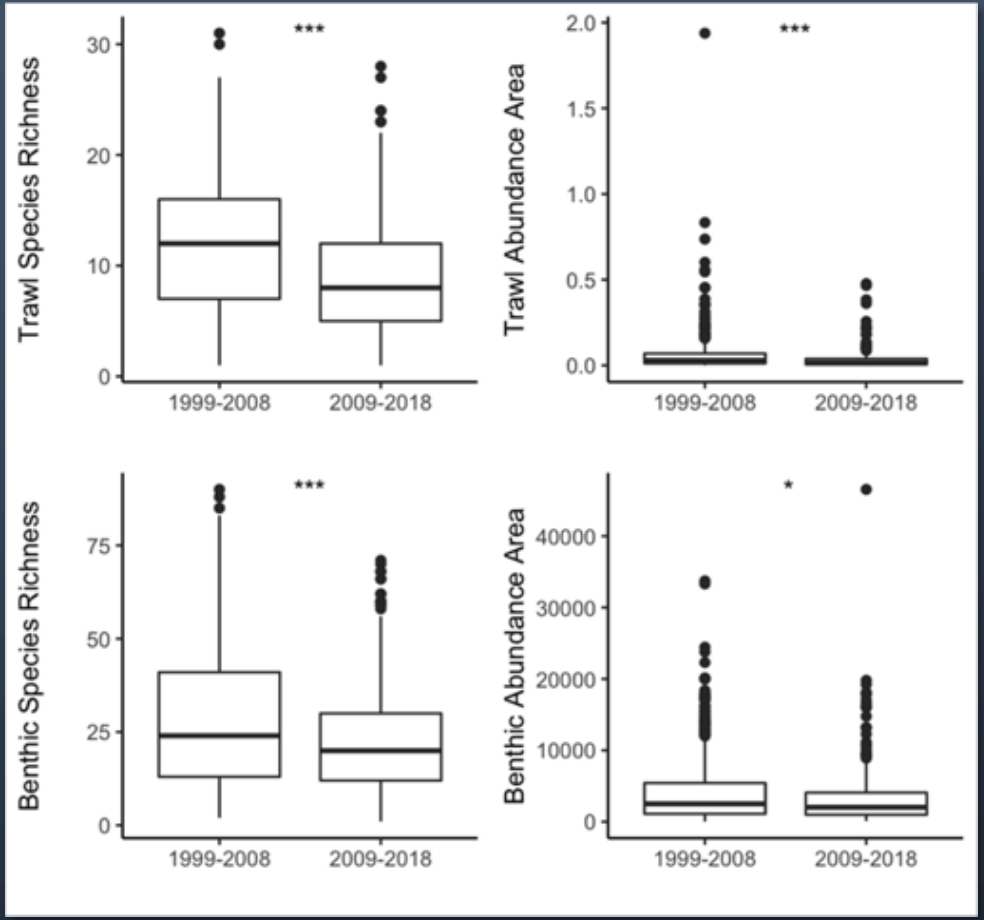
- *t*-tests comparing environmental data between developed and undeveloped watersheds
- Estuaries draining developed watersheds had higher levels of bacteria and sediment contaminants
- Measures of biological quality were not significantly different



$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

Environmental Data *t*-tests

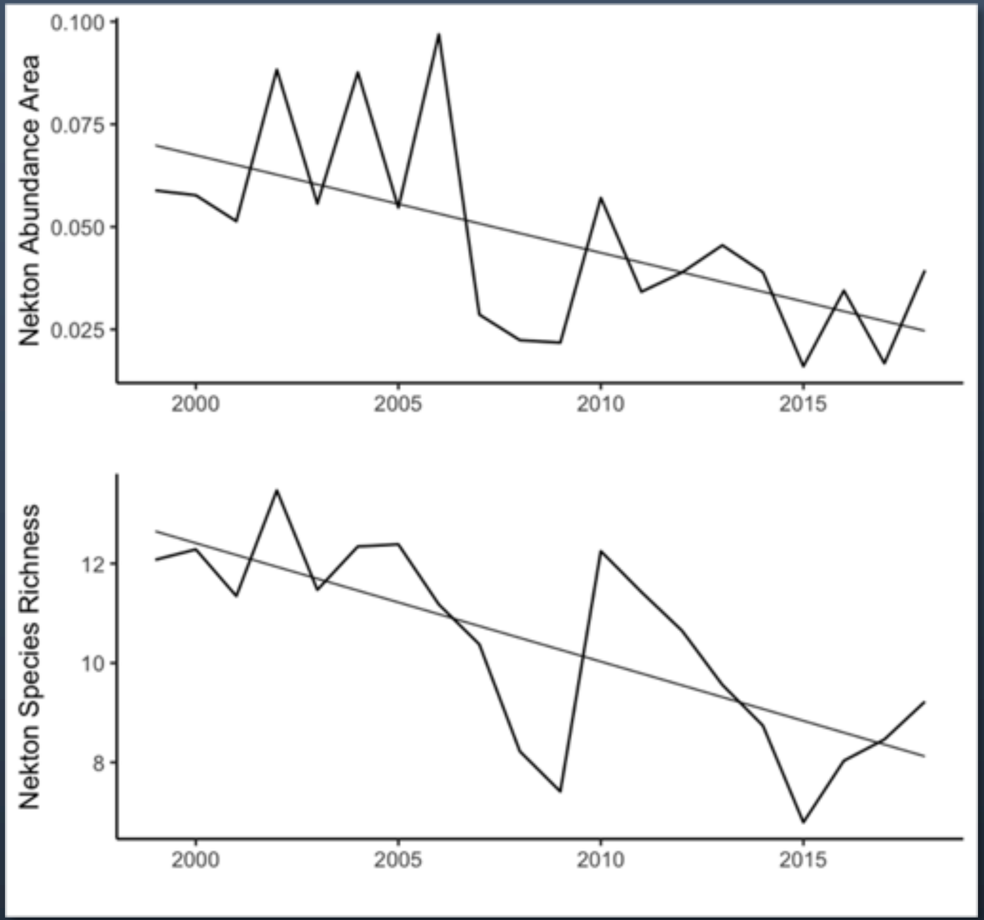
- *t*-tests comparing environmental data between early (1999-2008) and late (2009-2018) sample years
- Measures of biodiversity declined in later years of data
- Most water and sediment quality variables did not significantly differ between time periods



$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

Environmental Data Time Series Analysis

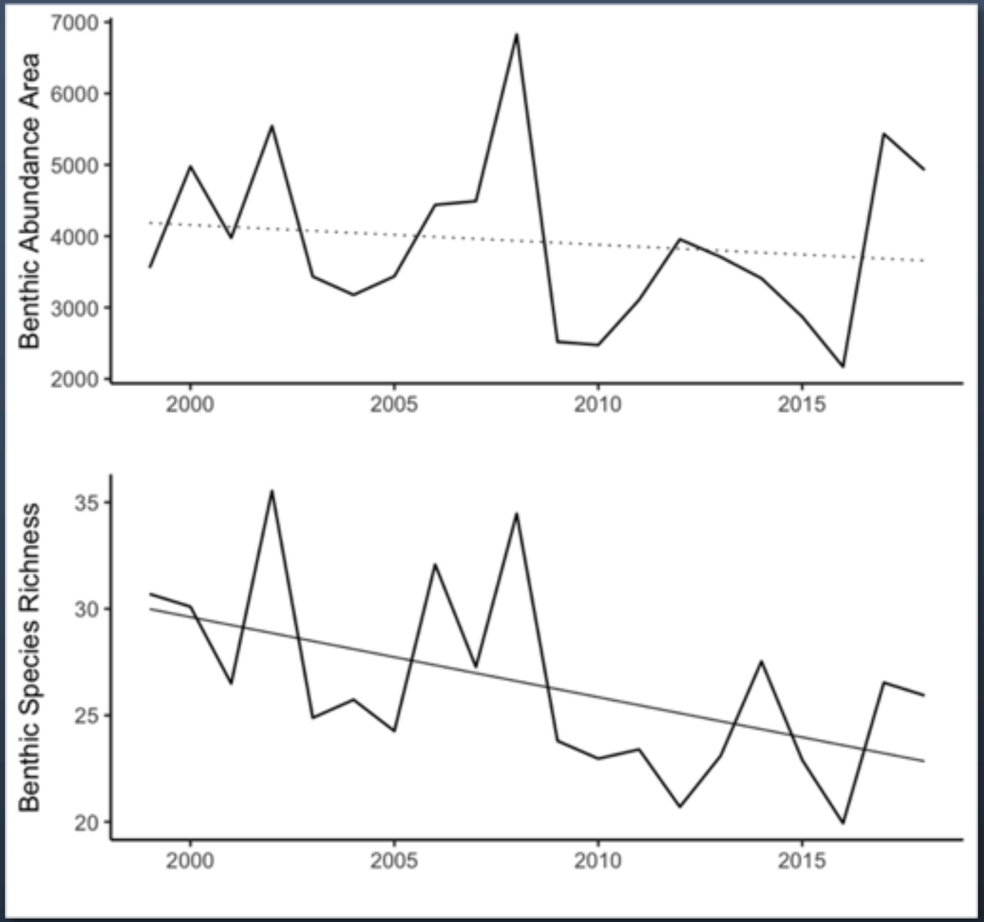
- Time series analysis using generalized least squares (GLS) regression
- Significant decline in both nekton abundance and species richness over the study period



$p \leq 0.05$ $p > 0.05$

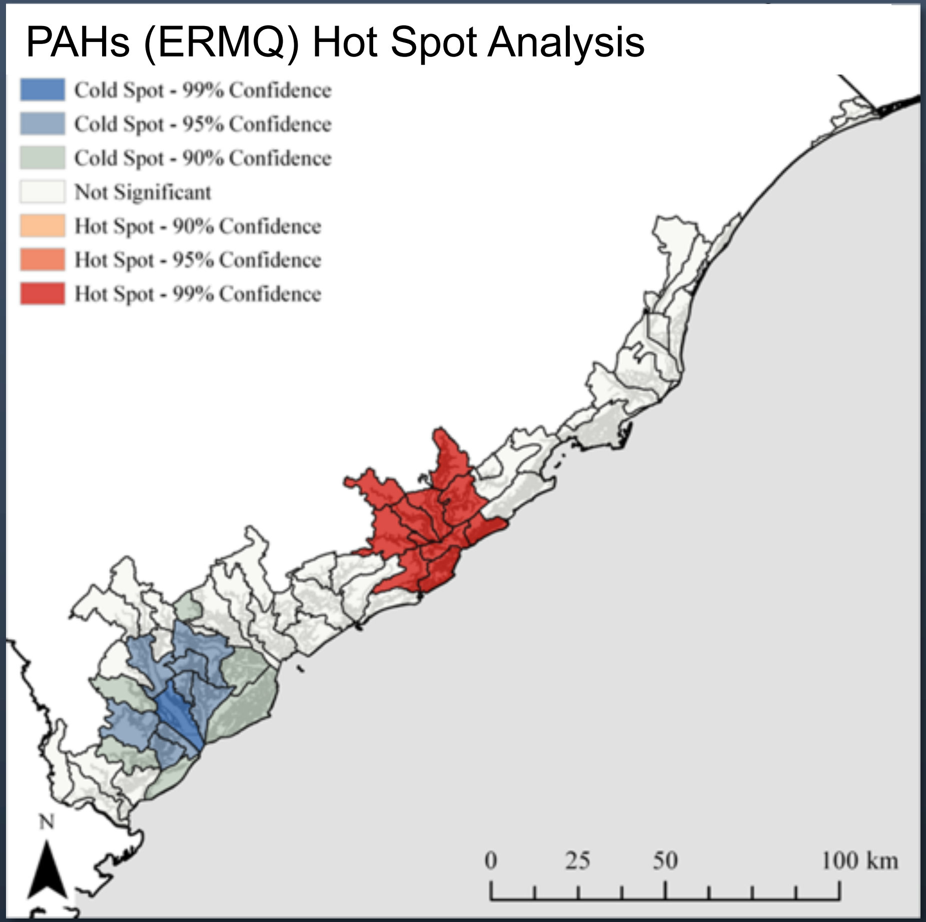
Environmental Data Time Series Analysis

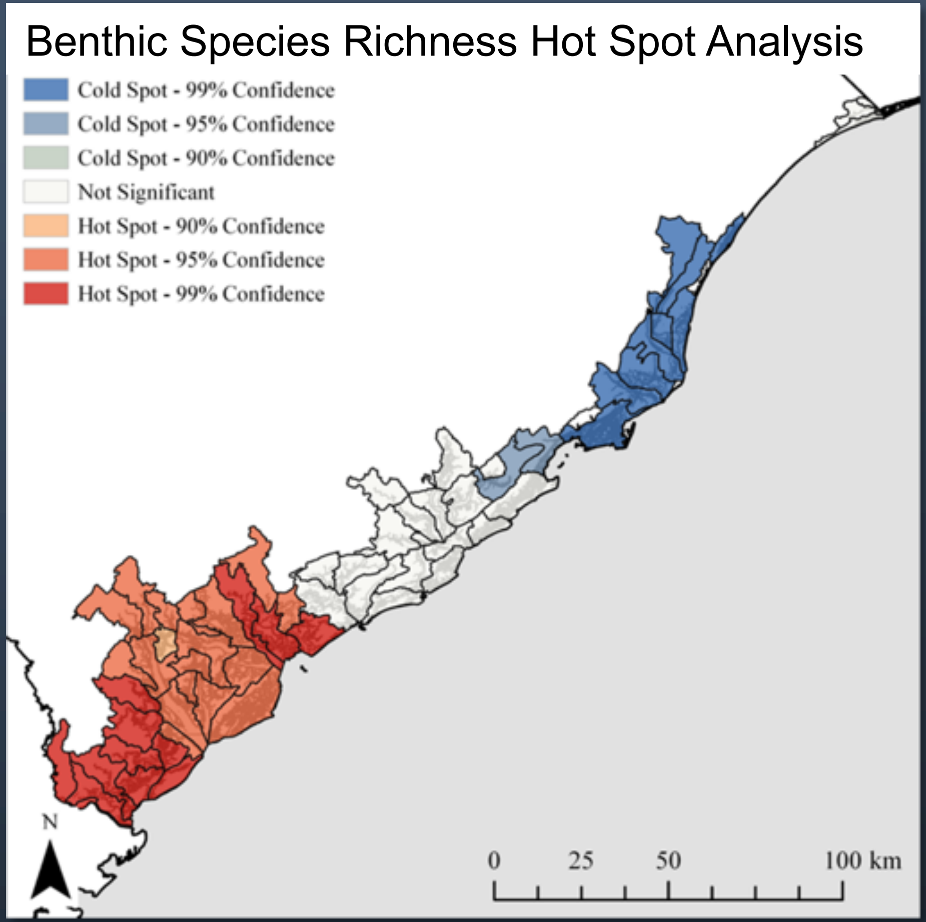
- Significant decline in benthic species richness over the study period, while change in benthic abundance not significant
- Suggests changes within benthic community structure (i.e., “functional homogenization”)



$p \leq 0.05$ $p > 0.05$

Environmental Data Hot Spot Analysis





Data Analysis

- Exploratory Data Analysis
  - How are these data changing over space and time?
- Linear Modeling
  - What variables are responsible for these changes?
  - How might the estuarine environment respond to climate change, increased development?

Stepwise Linear Regression

- Automated model selection process to create multiple linear regression formulas
- Ideal for handling large number of explanatory variables
- Adds and subtracts parameters, selects combination that produces “best” model (lowest BIC)
- 19 response variables, >100 explanatory variables, analyzed at 11 spatial scales = 209 models

$$y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots \beta_i x_i + \varepsilon_i$$

Model Selection and Refinement

- Selected the best set of models to explore in depth and refine
  - Analyzed residuals, remove outliers, transform response variables, explore interaction effects
- Chose 13 models summarizing water quality, sediment quality, biological condition
  - Fecal coliform, enterococcus, DDT, metals, PAHs, PCBs, ERMQ, nekton abundance, nekton species richness, benthic abundance and species richness, and MAMBI

Model Results: Fecal Coliform

Fecal Coliform =

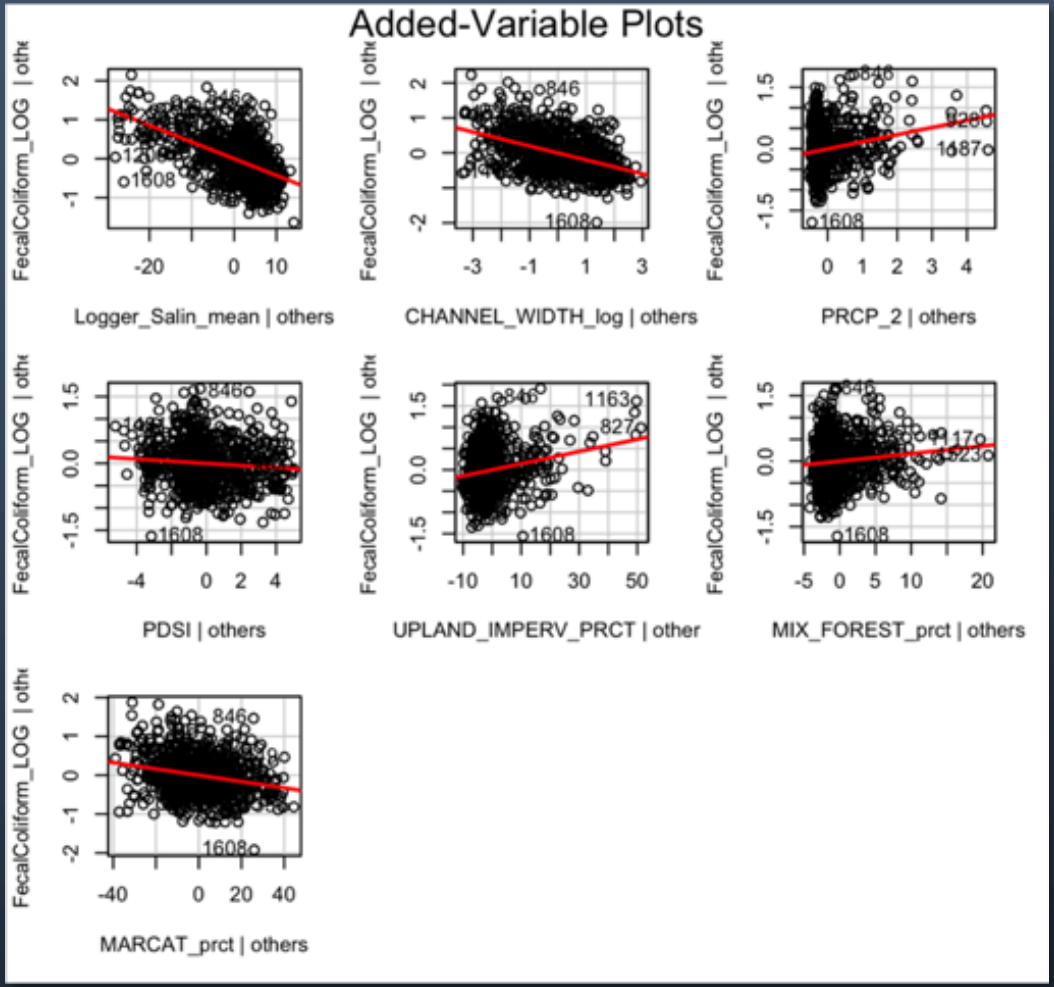
- \+ 2-day Rainfall***
- \+ Impervious Cover***
- \+ Mixed Forest***
- – Channel Width***
- – Salinity***
- – Marsh***
- – PDSI***

Adj. R^2 = 0.46

$F_{7, 790} = 98.18^{***}$

$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

(landcover analyzed by 2-km buffer)



Model Results: ERMQ (All Contaminants)

ERMQ All =

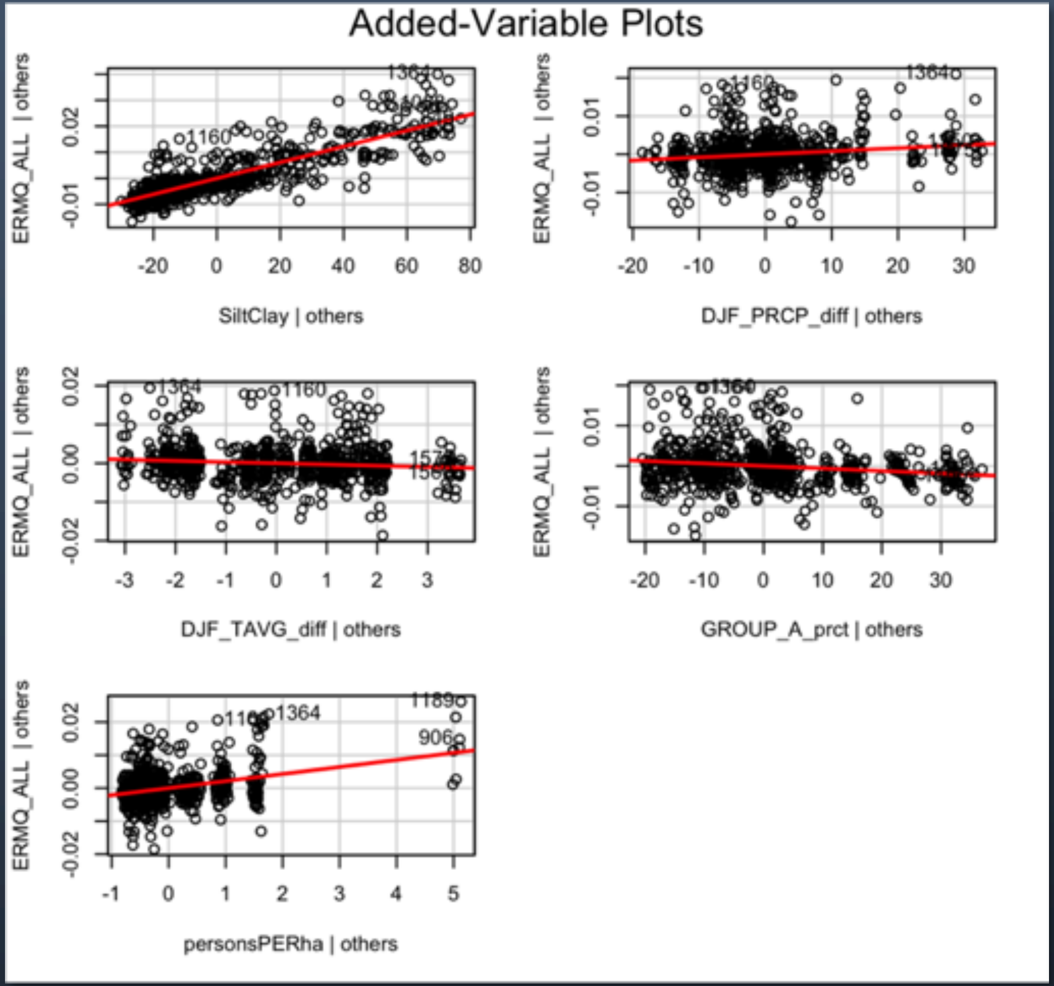
- \+ Silt-Clay Content***
- \+ Population Density***
- \+ Winter Precipitation***
- – Winter Temperature***
- – Group A Soils***

Adj. R^2 = 0.74

$F_{5, 782} = 452.47^{***}$

$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

(landcover analyzed by 10-digit HUC)

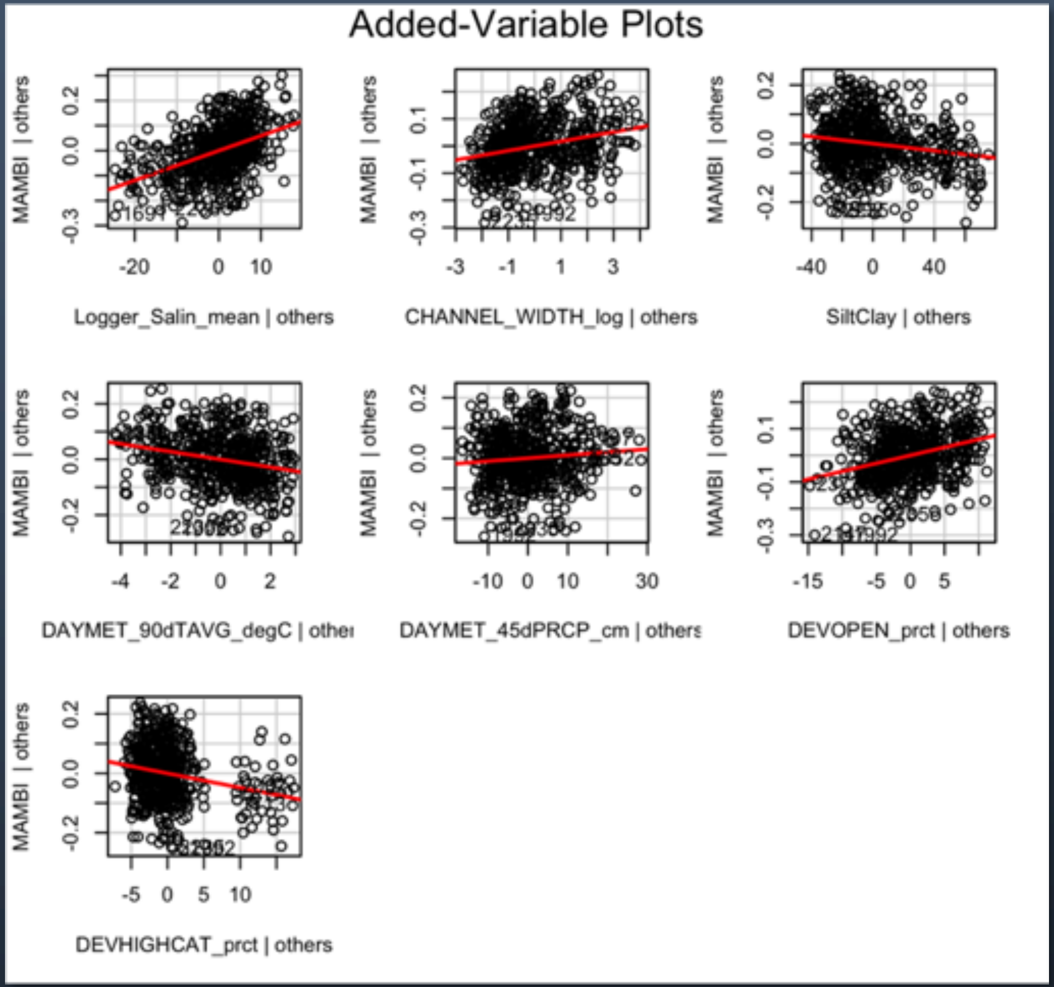


Model Results: MAMBI

MAMBI =

- \+ Channel Width***
- \+ Salinity***
- \+ Developed, Open Space***
- \+ 45-day precipitation total**
- – Silt-Clay Content***
- – Developed, High Intensity***
- – 90-day temperature average***

Adj. R^2 = 0.47
$F_{7, 563} = 71.65^{***}$
$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$
(landcover analyzed by 400km^2 buffer)



Model Results Summary

- Physical habitat (e.g., salinity, channel size, sediment composition) responsible for large proportion of variation within the response variables
- Measures of development correlated with higher levels of bacteria and higher concentrations of sediment contaminants
- Precipitation positively correlated with higher levels of bacteria and sediment contamination supporting runoff hypothesis, but temperature connection less clear
- Biological responses more dependent on weather/climate variables than landcover with warmer and drier conditions correlated to lower biological quality

Model Meta-Analysis

- Variables of physical habitat were the most prevalent predictors
- Impervious cover most frequent landcover variable followed by marsh
- Winter precipitation and winter temperature most frequent weather variables
- 10-digit HUC watersheds best spatial unit for sediment quality, 2km circular buffers for water quality, 12-digit HUC watersheds for biological models

Spatial Unit	Water Quality (R^2)	Sediment Quality (R^2)	Biological Quality (R^2)	All Models (R^2)
Buffer				
1	0.3537	0.3611	0.2095	**0.3045**
2	0.3596	0.3695	0.2091	**0.3091**
3	0.3497	0.3752	0.2162	**0.3193**
All	*0.3543*	*0.3686*	*0.2116*	***0.3093***
Grid				
25	0.3401	0.2891	0.2137	**0.2667**
100	0.3309	0.3120	0.2144	**0.2780**
400	0.3134	0.3187	0.2213	**0.2823**
1600	0.3055	0.3265	0.2148	**0.2831**
All	*0.3267*	*0.3116*	*0.2161*	***0.2775***
HUC				
08	0.3239	0.3894	0.2256	**0.3222**
10	0.3268	0.4013	0.2292	**0.3301**
12	0.3472	0.3850	0.2294	**0.3237**
14	0.3089	0.3923	0.2271	**0.3227**
All	*0.3267*	*0.3920*	*0.2278*	***0.3247***
Total	***0.3327***	***0.3564***	***0.2191***	***0.3033***

Predictive Modeling

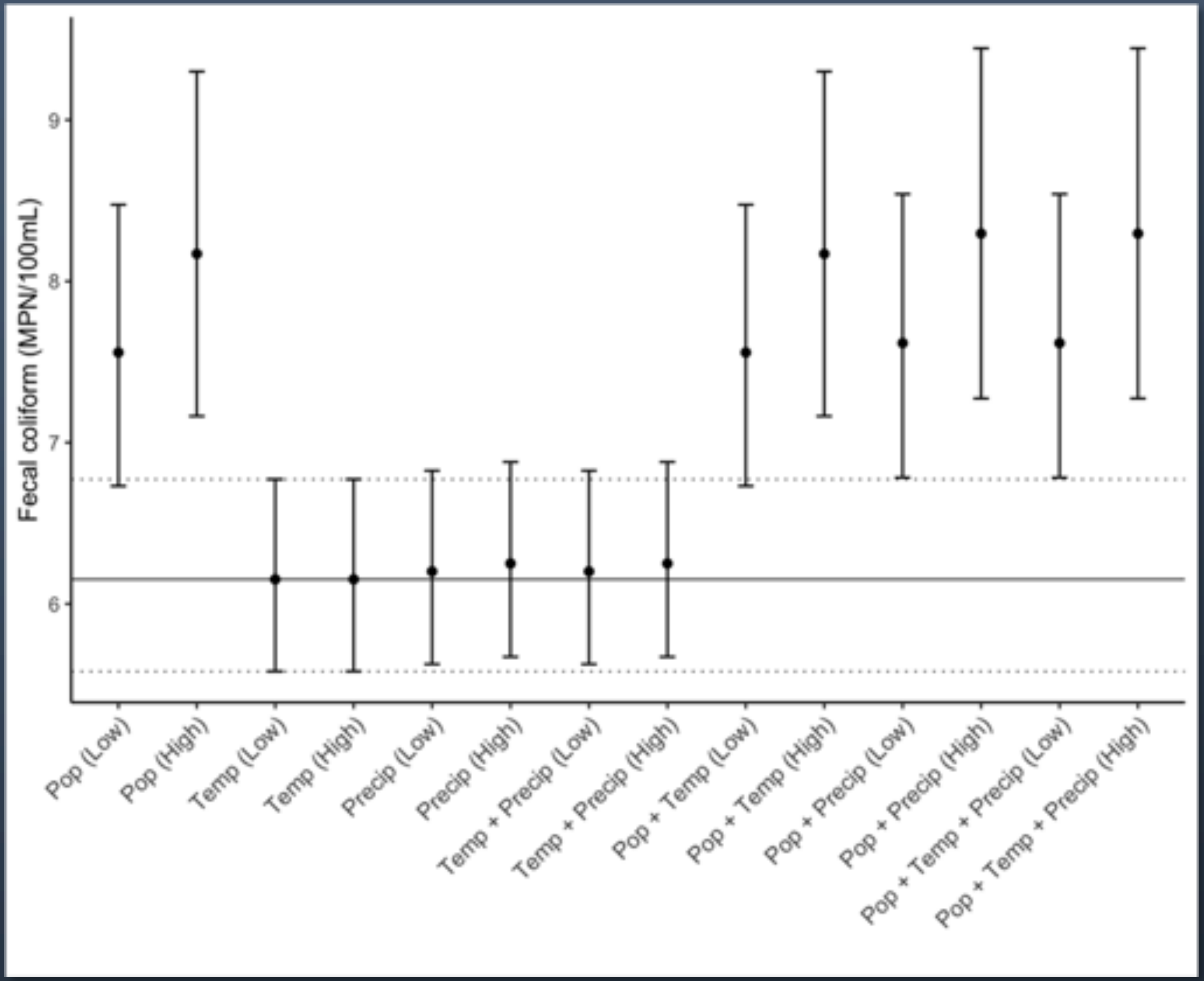
- Can these historic relationships be used to predict the outcome of SC's estuarine environment under climate change and continued development?
- Created 14 scenarios of change and used multiple linear regression formulas to make predictions

	Baseline	Low Projection	High Projection
Population Growth[1]	--	+130%	+180%
Coastal Residents (million)	1.2	2.8	3.4
Temperature Change[2]	--	+5%	+6.5%
Annual Temperature (°C)	19.0	20.9	21.4
Precipitation Change[2]	--	+5%	+10%
Annual Precipitation (cm)	129.7	136.4	142.8

[1]Hauer, Mathew E. "Population projections for US counties by age, sex, and race controlled to shared socioeconomic pathway." *Scientific data* 6 (2019): 190005.
[2]USGCRP, 2017: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp., doi: 10.7930/J0J964J6.

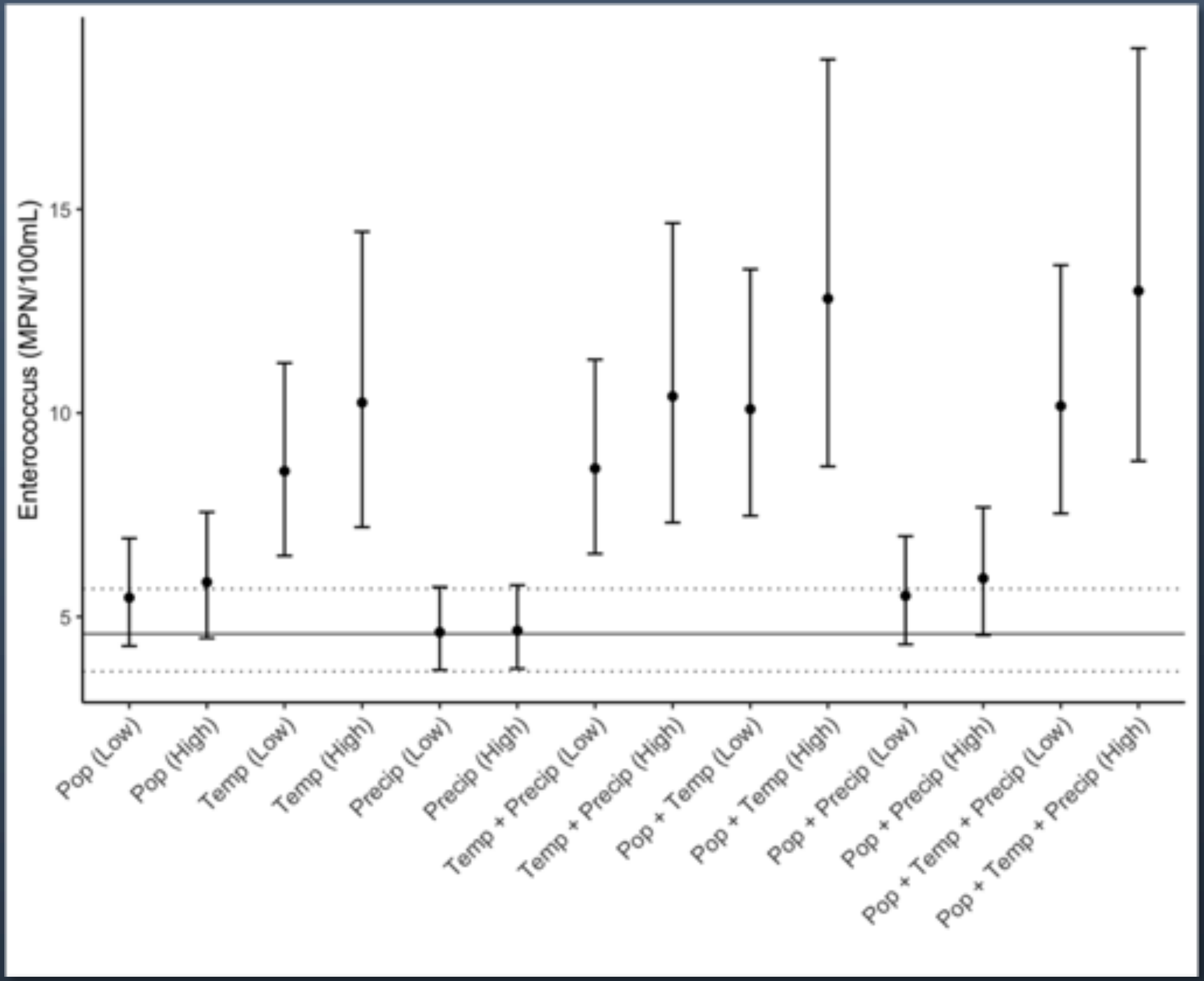
Predictive Modeling Results: Fecal Coliform

- Population growth increased bacteria levels significantly higher than baseline values
- Effect of climate change more subtle



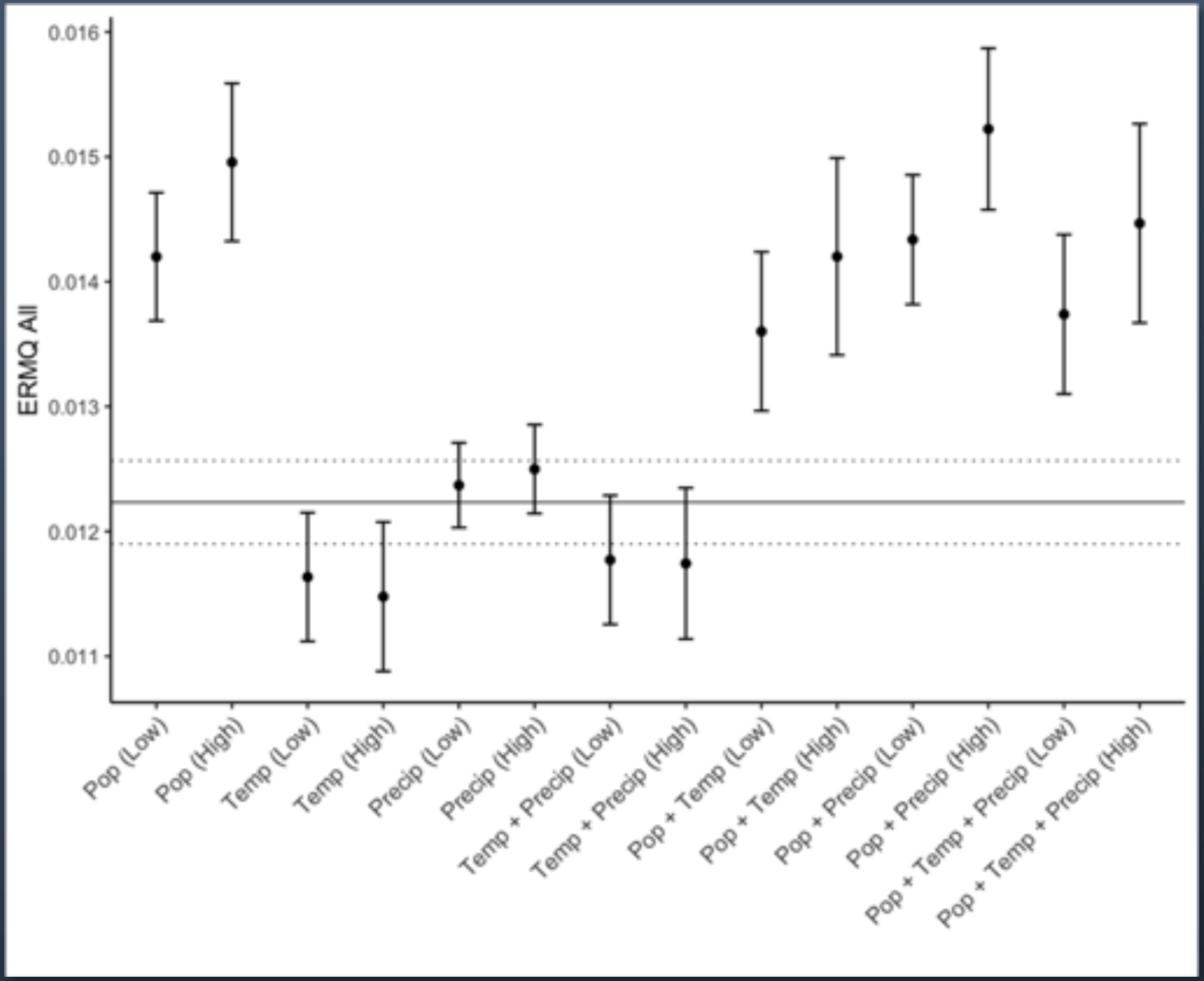
Predictive Modeling Results: Enterococcus

- Increased temperature resulted in higher levels of bacteria; precipitation less noticeable
- Population growth resulted in predictions only slightly above baseline
- Fecal coliform more sensitive to landcover changes, enterococcus more sensitive to climate change



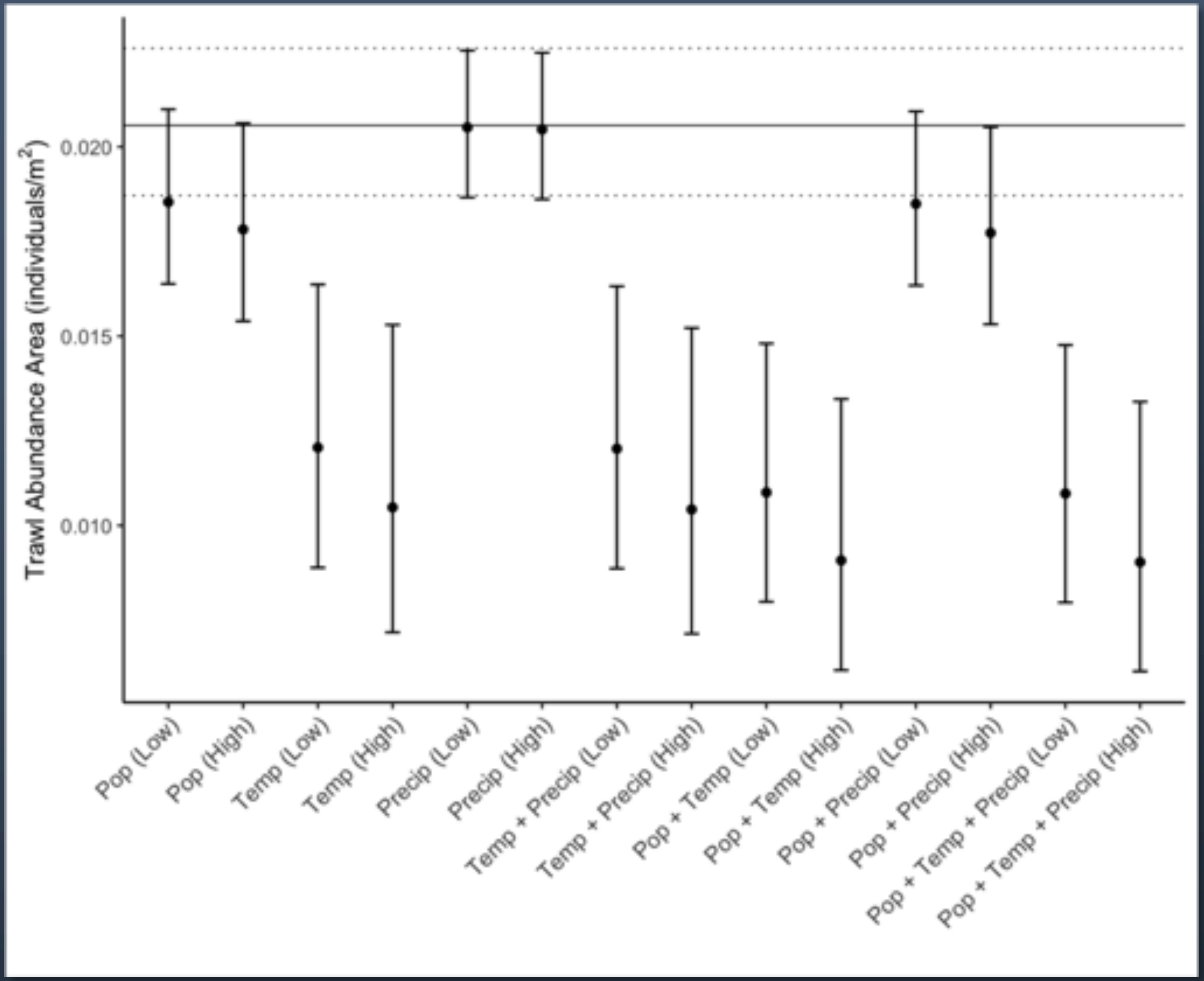
Predictive Modeling Results: ERMQ (All)

- Population growth increased predictions of sediment contamination
- Increased temperature linked to lower sediment contaminants
- Precipitation changes resulted in slight increases of ERMQ values, but confidence intervals overlapped with baseline conditions



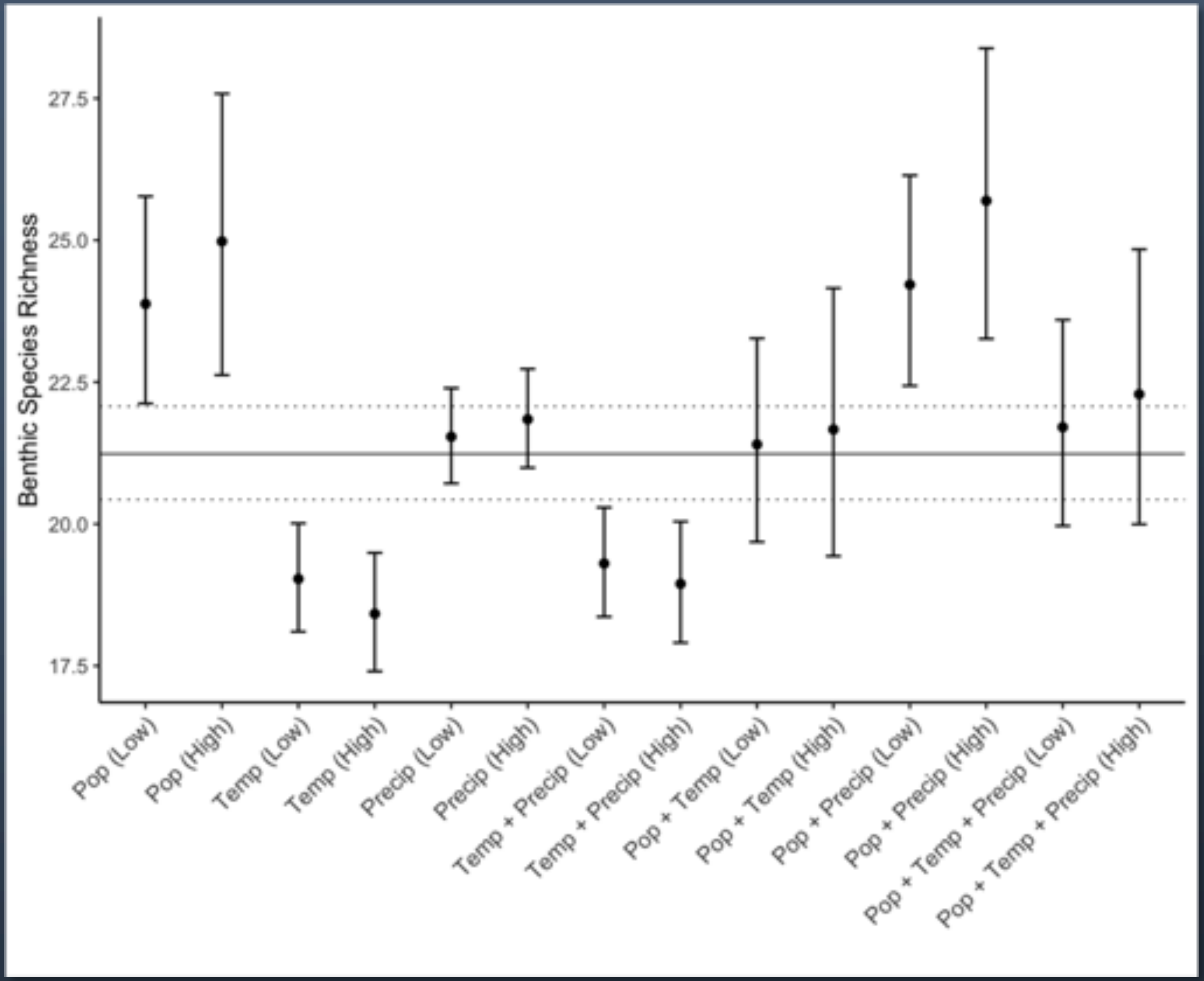
Predictive Modeling Results: Trawl Abundances

- Decreases in nekton abundance under population growth and temperature increases



Predictive Modeling Results: Benthic Species Richness

- Benthic species richness increased under population growth scenarios – the result of positive correlation with low intensity development in original model
- Increasing temperatures related to decline in benthic species richness



Predictive Modeling Results Summary

- Revealed important drivers of environmental change and the sensitivities of different explanatory variables
- Increased development could result in higher concentrations of fecal coliform bacteria, higher levels of sediment contamination, declines in nekton abundance, and increased benthic species richness
- Temperature increases linked to higher concentrations of enterococcus bacteria and declines in nekton biodiversity
- Precipitation increases were not as influential in the predictive models as expected
- Potential for compounded effects

Key Messages

- H_1: Degraded metrics of environmental quality in estuarine systems will relate to increasing development intensity within connected upland watersheds. Environmental impacts may include higher levels of sediment contamination, lower nekton diversity and abundance, fewer stress-sensitive benthic invertebrate taxa, and higher frequencies of bacterial contamination
- Measures of development correlated with higher bacteria concentrations and sediment contamination; its effects on the biology more varied and difficult to define

Key Messages

- H_2: Weather patterns associated with climate change (e.g., higher temperatures, extreme rainfall events) will be associated with degraded metrics of environmental quality in estuarine systems (as listed in H_1)
- Precipitation correlated with higher levels of bacteria and sediment contamination supporting runoff hypothesis
- Temperature often negatively correlated with measures of biodiversity

Key Messages

- Importance of long-term environmental datasets and demonstrated effectiveness of a data synthesis methodology
- Although SC is still a largely natural landscape, the effects of development were still observable at large spatial scales
- SC's estuarine habitat is diverse and was not easy to summarize with a one-size-fits-all model
- Estuarine environment has been influenced by landcover and climate. Modeling can help understand these relationships and demonstrate the potential consequences of climate change and continued development

Policy and Management Solutions

- Ecologically focused stormwater management should be central to sustainable development – best management practices (BMPs) and low-impact development (LID) design
- Examples: green roofs, constructed wetlands, bioswales, permeable pavement, rainwater harvesting
- While climate change is more difficult to address, green infrastructure can help create a more resilient coast

Acknowledgements

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- Conference support from MESSA, CofC Graduate School, and SCDNR
- Thanks to my committee members, coworkers at the Environmental Research Section at DNR, peers and professors in the environmental studies program, friends, and family
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- GitHub: @WhateverLloyd