Drivers and Impacts of Marsh Migration in the Coastal Critical Zone:

The need for understanding and modeling complex feedbacks

Holly Michael, Julia Guimond, Dannielle Pratt, Brian Moyer, Sean Fettrow, Yu-Ping Chin, Sergio Fagherazzi, Keryn Gedan, Matthew Kirwan, Angelia Seyfferth, Stephanie Stotts, Katherine Tully, Kevan Moffett and others…

Boston University
VIMS William & Mary Virginia Institute of Marine Science
The George Washington University Washington, DC
NSF
University of Delaware Delaware Environmental Institute
University of Maryland Eastern Shore
University of Maryland

Coastal Environments

- Mediate Fluxes from land to sea (C, N, Contaminants)
- Hydrologically, biogeochemically, ecologically diverse & complex

Coastal Environments

- **Mediate Fluxes from land to sea (C, N, Contaminants)**
- **Hydrologically, biogeochemically, ecologically diverse & complex**
- **Highly Dynamic over multiple timescales**

Waves [1 s] **Tides [1 d]** **Seasons [1 y]** **Climate [10000 y]**

→ Need to work across scales, settings, and disciplines to estimate land-sea fluxes and predict their future evolution

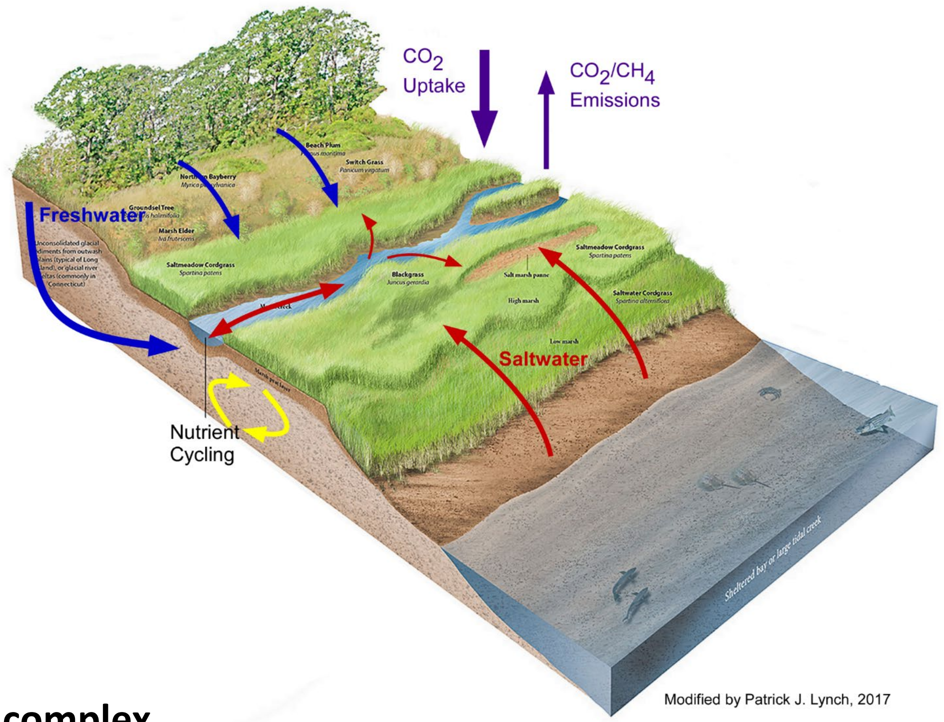
→ Huge challenge for modeling – both scales and mechanisms

Coastal Wetlands

Hydrologically complex
- Freshwater from land
- Saltwater input through tidal channels

Ecologically complex
- Distinct vegetation zonations

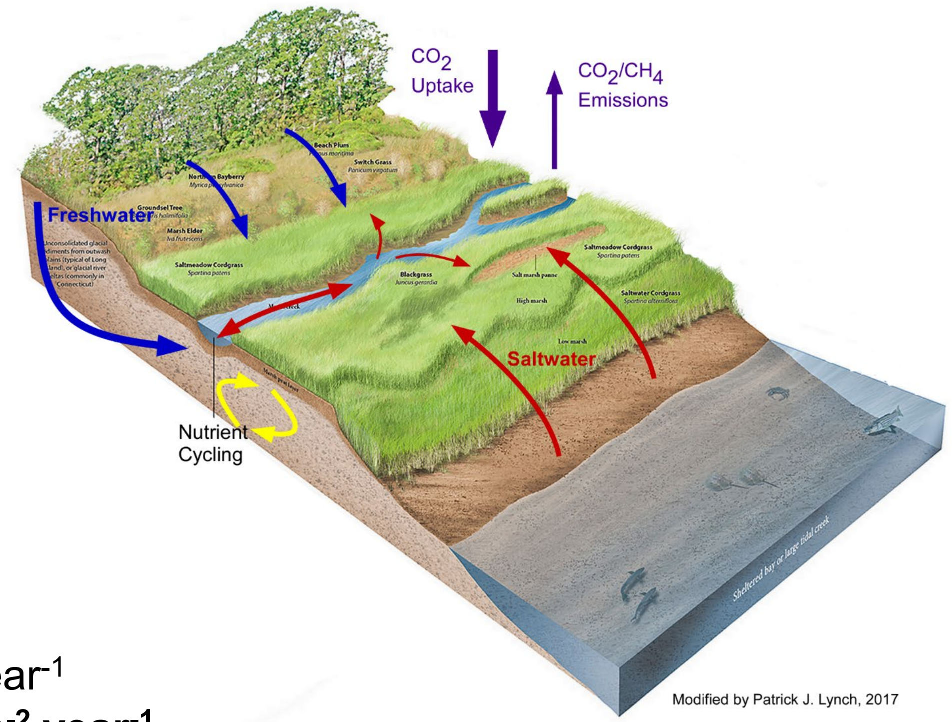
Biogeochemically complex
- “Hotspots” where nutrients are processed and stored
- High rates of carbon burial



Modified by Patrick J. Lynch, 2017

Najjar et al. 2018

Coastal Wetlands



Ecosystem Services

- Fishery and Coastal Wildlife Habitat
- Storm Surge Protection
- Contaminant Trapping/Breakdown
- Carbon Sequestration

Forests → 1-10 g C m^{-2} $year^{-1}$

Tidal Marshes → **18-1713 g C m^{-2} $year^{-1}$**

Up to 1000X greater storage rate

Coastal Wetlands

→ **Highly vulnerable to climate, human pressures**

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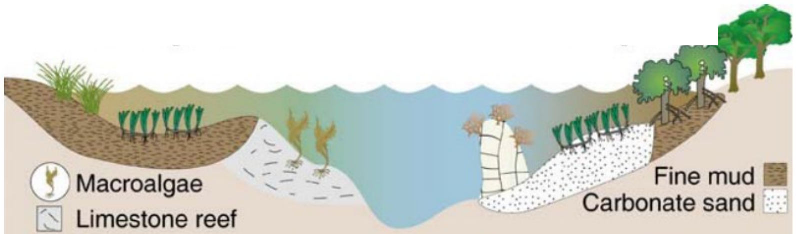


Ecosystem	Area (10^6 ha)	Loss (% $year^{-1}$)	Value (US\$ ha^{-1} $year^{-1}$)
Seagrass	18	2–5	19 004
Salt marsh	140	1–2	9 990
Mangrove	15	1–3	9 990
Coral	62	4–9	6 075
Tropical forest	1 900	0.5	2 007

Source: Duarte et al, 2008

Coastal Wetlands

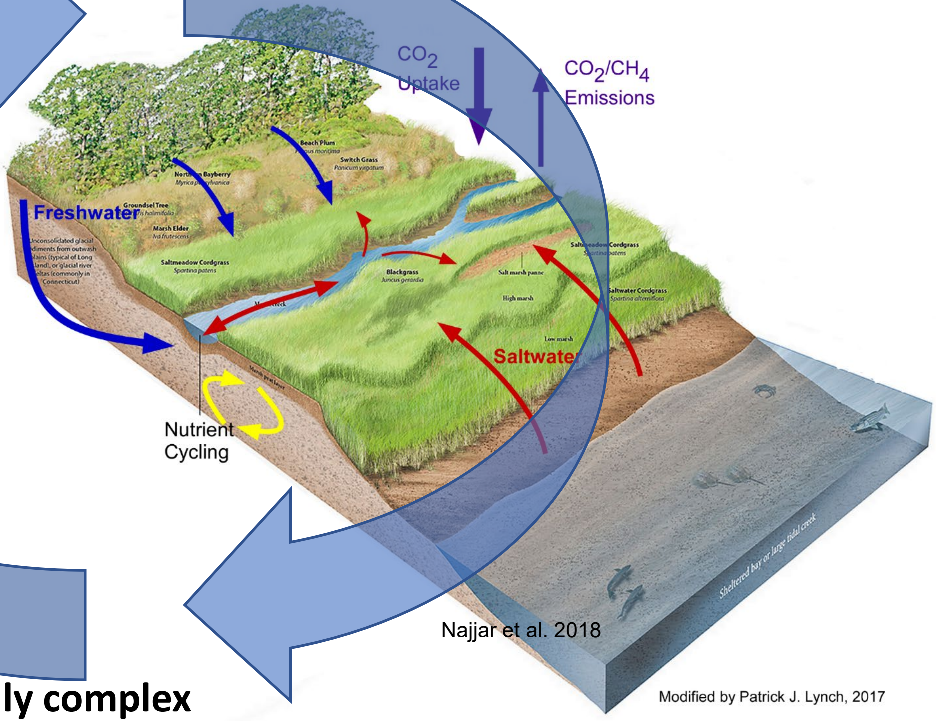
Hydrologically complex

- Freshwater from land
- Saltwater input through tidal channels

Ecologically complex

- Distinct vegetation zonations

Biogeochemically complex



→ LINKS & FEEDBACKS KEY TO PREDICTING FUTURE EVOLUTION OF COASTAL LANDSCAPES AND LAND-SEA FLUXES

Salt Marsh Hydrology: Linked observations and modeling

Physical-biological-geochemical feedbacks impacting carbon fluxes and marsh migration

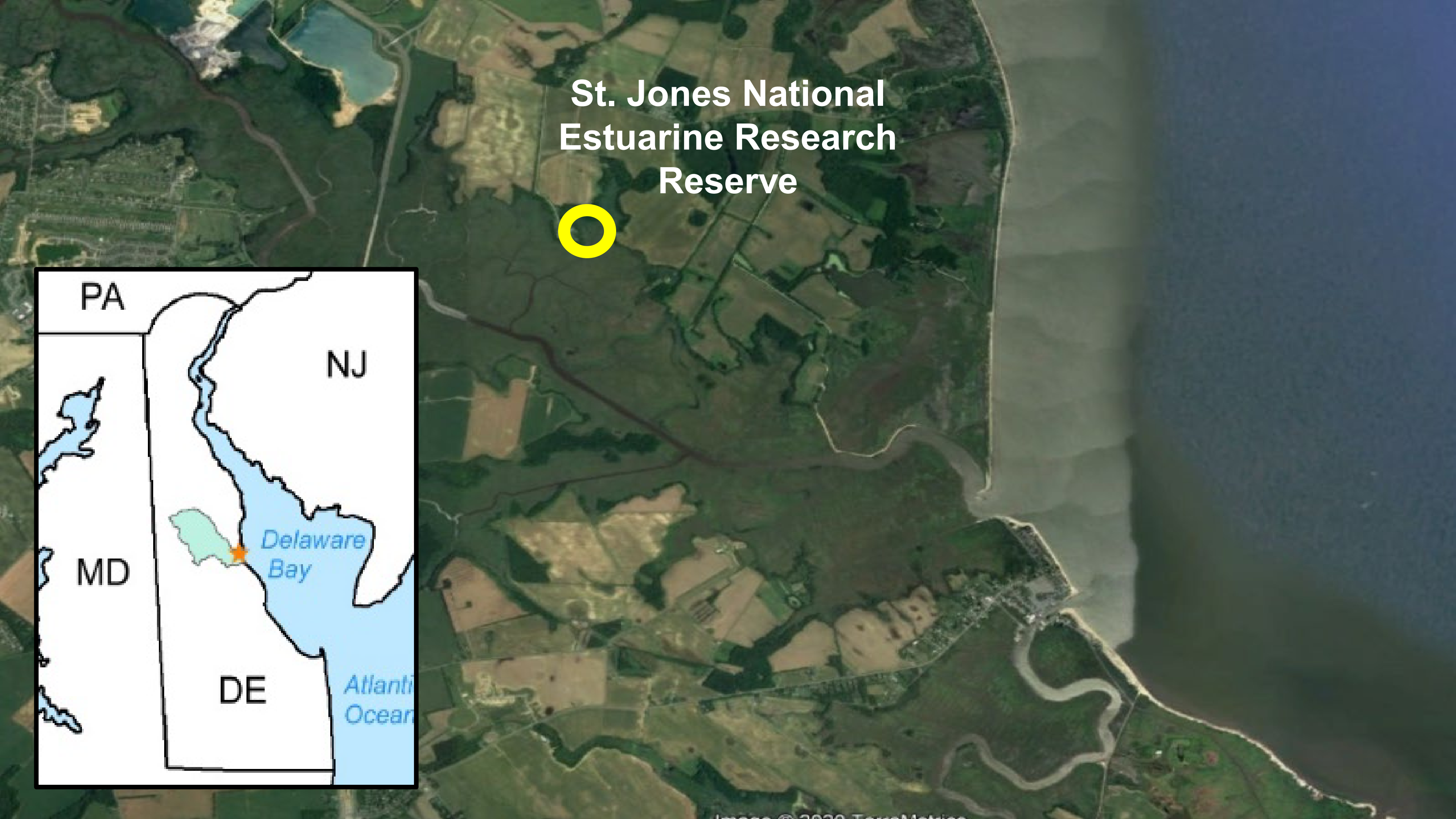
Julia Guimond

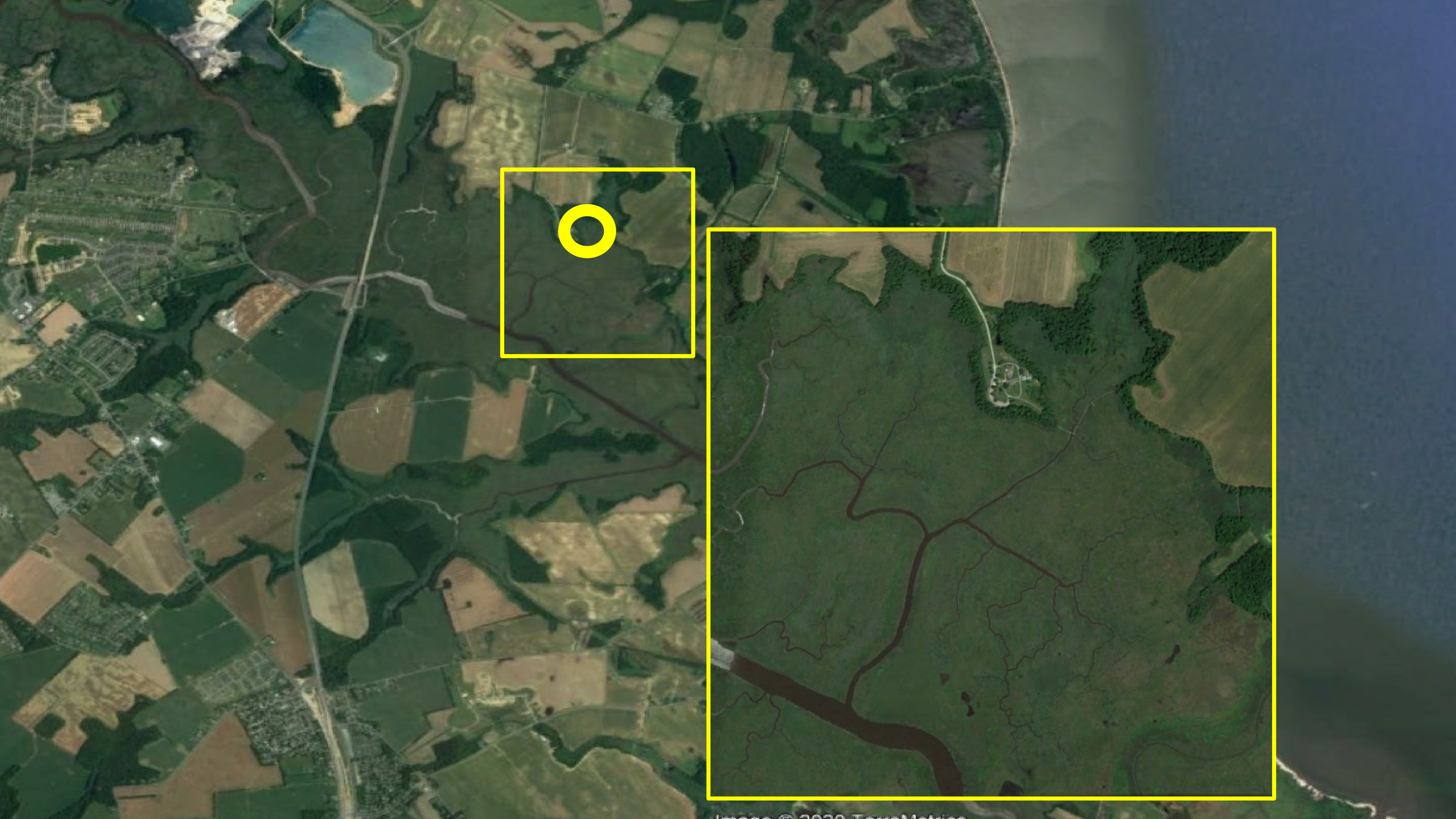
Kevan Moffett (U. Washington Vancouver)

Angelia Seyfferth (UD)

Collaborators:

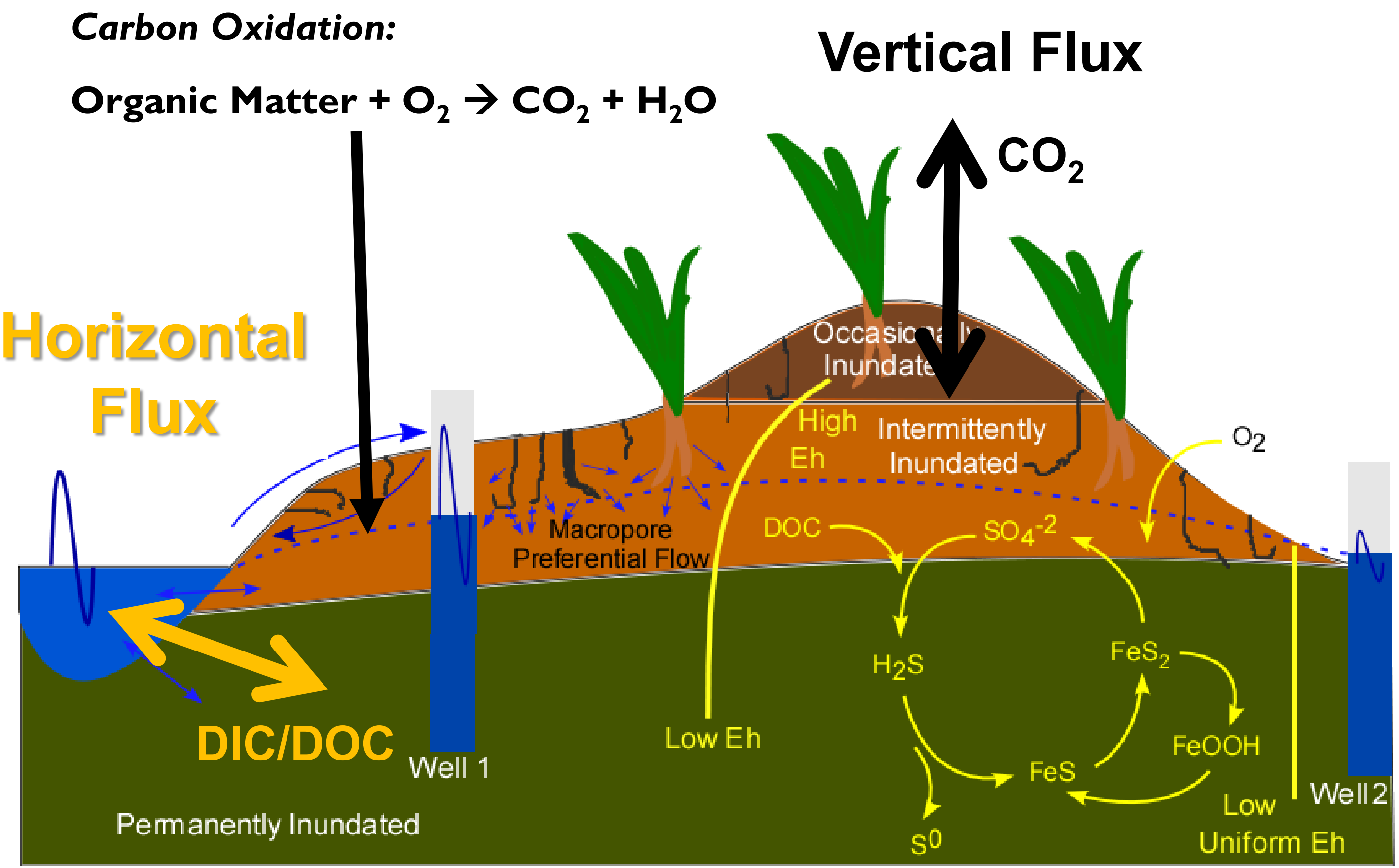
Julia Guimond (*University of Delaware, now WHOI*)
Angelia Seyfferth (*University of Delaware*)
Kevan Moffett (*Washington State University Vancouver*)


St. Jones National Estuarine Research Reserve
PA
NJ
MD
DE
Delaware Bay
Atlanti
Ocean



Salt Marsh:

Physical-biological-geochemical linkages impacting C fluxes



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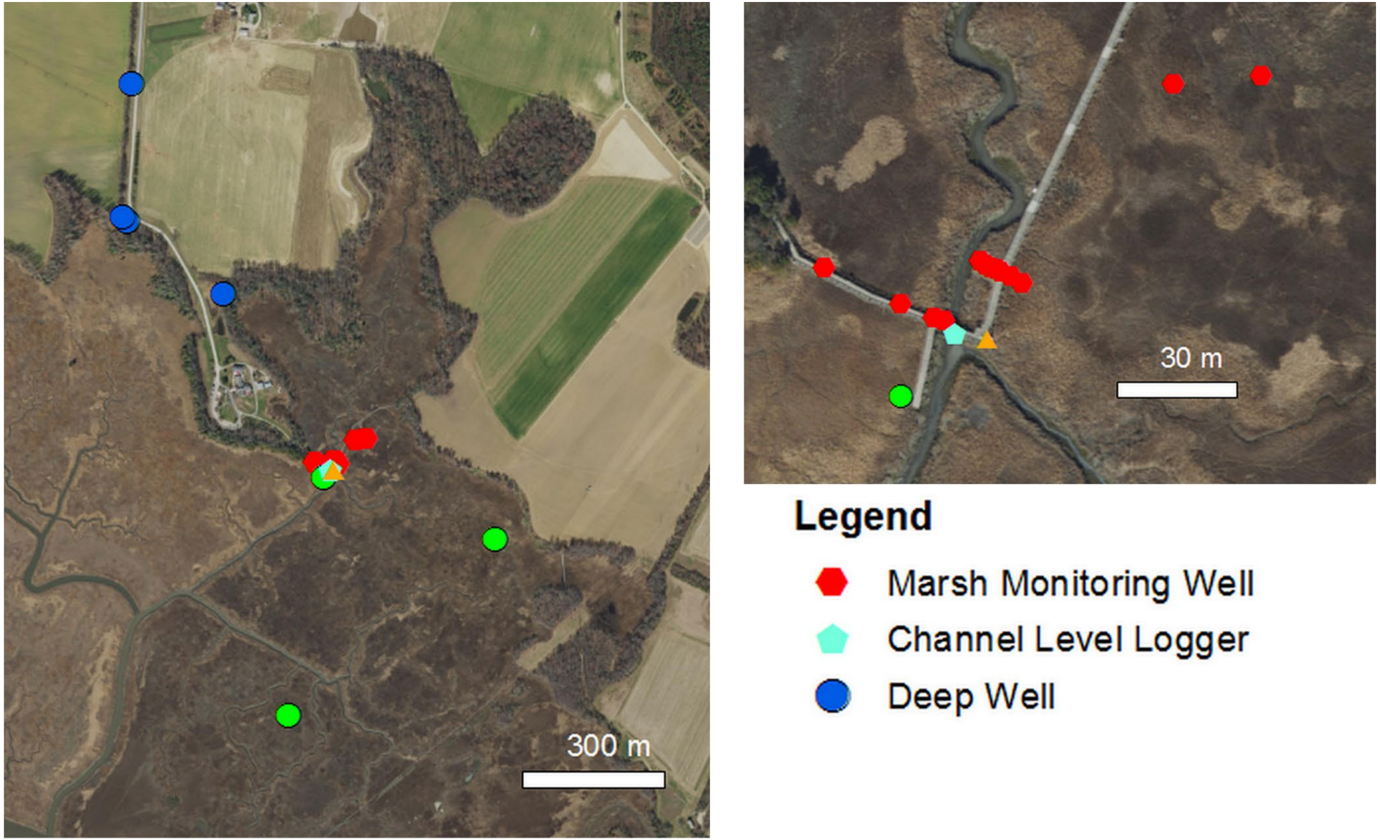


Hydrology

Monitoring Wells
with loggers

Piezometers

Slug Tests

Seepage
Meters

Biology and Geochemistry

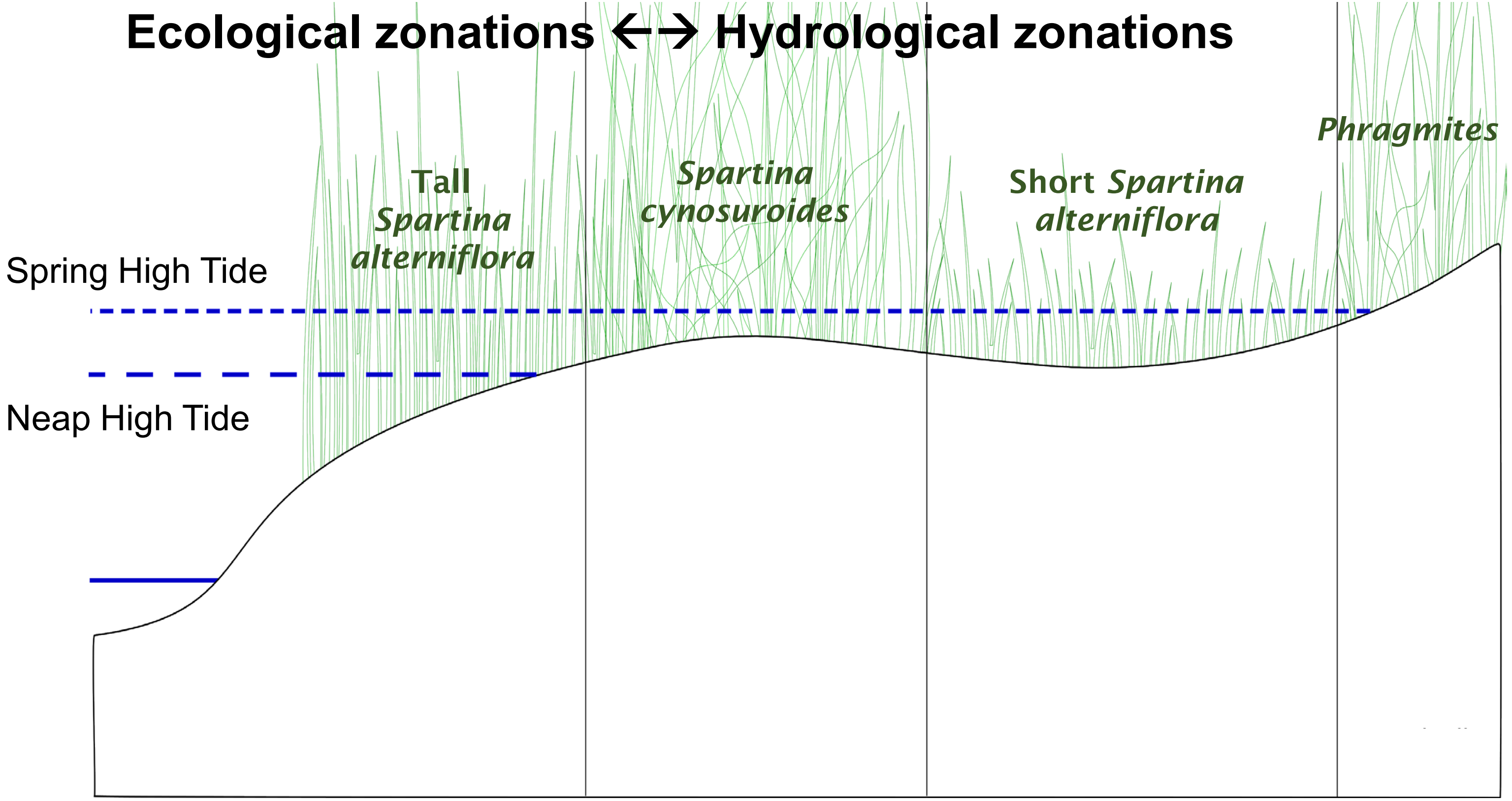
Macropore Counts

Porewater DOC/DIC Concentrations

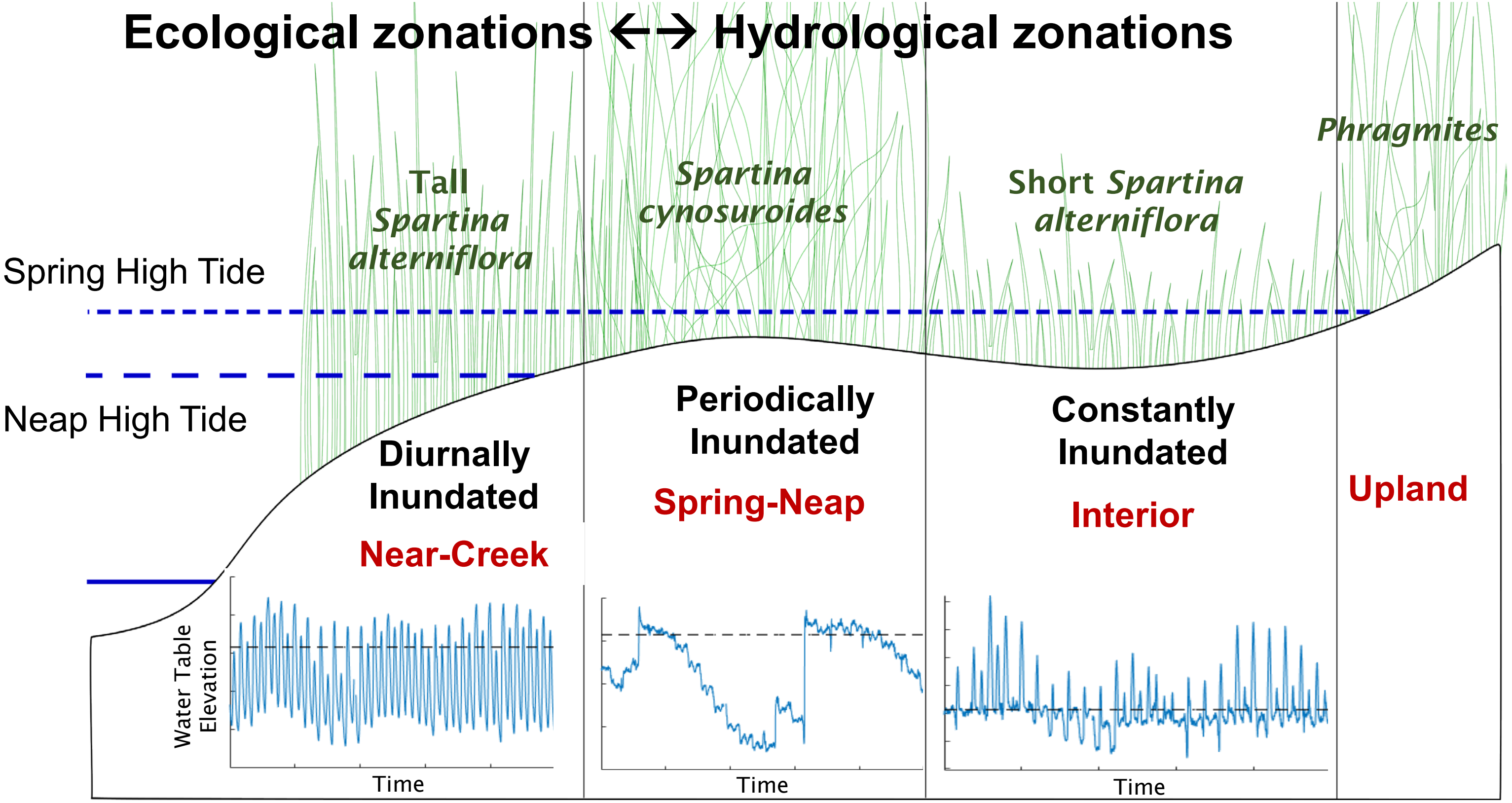
Multi-depth Redox Sensors

Burrow Casts

Ecological zonations ←→ Hydrological zonations

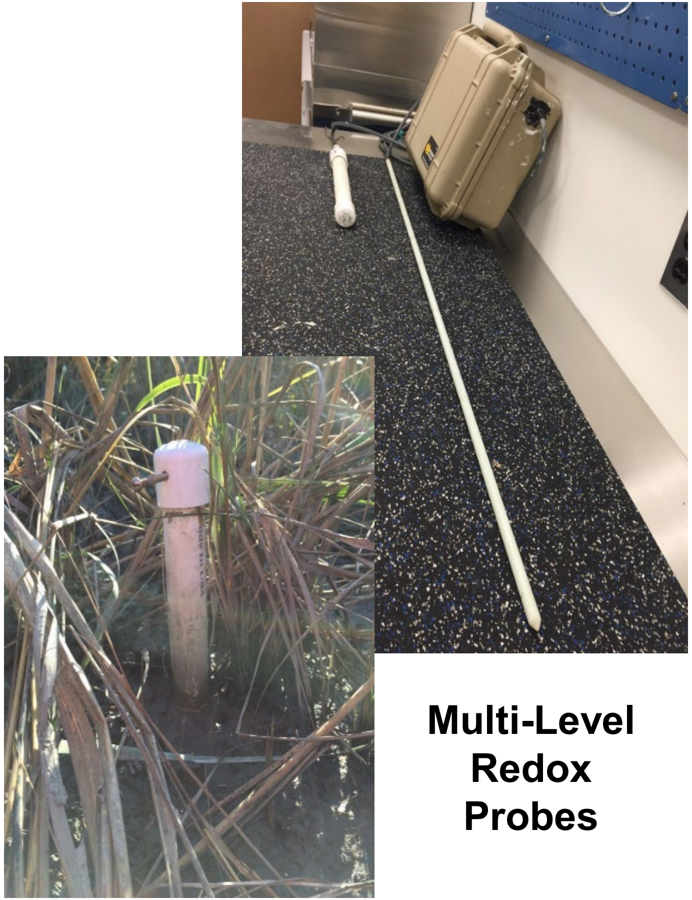


Ecological zonations ←→ Hydrological zonations

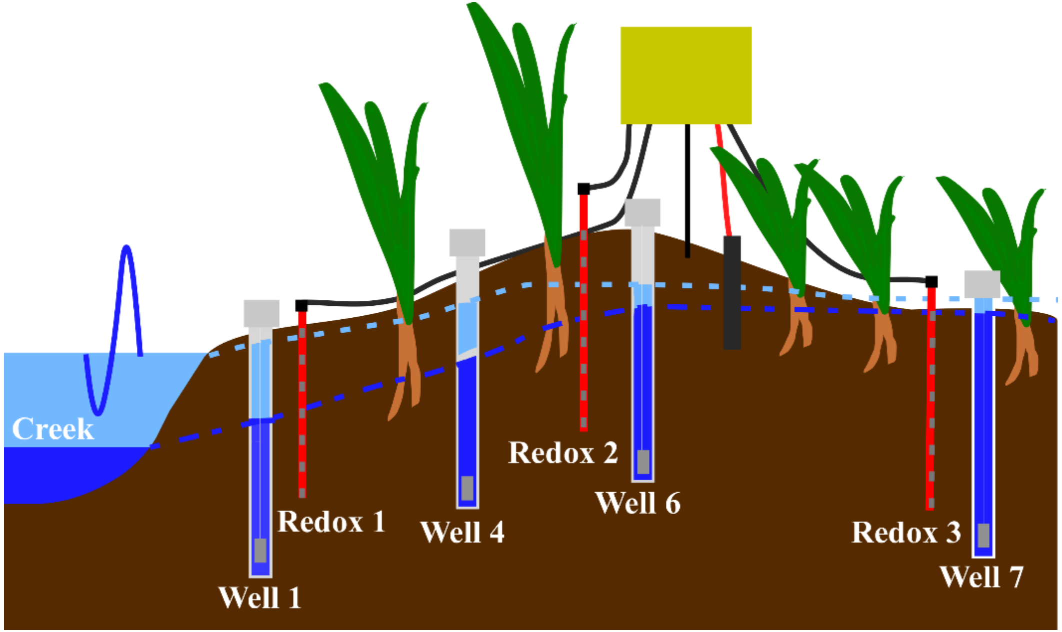


Guimond et al., ERL, 2020

Spatial (and temporal) changes in hydrology cause differences in redox conditions



Multi-Level Redox Probes



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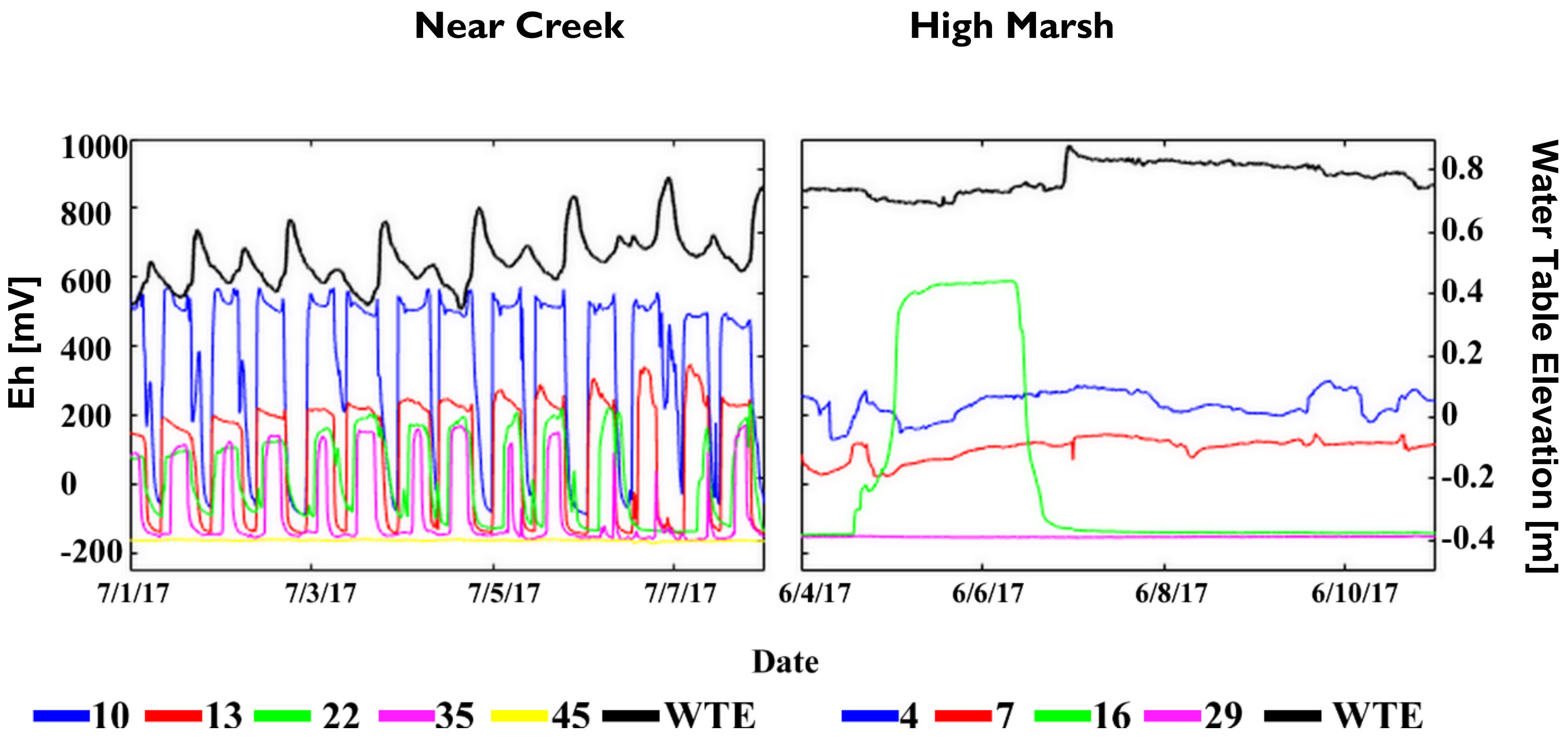

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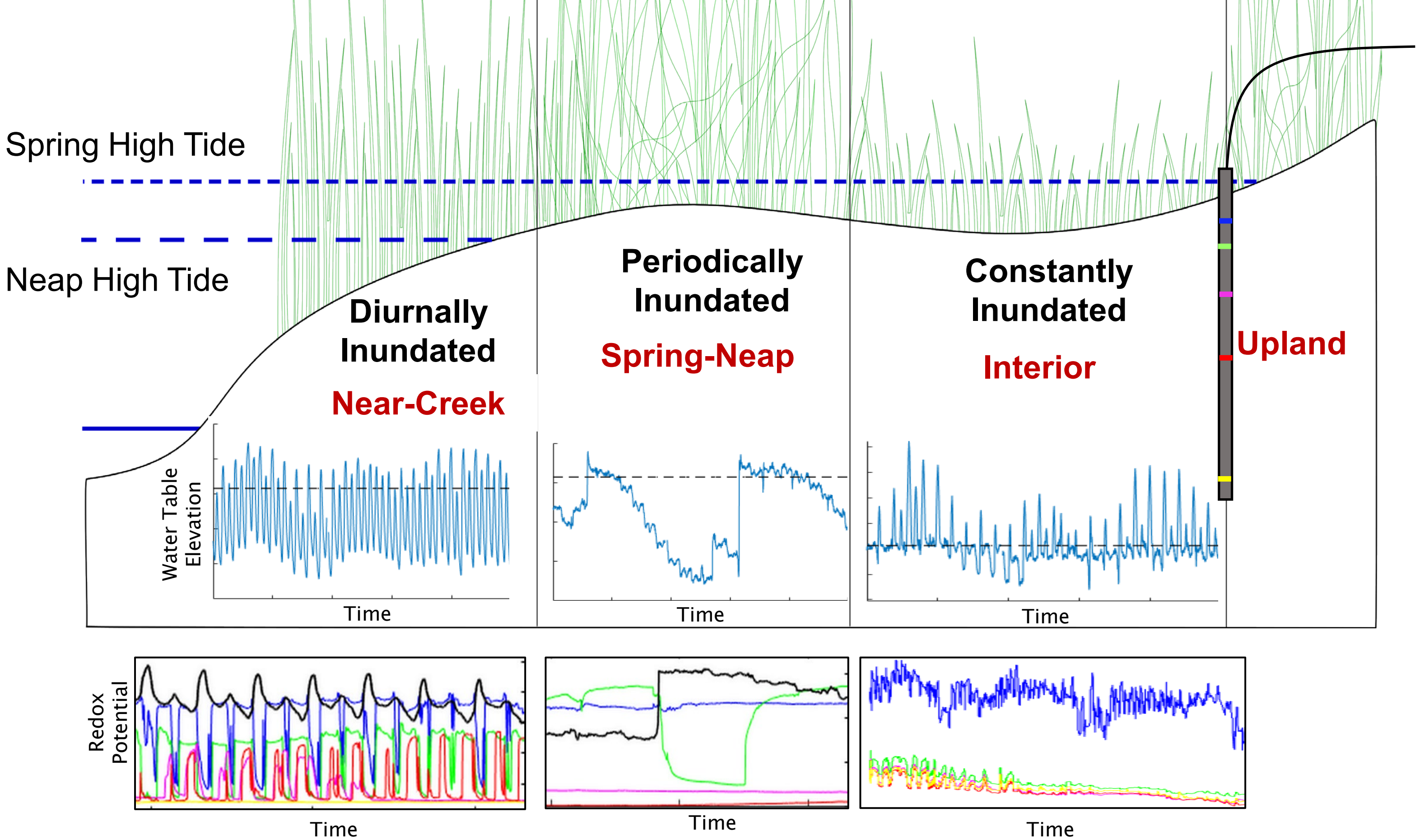
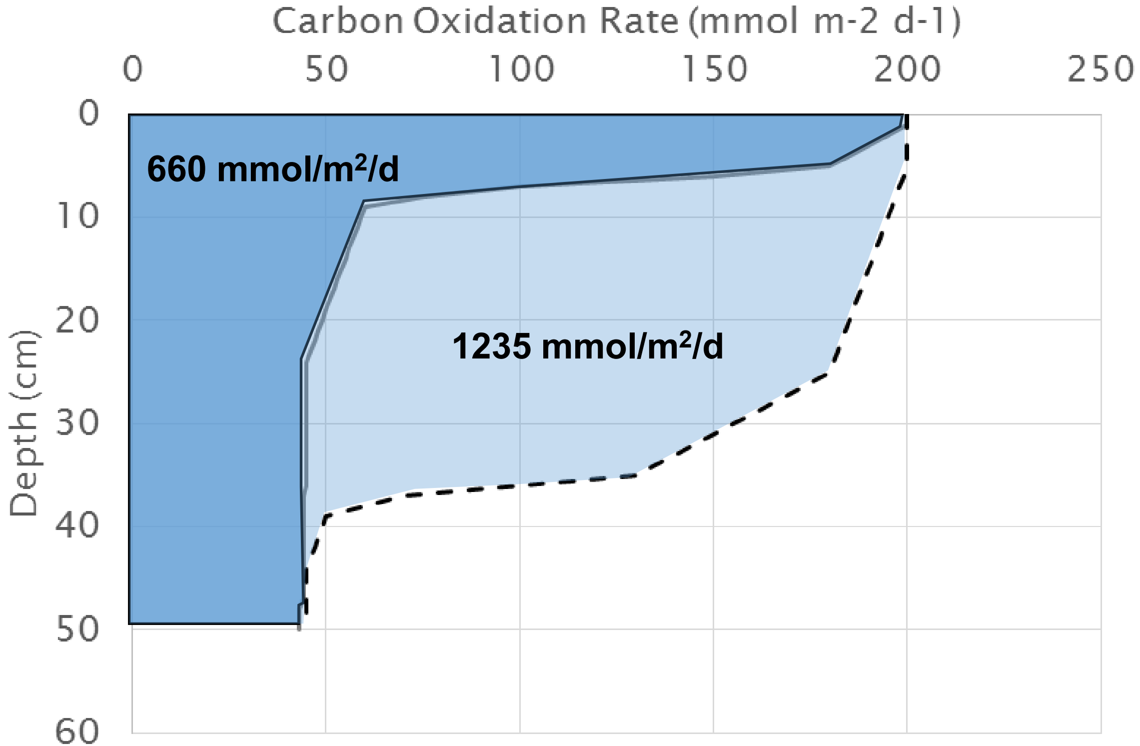


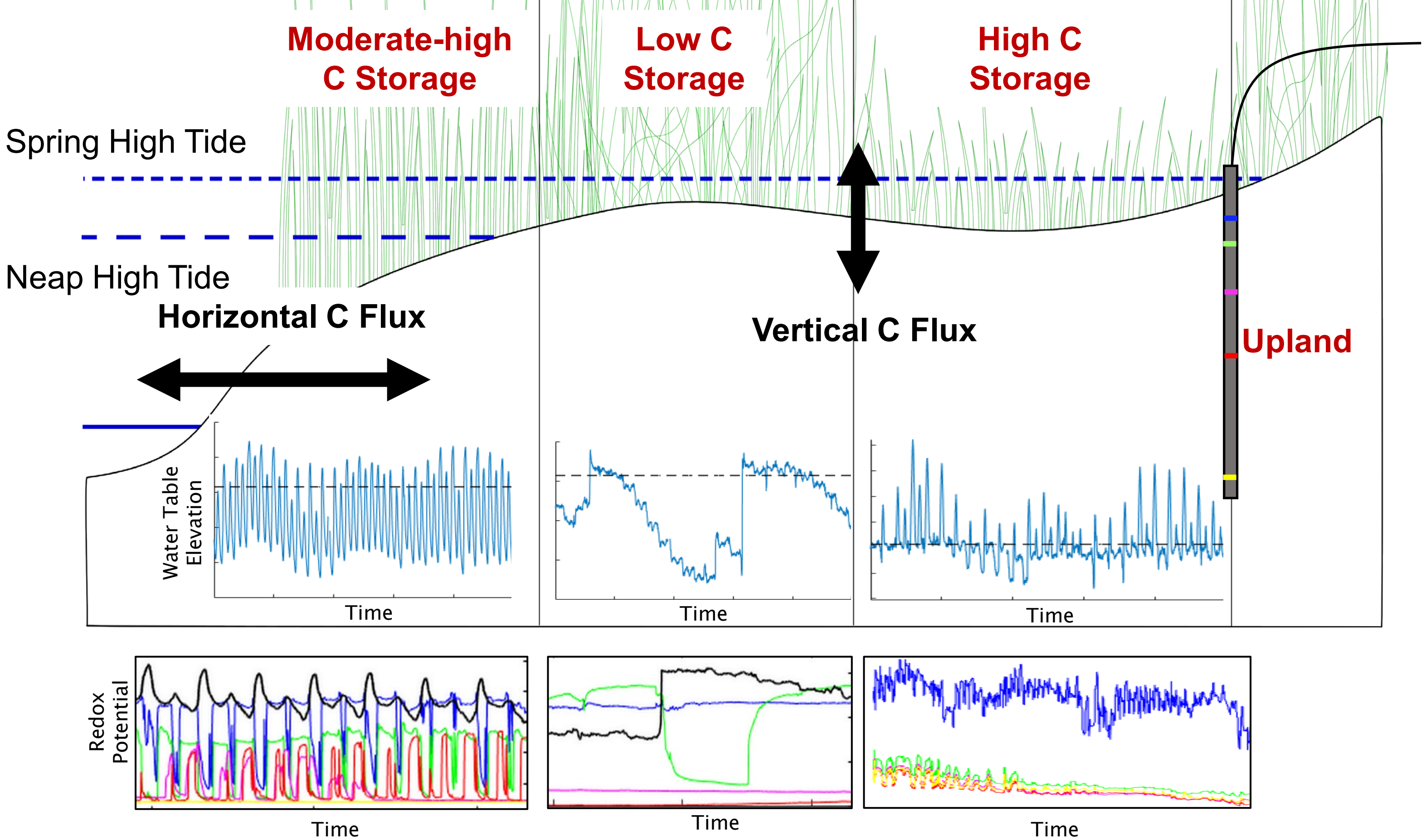
Greater depth of high Eh → Greater Oxidation rate → Greater vertical C flux



Plot derived from Kostka et al, 2002a, 2002b);
Bothfield, 2016; Middleburg et al., 1996

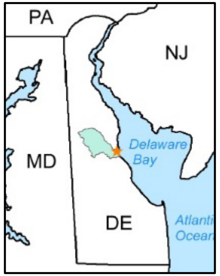
Guimond et al., ERL, 2020

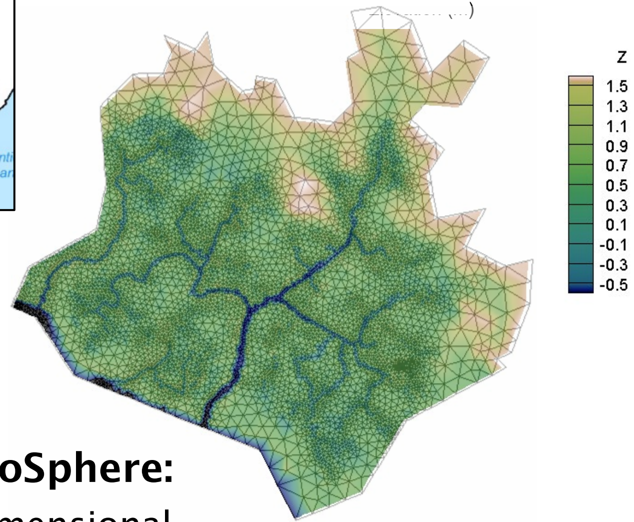
Spatial (and temporal) changes in hydrology cause differences in redox conditions and carbon storage and fluxes

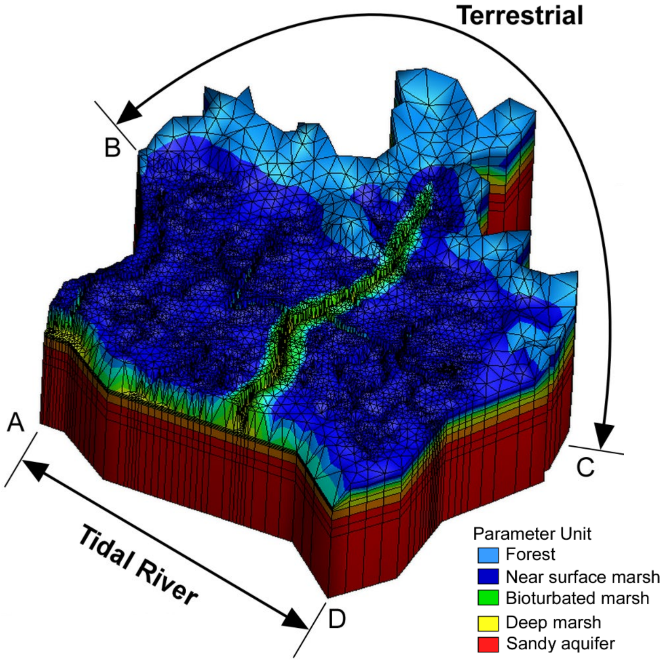


Physical-Biogeochemical Linkages

→ *Predictive modeling to understand response to SLR*







HydroGeoSphere:

- Three-dimensional
- Coupled surface-subsurface model
- Variably saturated

(Therrien et al. 2006)

Guimond et al., *Water Resources Research*, 2020

See also: Yu et al., WRR, 2016; Yang et al, AWR, 2019; Guimond and Michael, WRR, 2021; Paldor and Michael, WRR, 2021; Paldor et al., GRL, 2022; Paldor et al., HESS, 2022

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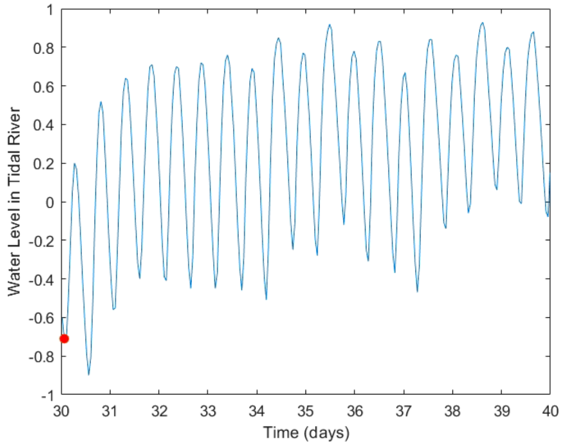

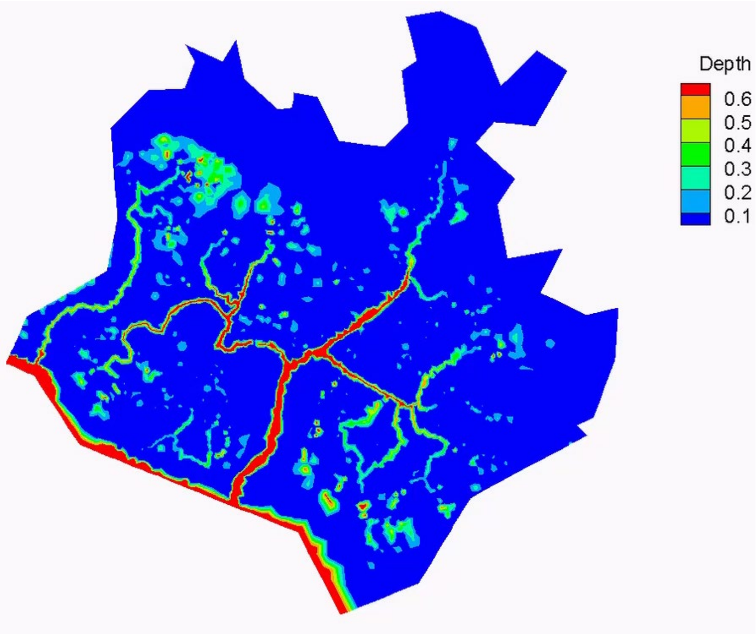

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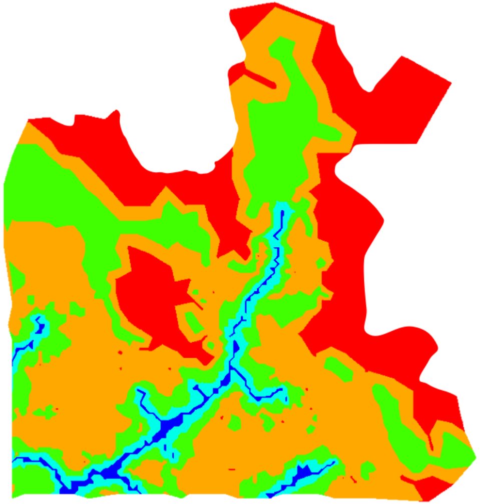
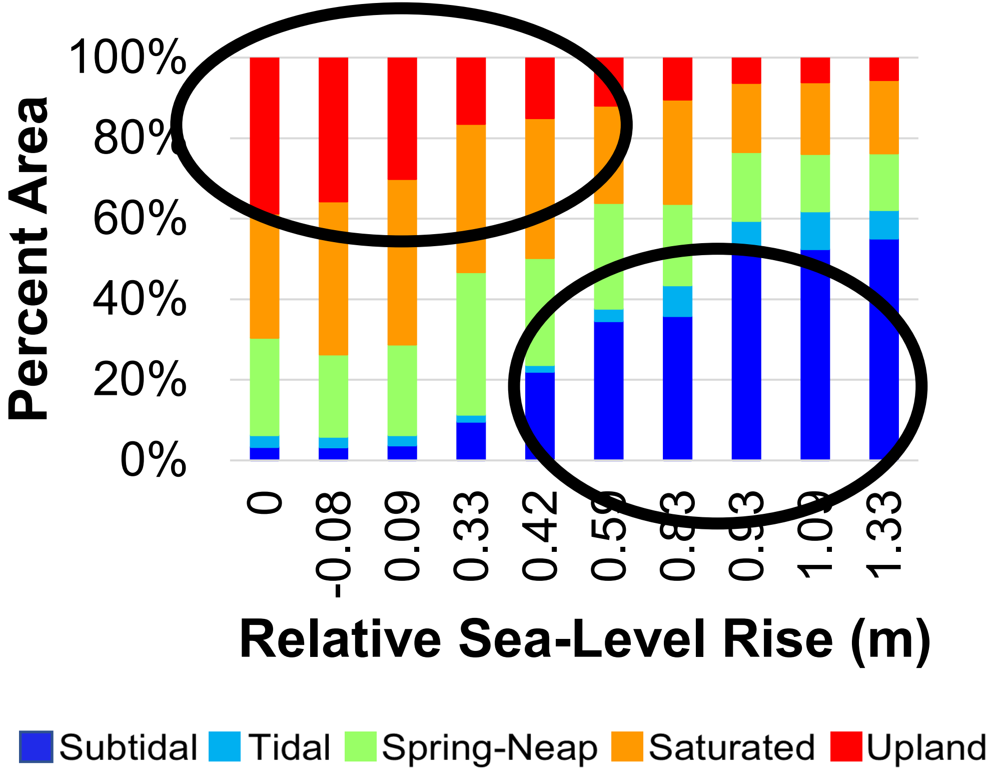
Physical-Biogeochemical linkages

Hydrological zonations → Carbon sequestration rates





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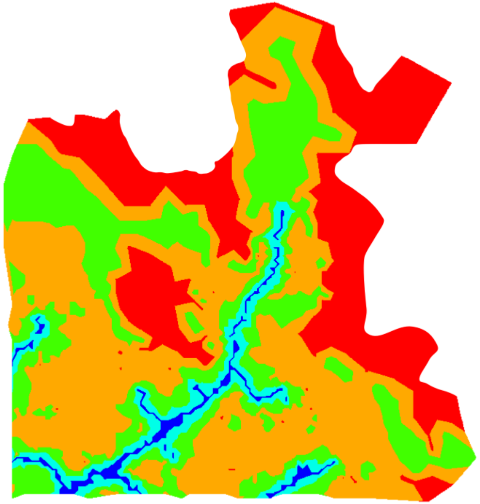
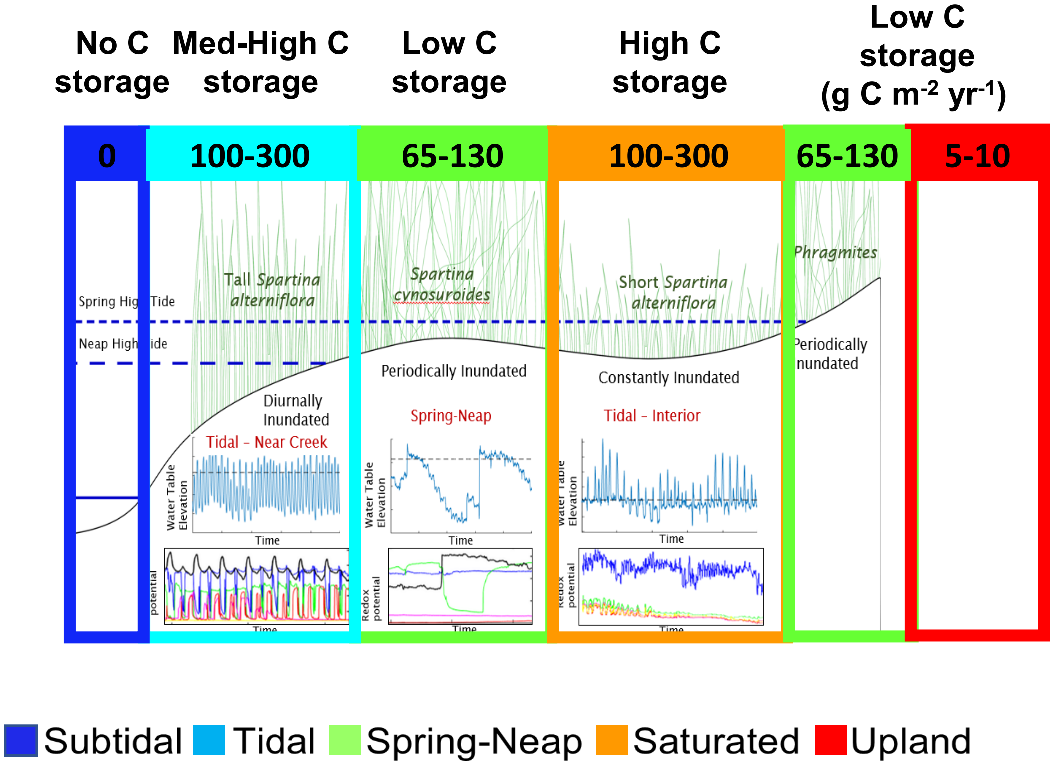


Carbon Burial

$(g\ C\ m^{-2}\ yr^{-1})$	
Subtidal	0
Tidal	300
Spring-Neap	130
Interior	300
Upland	10



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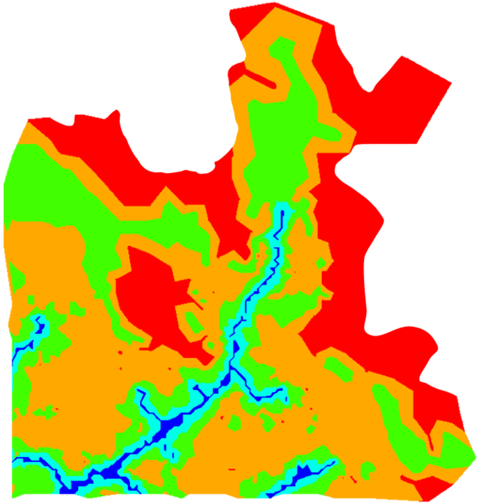

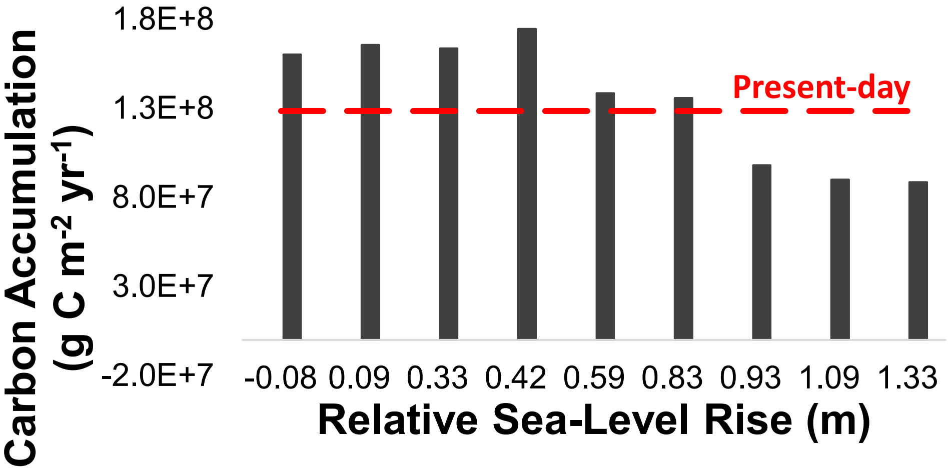

Carbon Burial (g C m^{-2} yr^{-1})	
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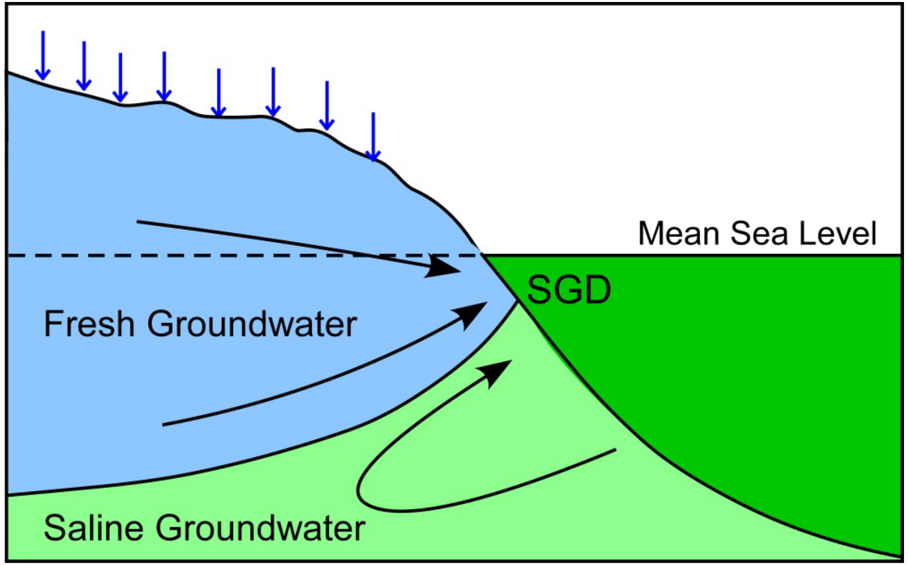
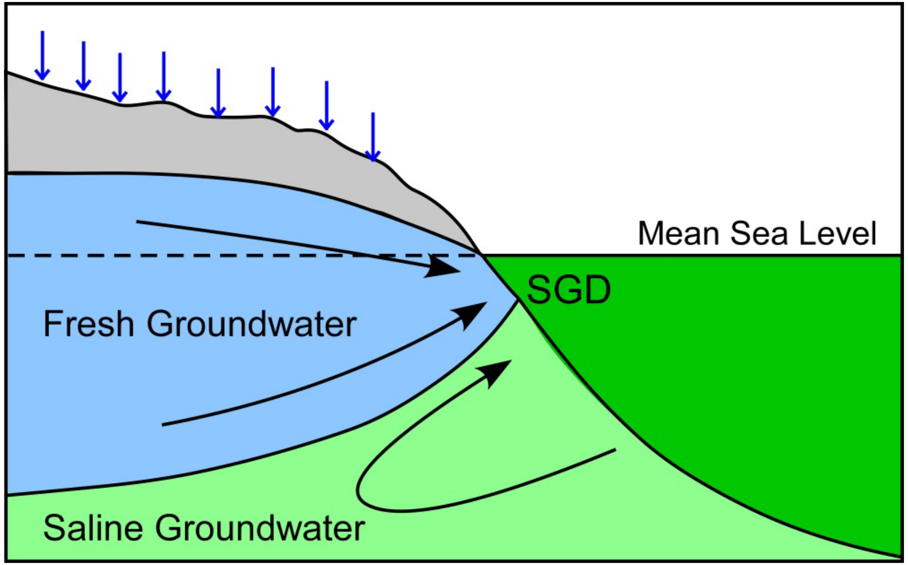
Guimond et al., *Water Resources Research*, 2020

Influence of SLR on the upland water table…

Topography-Limited Systems



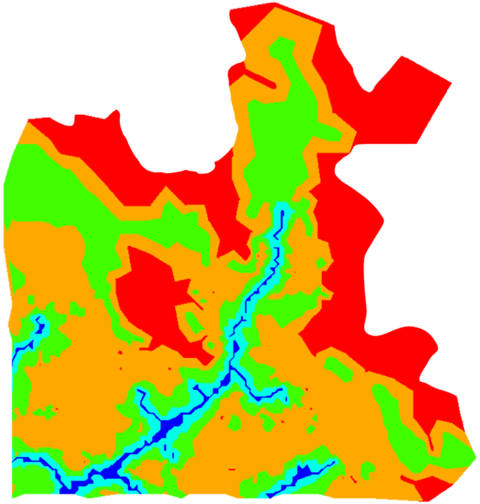
Recharge-Limited Systems

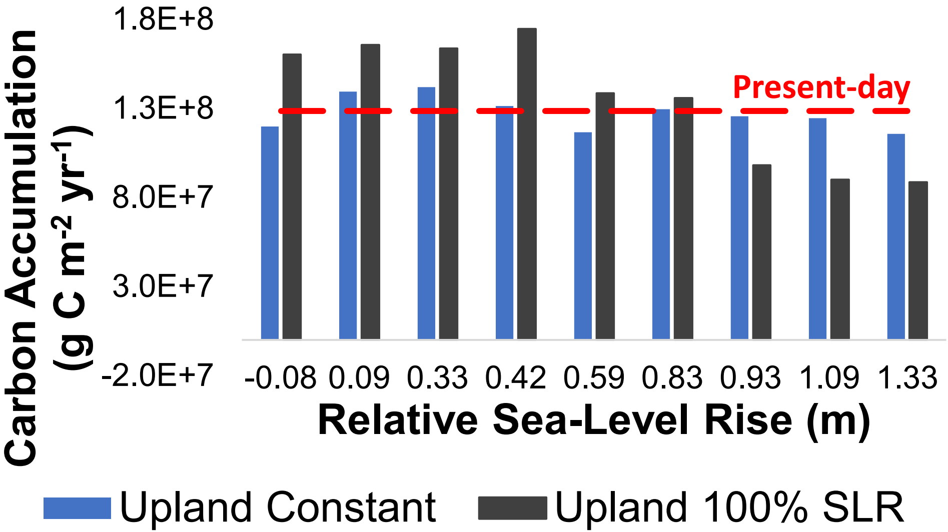


Michael et al., WRR 2013

Physical-Biogeochemical linkages

Hydrological zonations → Carbon sequestration rates





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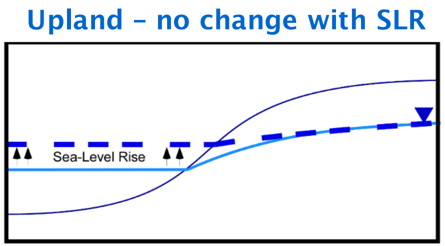
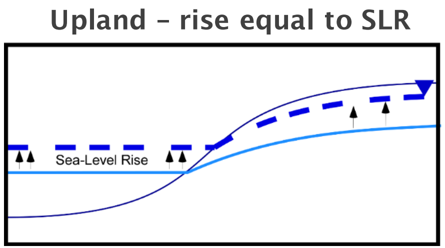
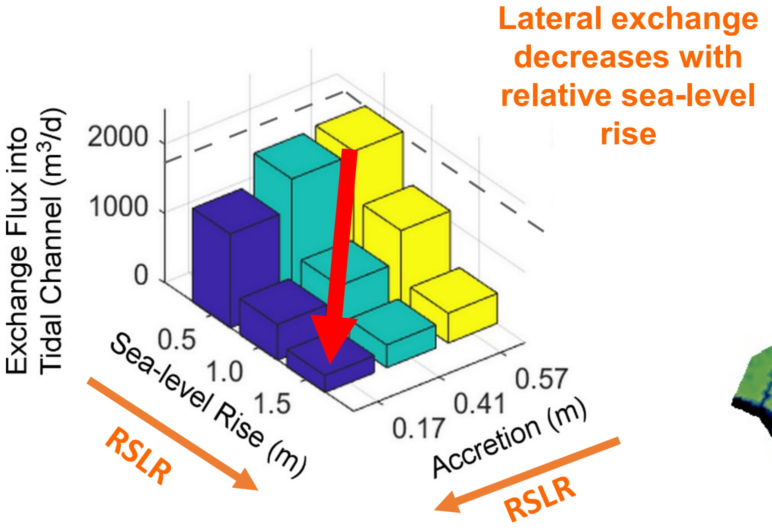


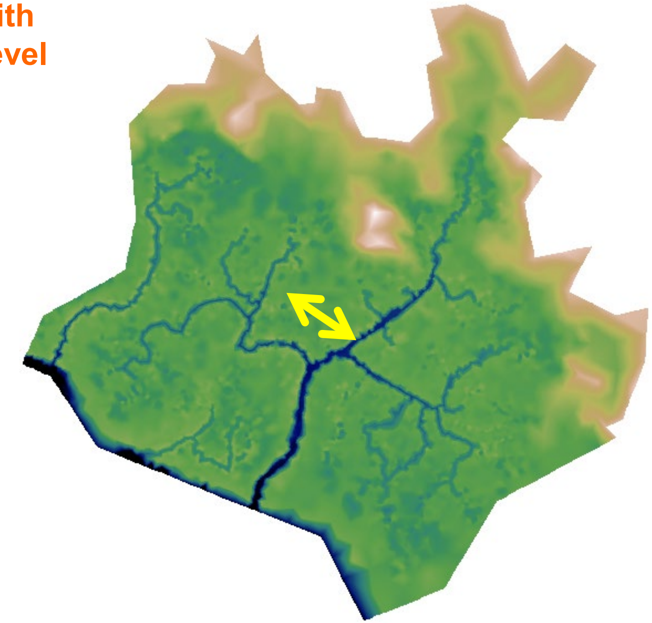


Guimond et al., *Water Resources Research*, 2020

Physical-Biogeochemical linkages

→ *SLR changes groundwater discharge to tidal channels*





Guimond et al., *Water Resources Research*, 2020

Physical-Biogeochemical linkages

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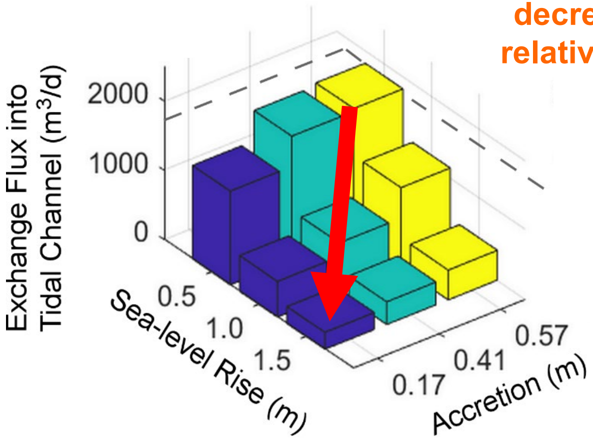
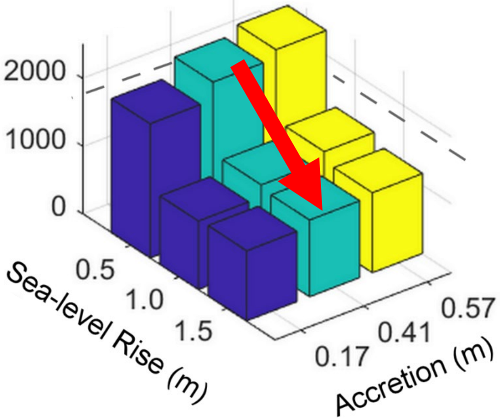
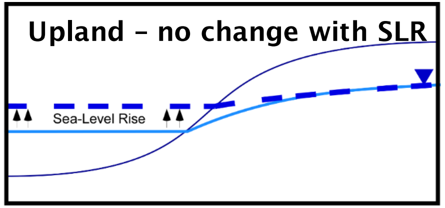


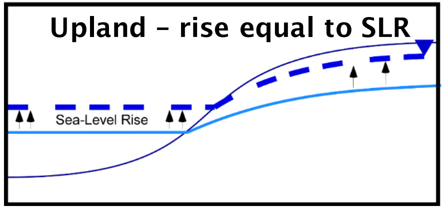
Lateral exchange decreases with relative sea-level rise





Topography-limited

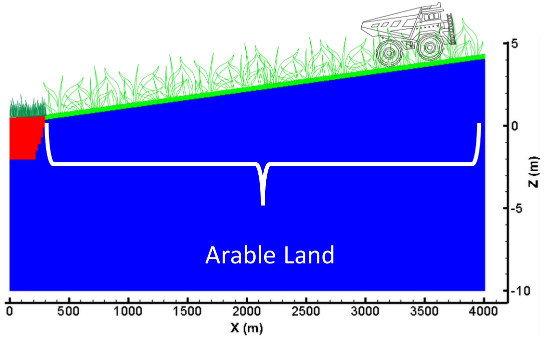
Changes in upland head due to sea-level rise mediates changes in lateral flux

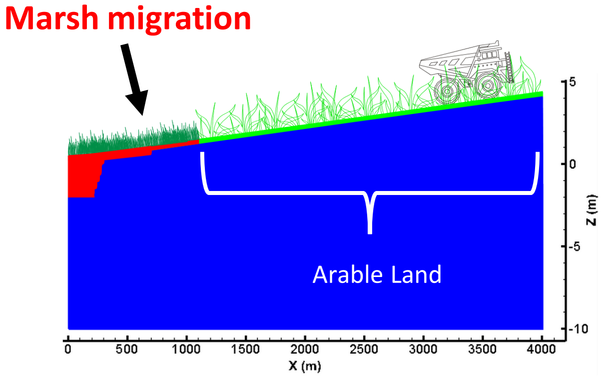


Recharge-limited

Guimond et al., *Water Resources Research*, 2020

How does marsh migration feed back into flooding and salinization at the land-sea margin?





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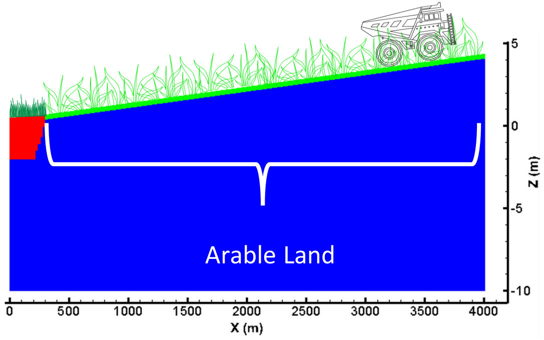
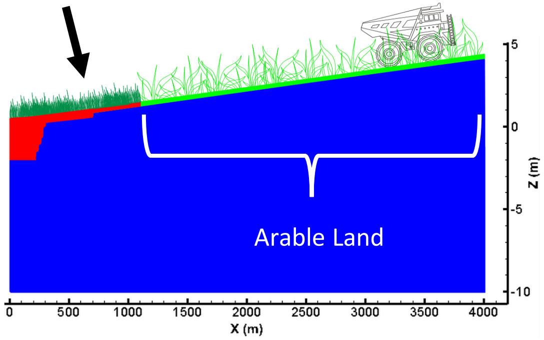
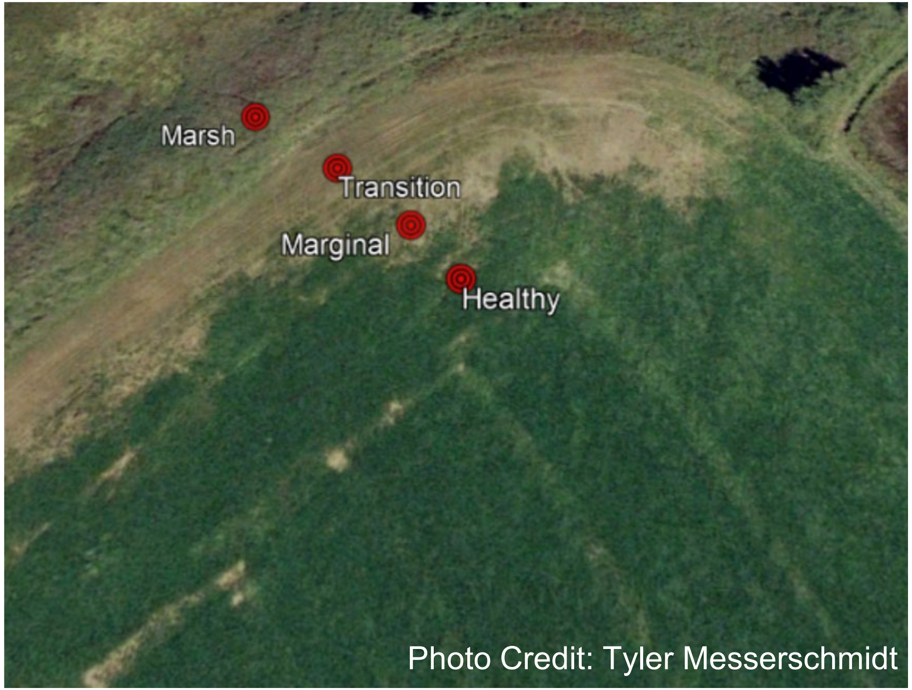


Marsh migration



Delaware Farm (CZN site)



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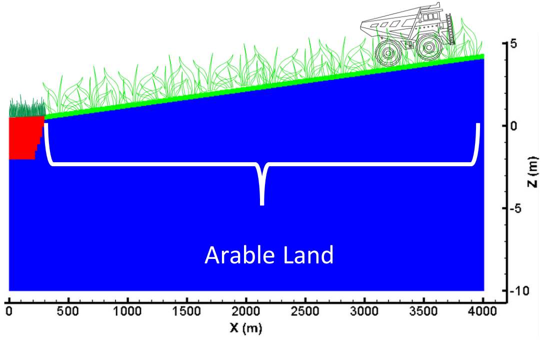

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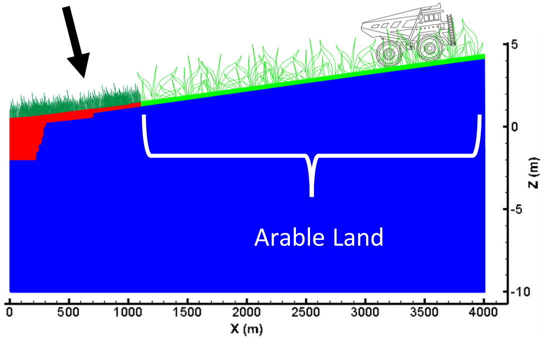
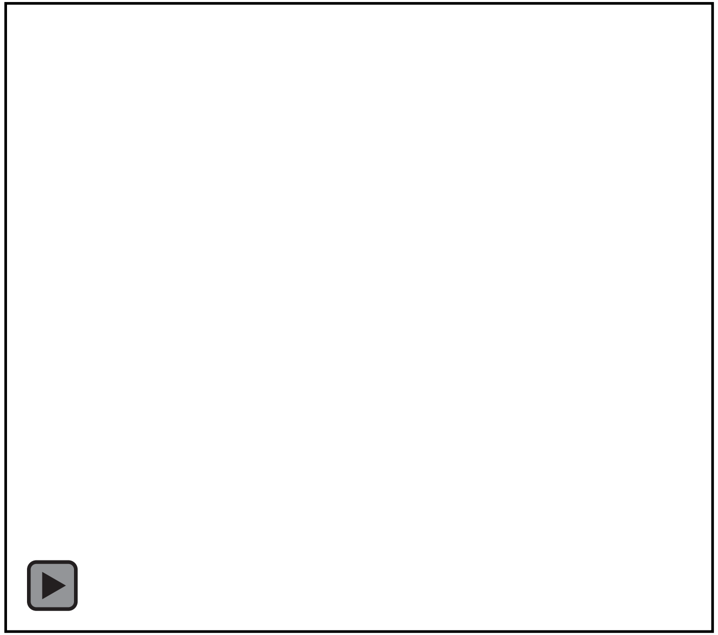


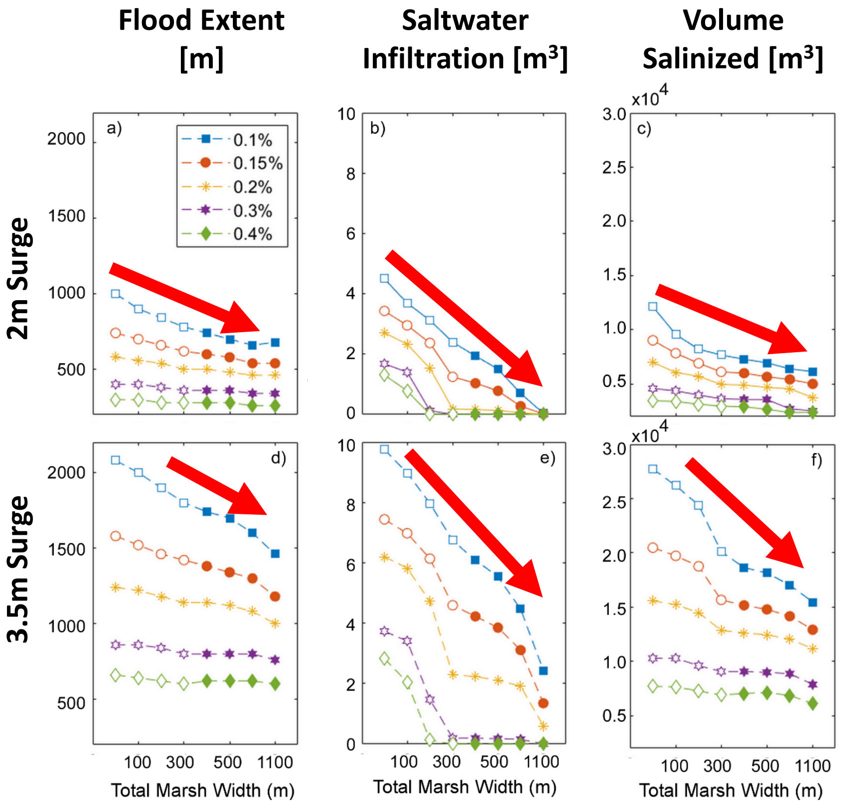
HydroGeoSphere

(Therrien et al. 2006)



Guimond et al, WRR, 2021

Marsh migration protects farmland from surge flooding, saltwater infiltration, and aquifer salinization

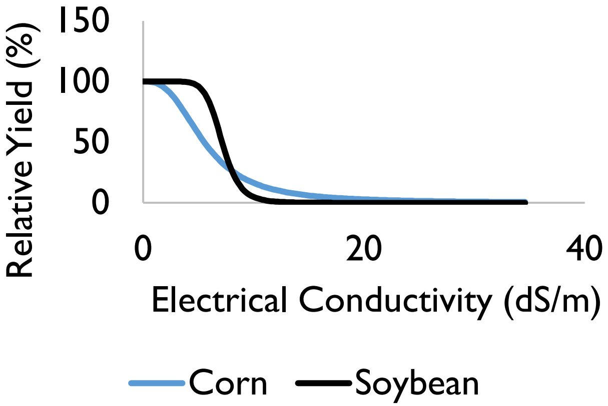


Decrease in the landward flood extent with an <u>increase in marsh width</u> and <u>terrestrial slope</u>.

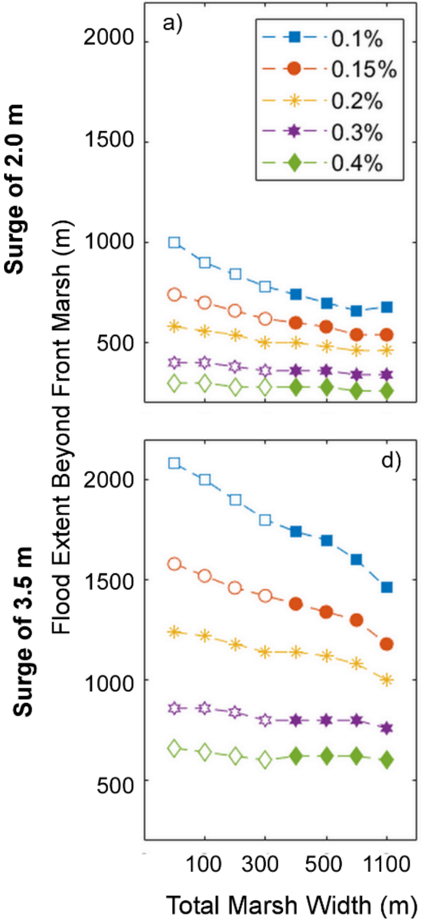
Increase in flood extent with <u>an increase in surge height</u>.

Marsh migration protects farmland from surge flooding, saltwater infiltration, and aquifer salinization *and increases ecosystem services*

Marsh migration:
→ Protects farmland from surge flooding, saltwater infiltration, and aquifer salinization
→ Protects irrigation water from salinization
→ Protects crop yields



Steppuhn et al., 2005

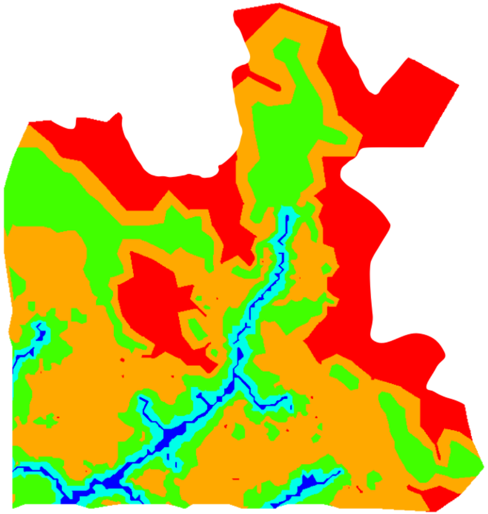


Cost-Benefit analysis:
→ Marsh migration can benefit farms while increasing ecosystem services
→ Policy implications?

Guimond et al, WRR, 2021

Insights: Feedback between sea level, marsh zonations, hydrologic setting, and carbon fluxes

Establishing linkages between physical, chemical, and ecological ecosystem components → Use of mechanistic models to forecast future change

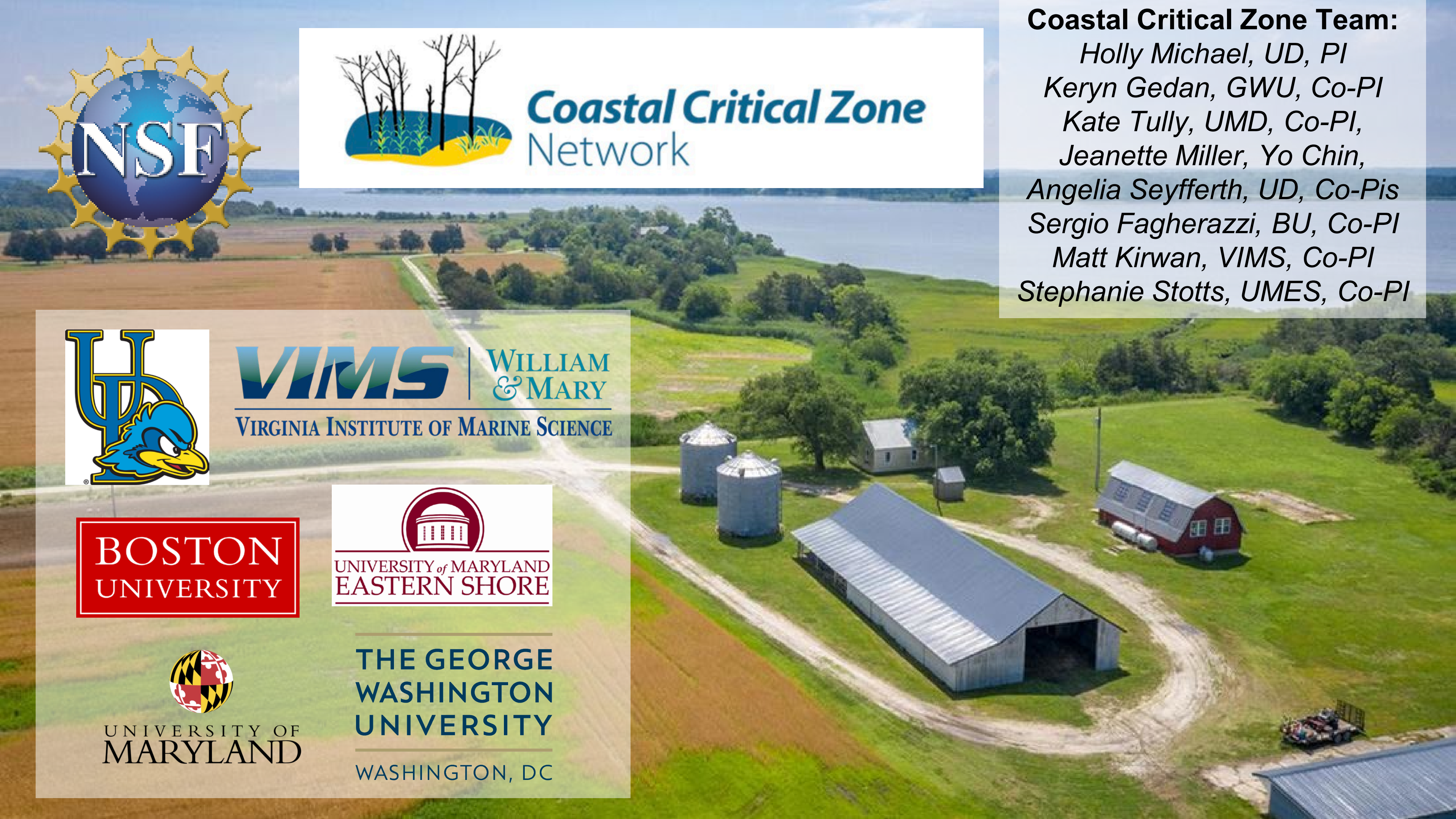


Coastal wetland zonation patterns are dynamically linked to relative sea-level rise and terrestrial (upland) groundwater table, highlighting the importance of regional hydrology and geology in the fate of coastal wetlands (and the need to model the whole system)

Marsh migration into agricultural land could add protection from salinization and provide societal benefits

→ ***What are the implications of marsh migration on nutrient fluxes and ecosystems?***

→ ***What do we need to be able to model it?***



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Kate Tully, UMD, Co-PI,
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Coastal Critical Zone Network

NSF

VIMS | William & Mary
Virginia Institute of Marine Science

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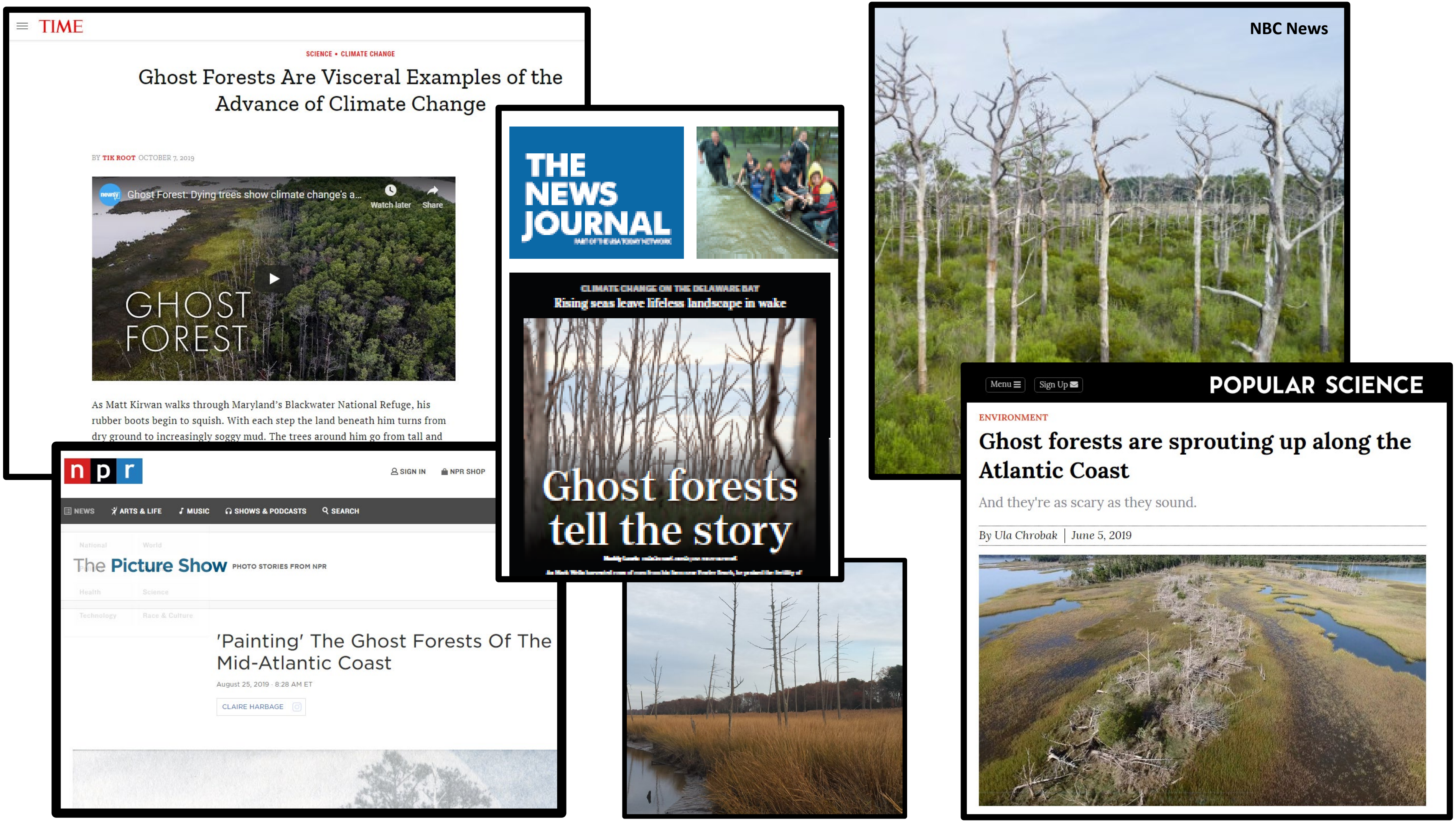
TIME
SCIENCE • CLIMATE CHANGE
Ghost Forests Are Visceral Examples of the Advance of Climate Change
BY TIK ROOT OCTOBER 7, 2019
Ghost Forest: Dying trees show climate change's a...
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GHOST FOREST
As Matt Kirwan walks through Maryland's Blackwater National Refuge, his rubber boots begin to squish. With each step the land beneath him turns from dry ground to increasingly soggy mud. The trees around him go from tall and
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'Painting' The Ghost Forests Of The Mid-Atlantic Coast
August 25, 2019 · 8:28 AM ET
CLAIRE HARBAGE
THE NEWS JOURNAL
CLIMATE CHANGE ON THE DELAWARE BAY
Rising seas leave lifeless landscape in wake
Ghost forests tell the story
NBC News
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Ghost forests are sprouting up along the Atlantic Coast
And they're as scary as they sound.
By Ula Chrobak | June 5, 2019

≡ BAY JOURNAL

Saltwater intrusion laying waste to Delmarva farms as sea level rises

"This is how it starts." Bob Fitzgerald looks over what started as a "little wet spot" that has swollen in just
2-acre void.

Dave Harp

Turning Salt-Damaged Fields into Marshes Could Save Maryland Farmland—and The Chesapeake Bay

As sea levels rise, saltwater is entering farms near the bay, damaging crops and releasing legacy nutrients into already-polluted waterways.

BY VIRGINIA GEWIN
ENVIRONMENT, FARMING, Water
Posted on: February 20, 2019 | 1 Comment

The Washington Post

Democracy Dies in Darkness

National

Ruined crops, salty soil: How rising seas are poisoning North Carolina's farmland

East Carolina University graduate students Trevor Burns, left, and Tyler Palochak check ground
near Engelhard, N.C., in January. (Eamon Queeney/for The Washington Post)

By Sarah Kaplan
March 1

The Southern Maryland Chronicle

Flooding

https://ampagronomy.com/soil-salinity-management-the-aftermath-of-hurricanes/

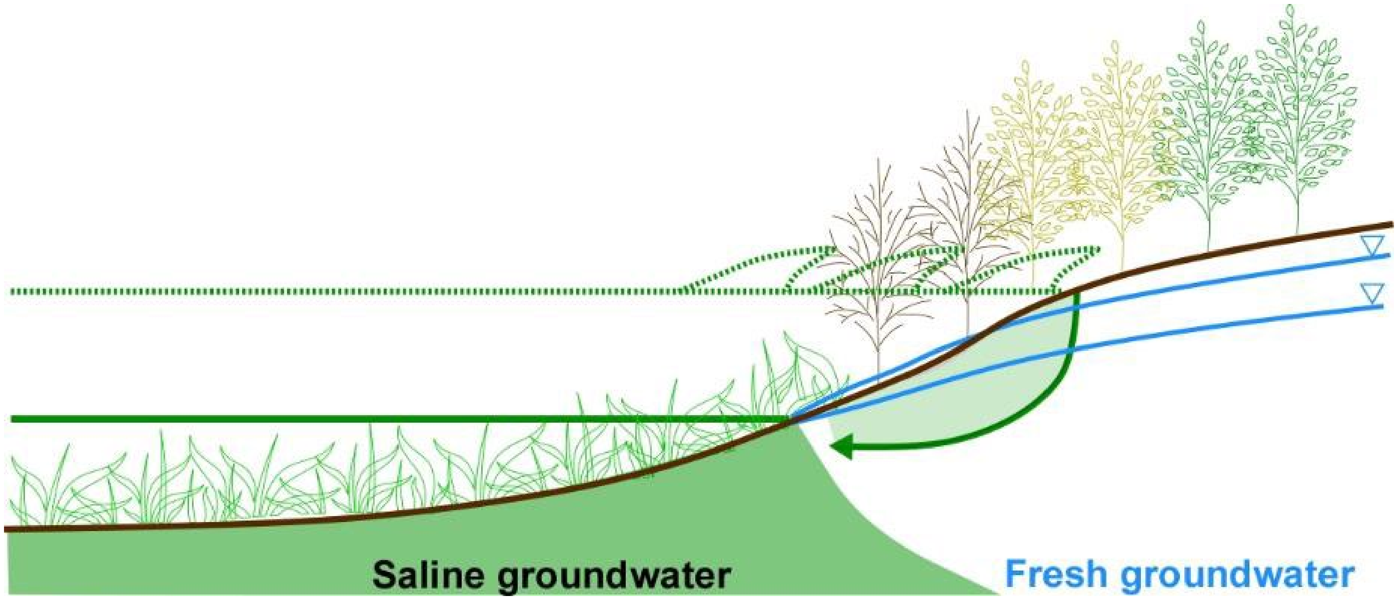
Effects of salt

https://www.climatehubs.usda.gov/index.php/hubs/southeast/topic/saltwater-intrusion-and-salinization-coastal-forests-and-farms

Concurrent changes in water and chemical cycling are altering the functioning of the coastal Critical Zone

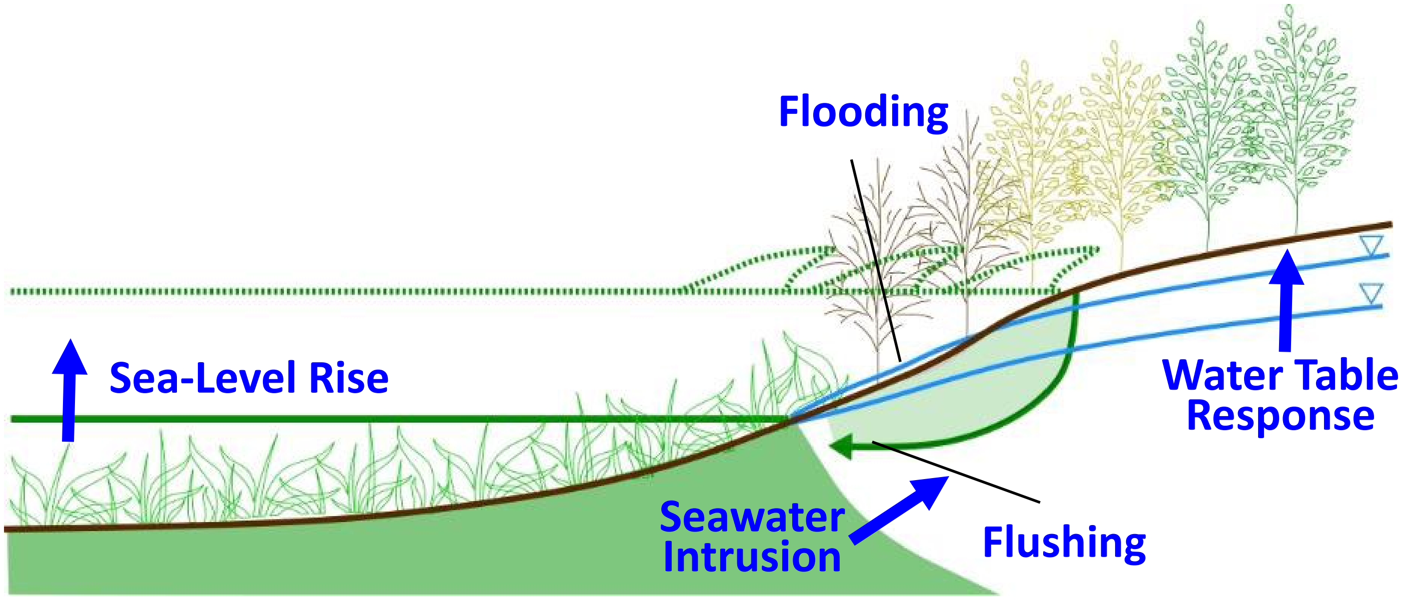
Our Thematic Cluster is quantifying the coupled processes and feedbacks that govern the HEGB transformations in the coastal CZ to understand how shifts in the transition zone will translate to changes in cycling, fluxes, and storage of critical elements at the land-sea margin.

What are the key drivers of these changes?

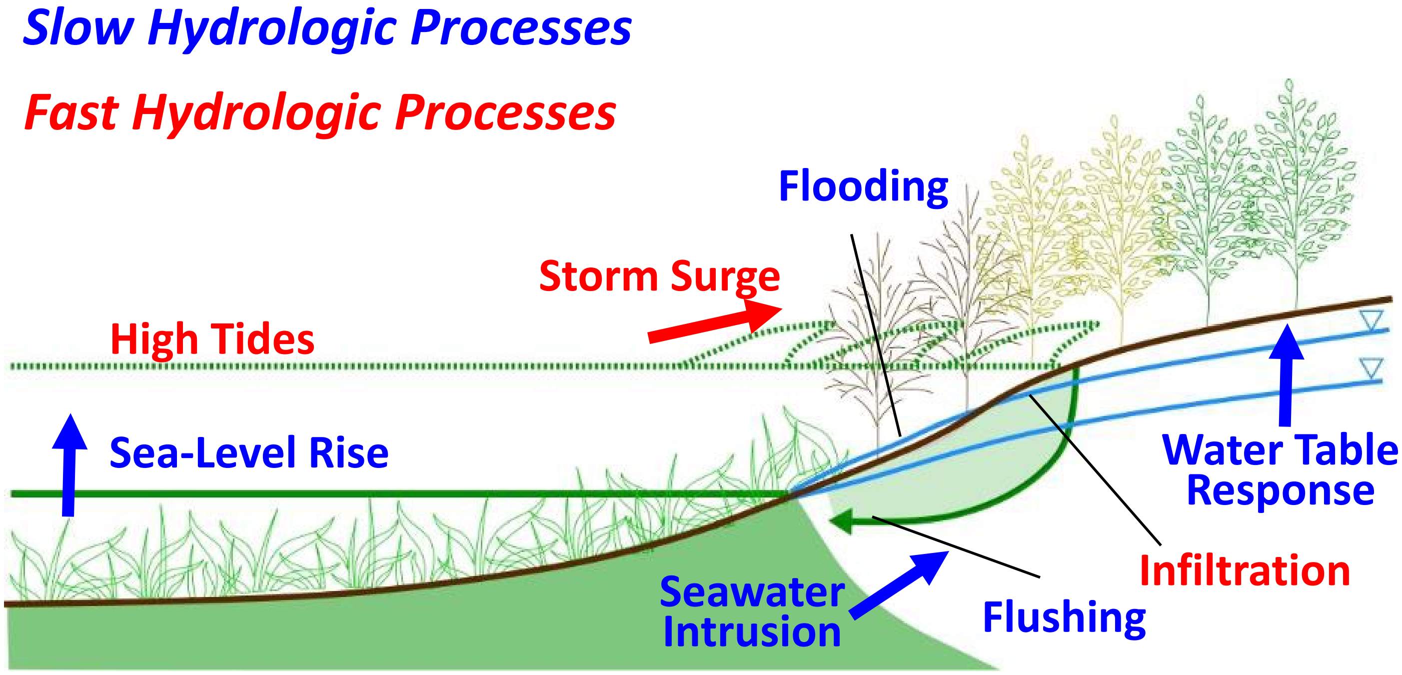


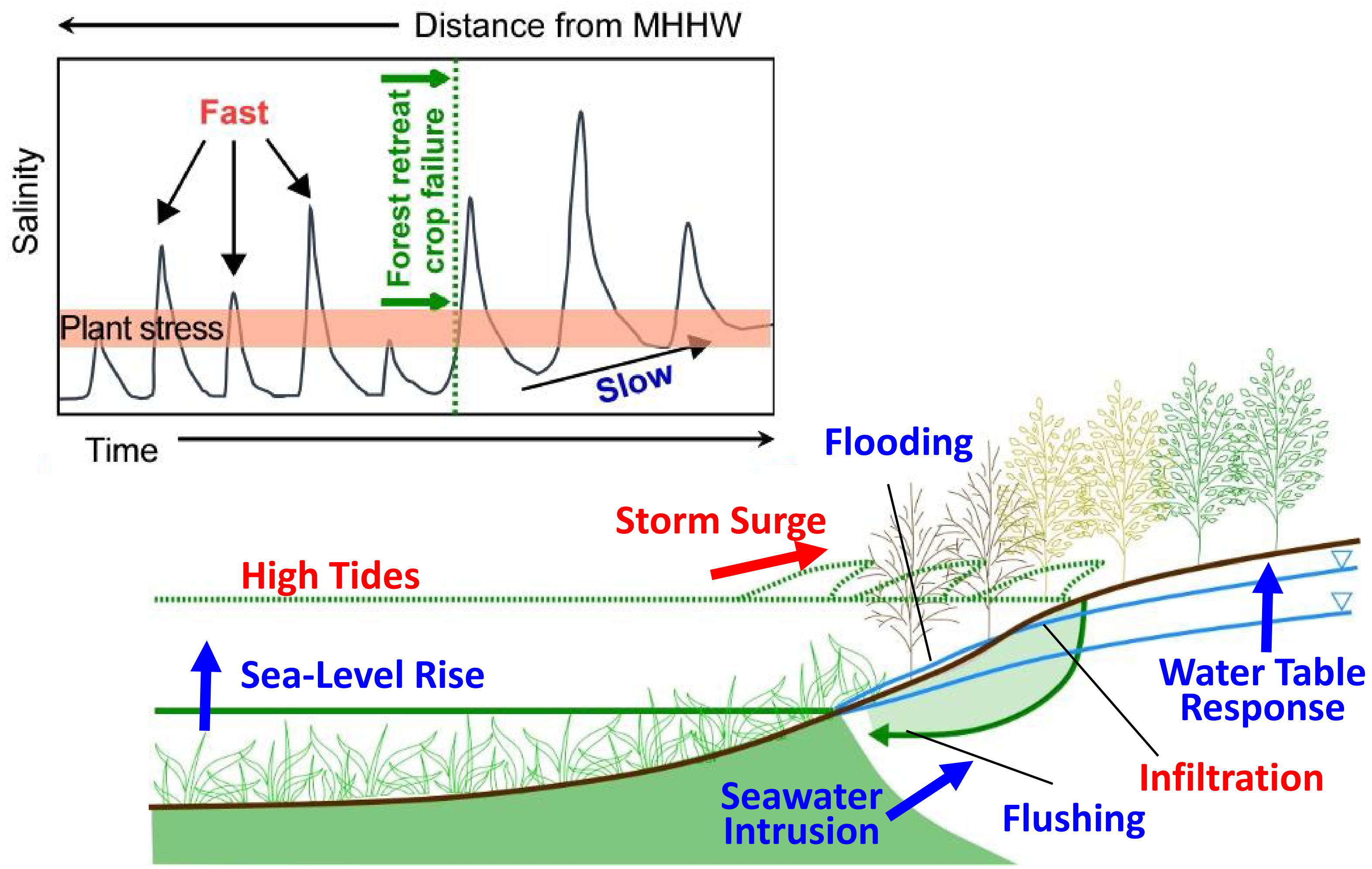
What are the key drivers of these changes?

Slow Hydrologic Processes

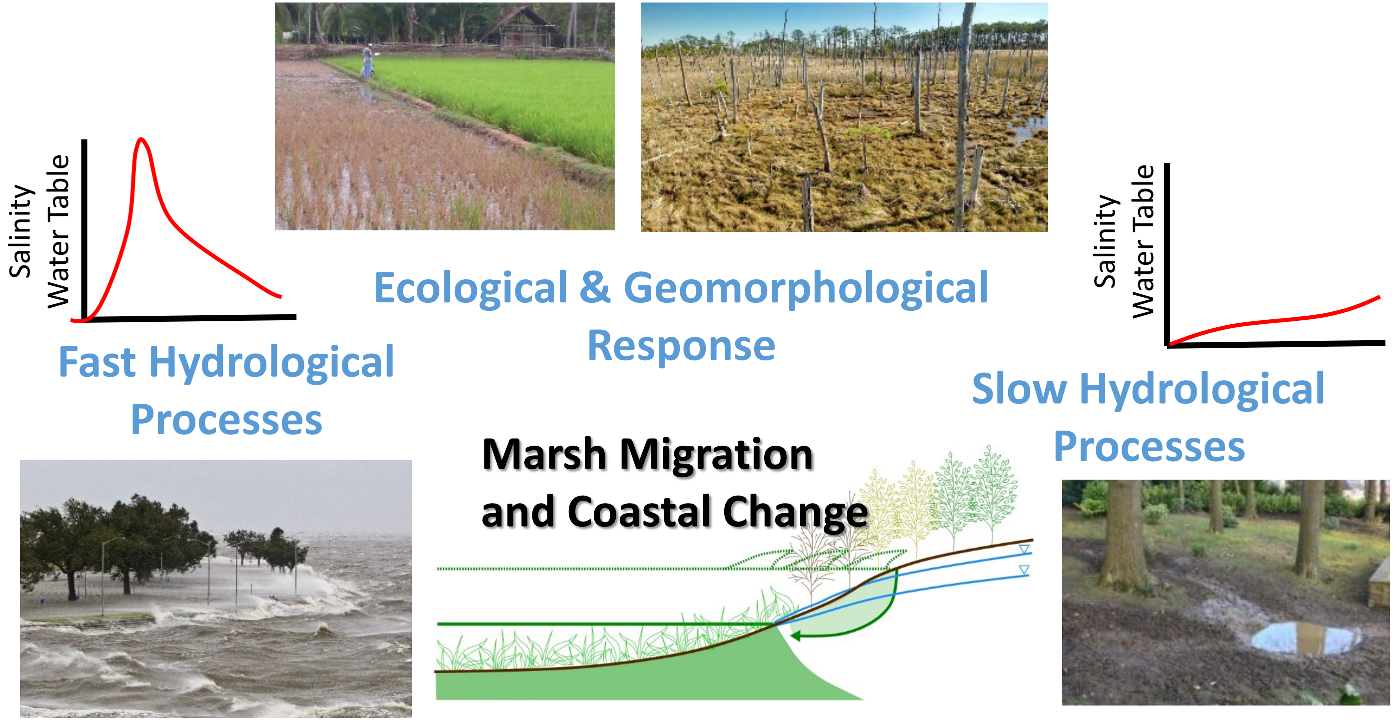


What are the key drivers of these changes?



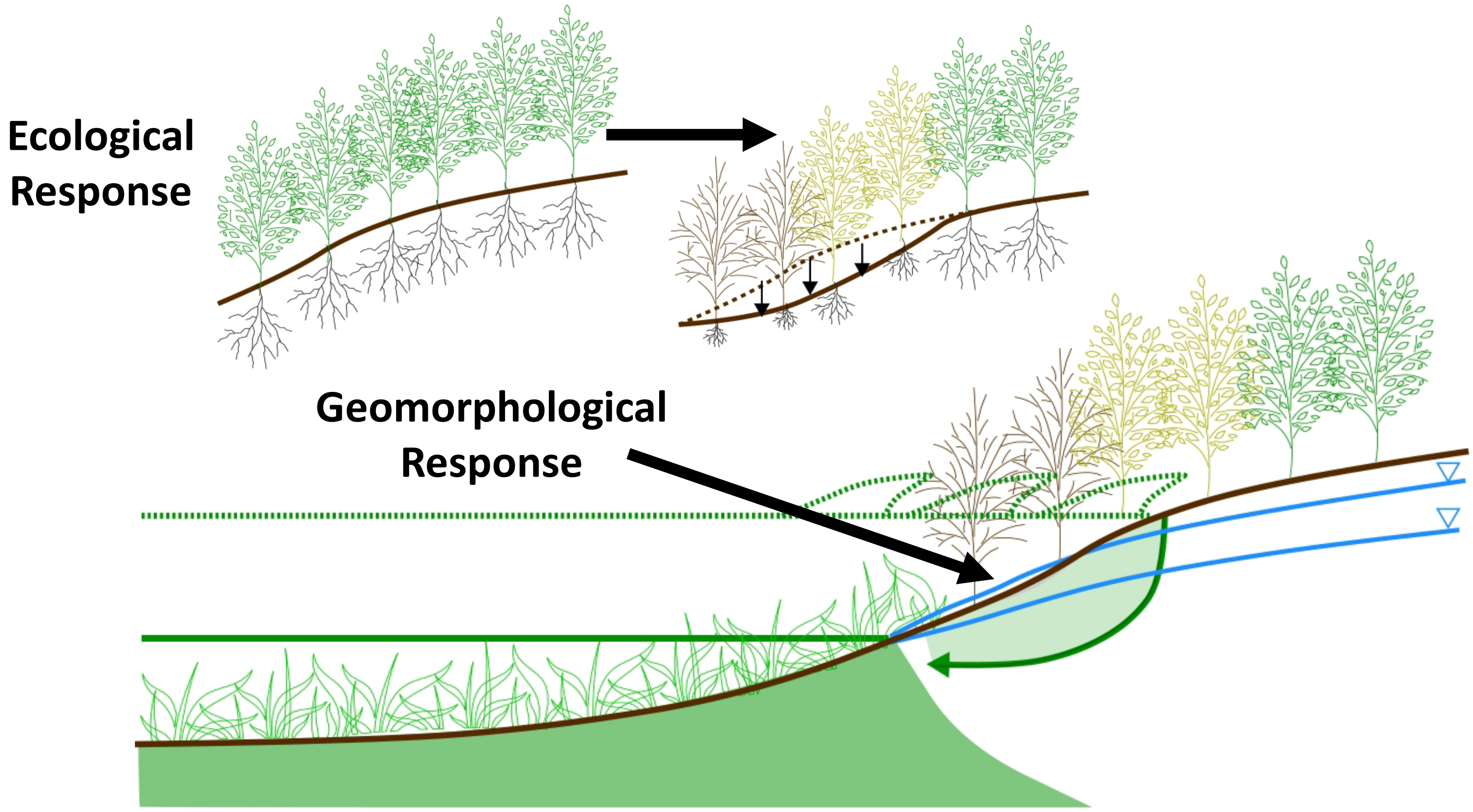


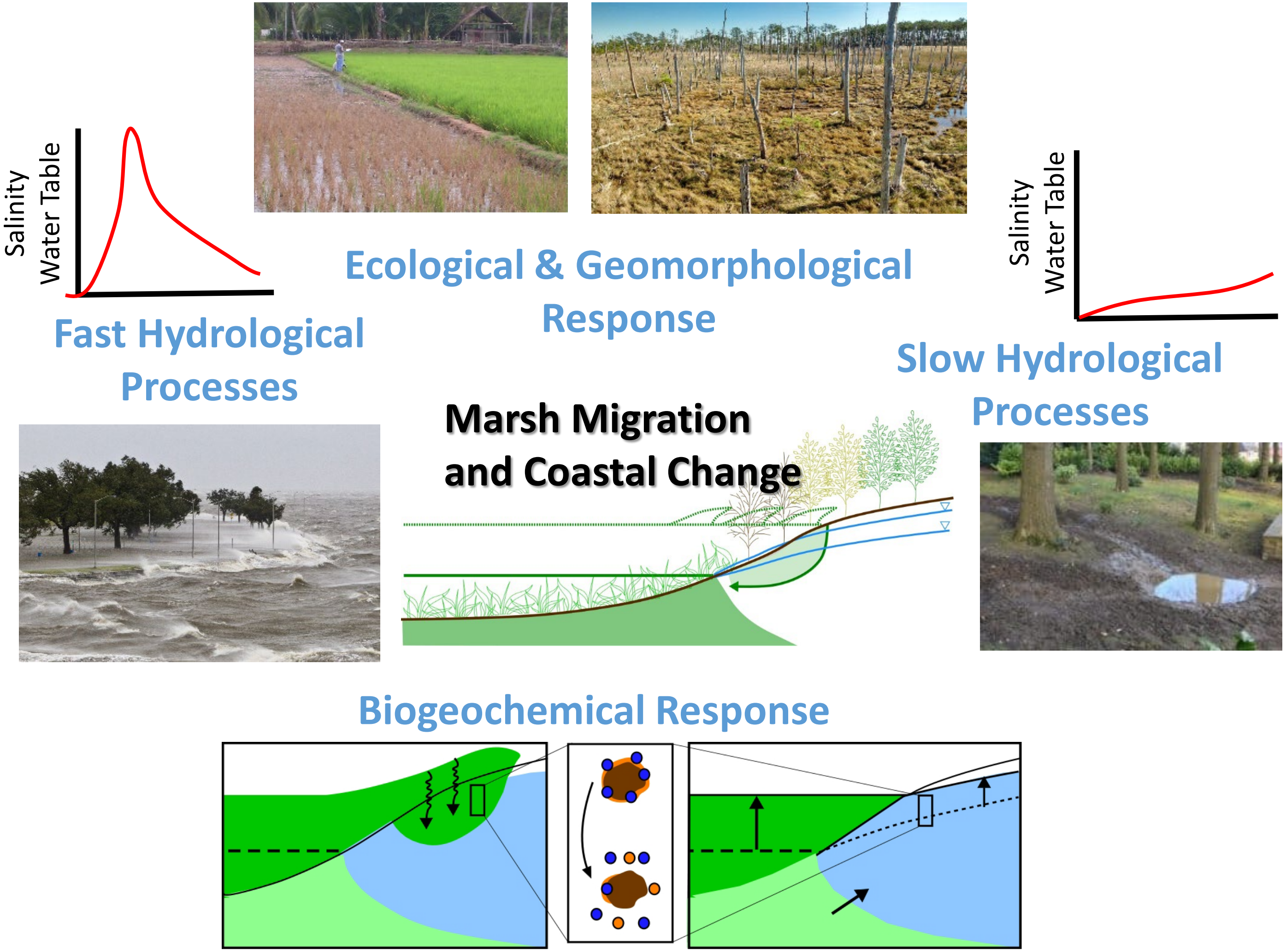
Distance from MHHW
Salinity
Fast
Forest retreat
crop failure
Plant stress
Slow
Time
Flooding
Storm Surge
High Tides
Sea-Level Rise
Water Table
Response
Infiltration
Seawater
Intrusion
Flushing



Salinity
Water Table
Fast Hydrological Processes
Ecological & Geomorphological Response
Salinity
Water Table
Slow Hydrological Processes
Marsh Migration and Coastal Change

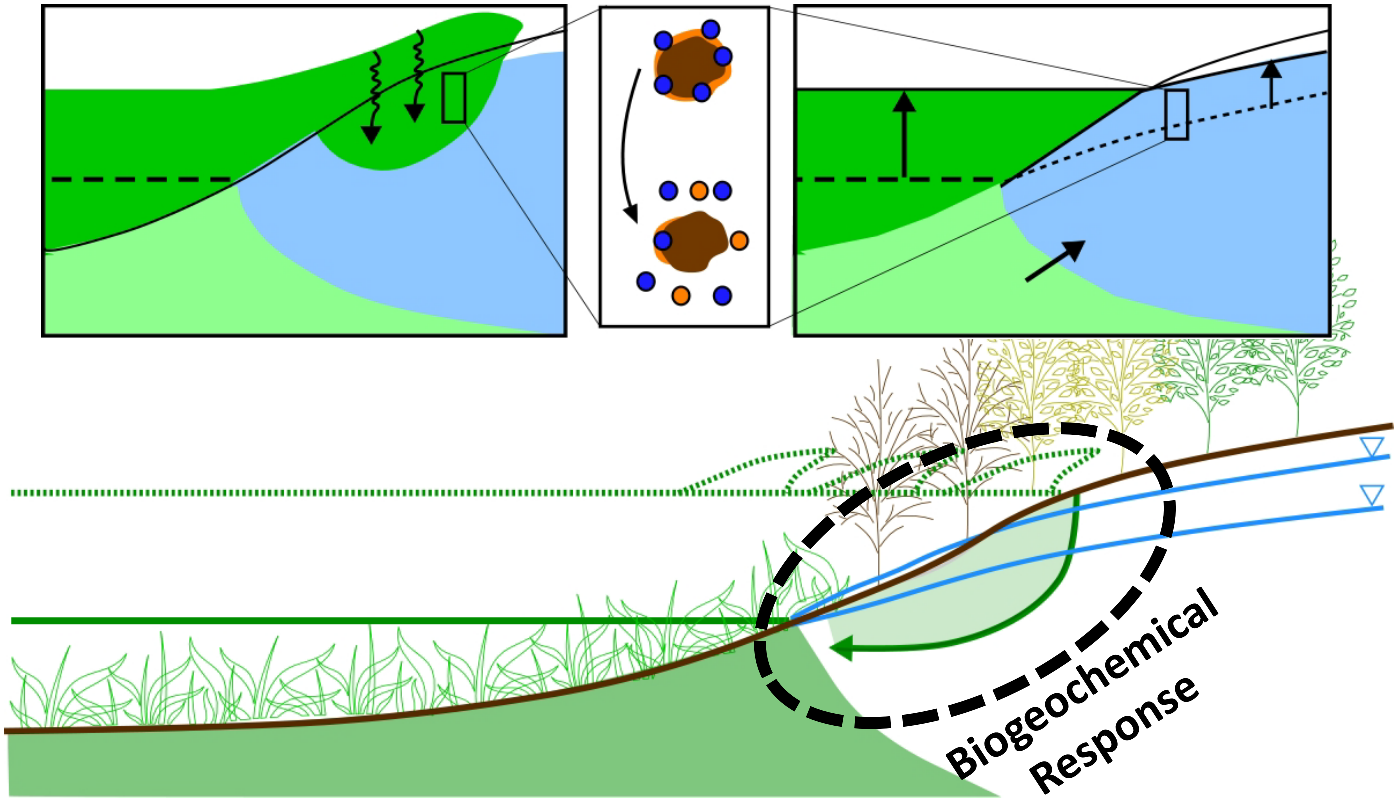
Feedbacks between hydrology, ecological response, and geomorphological change



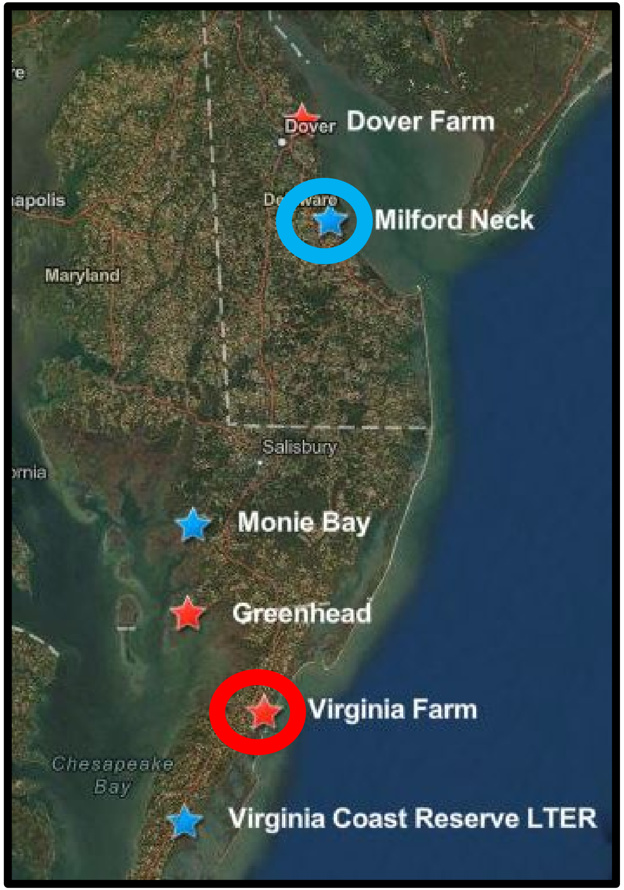


Salinity
Water Table
Fast Hydrological Processes
Ecological & Geomorphological Response
Salinity
Water Table
Slow Hydrological Processes
Marsh Migration and Coastal Change
Biogeochemical Response

Impacts of marsh migration on land-sea chemical fluxes



Our Network of Sites



Three study locations in Delmarva:

- Virginia Coast
- Delaware Bay Coast
- Chesapeake Coast

Each location has two sites (total of six):

- Marsh-forest transition
- Marsh -agriculture transition

VA Farm

DE Forest

Measurements, Instrumentation, & Analysis

Hydrology

- Surface water & groundwater levels, salinity
- Streamflow
- Soil moisture
- Meteorological data
- Slug tests
- Cameras (flooding)

Ecology

- Sap flux sensors
- Band-dendrometers (tree diameter, μm scale)
- Photosynthesis, water use efficiency
- Plant canopy analyzer
- Tree-ring chronologies
- Vegetation surveys (plot monitoring, cameras, and drones)

Biogeochemistry

- In-situ multi-level redox potential
- Groundwater samplers
- Isco surface water samplers
- DOC, TDN, P, NO_3, NH_4, DON, Cl^-, SO_4^{2-}, Fe, Mn, pH, DO…
- Voltammetry, HPSEC, UV absorbance, EEM, FT-ICR-MS, spectroscopy, NEXAFS…
- Laboratory Manipulations

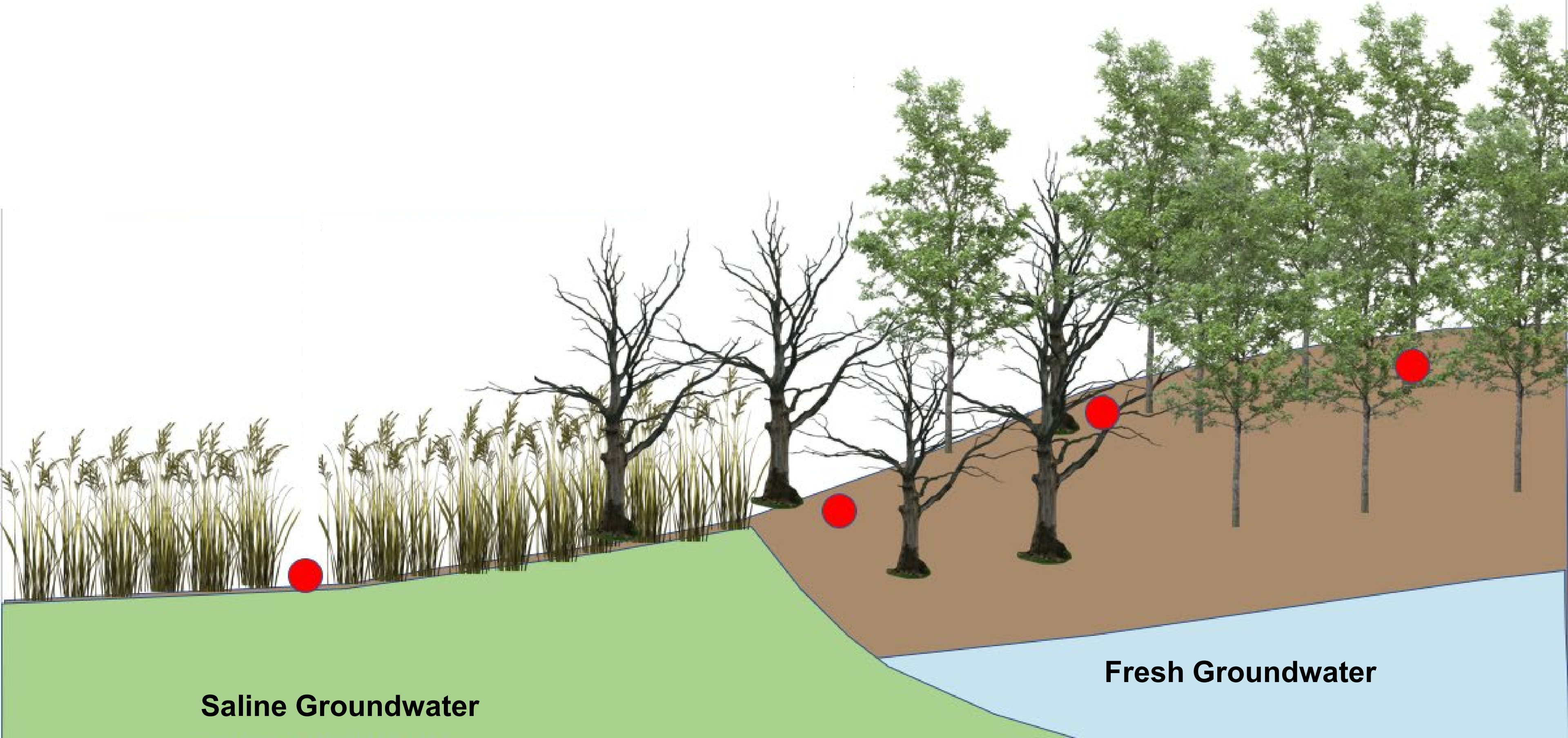
Geomorphology

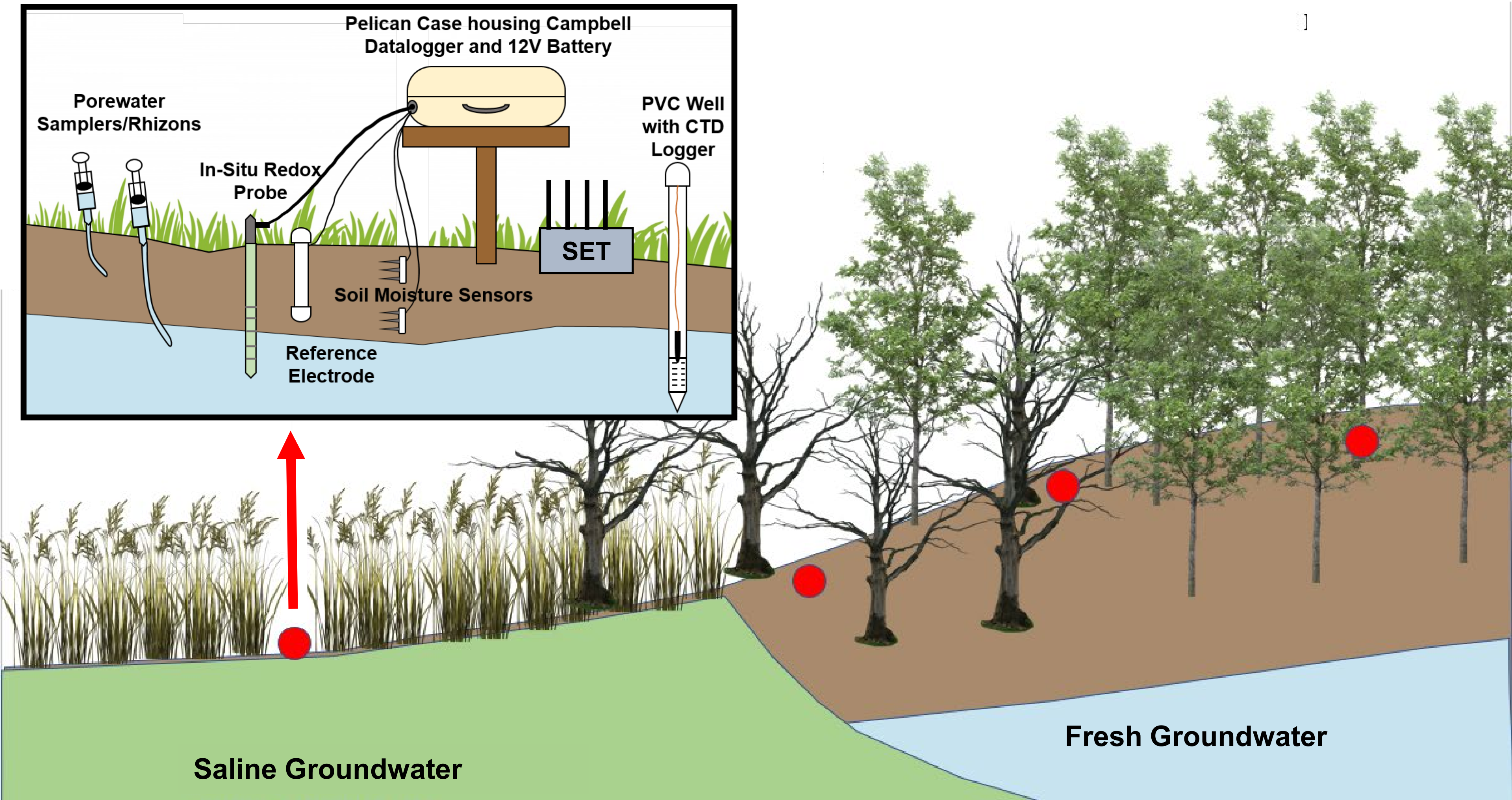
- Laser level surveys
- RSET's
- RTK GPS
- Marker horizons

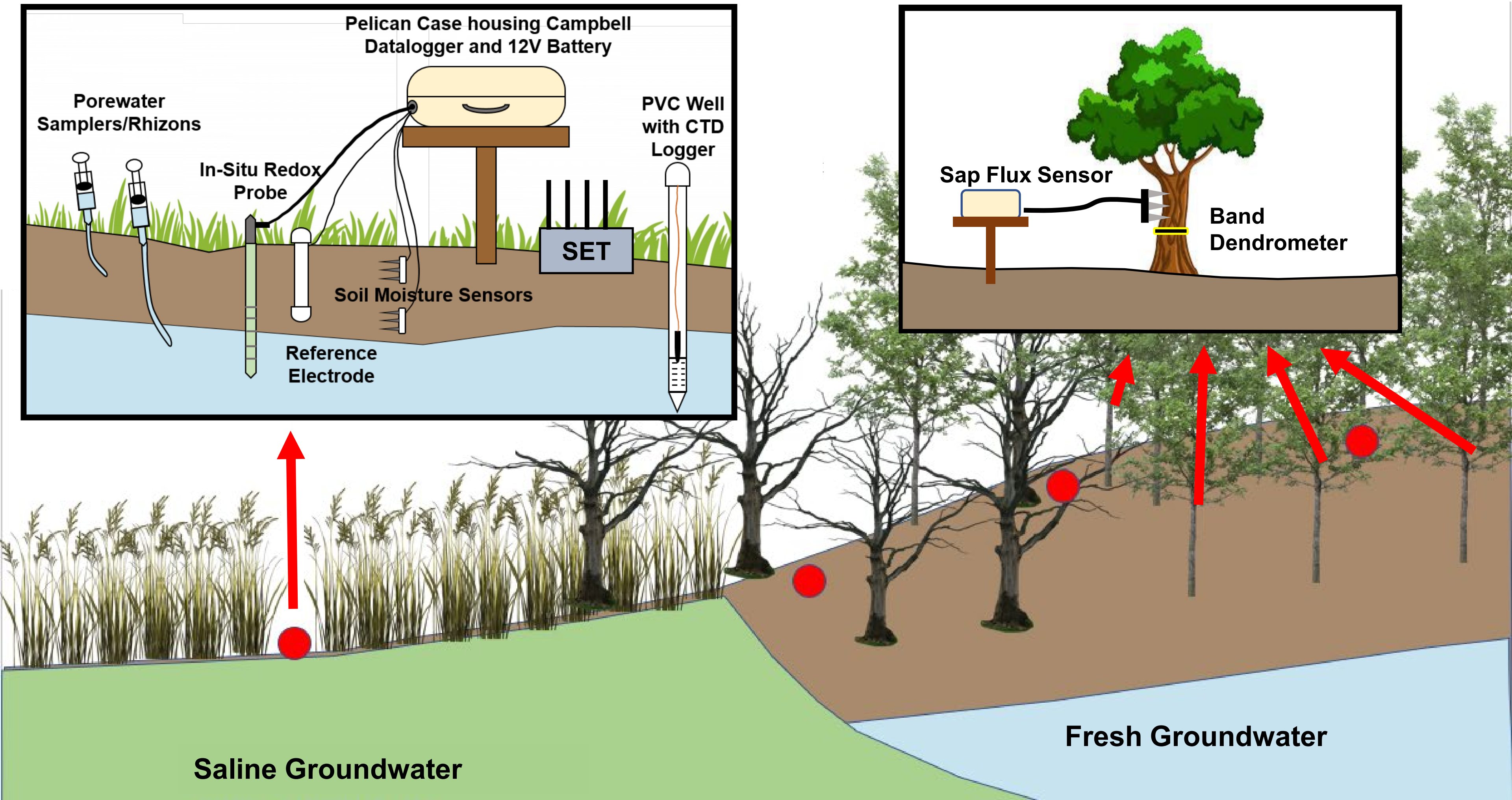
Modeling

- 3D Hydrogeosphere mechanistic models of flooding and salinization over short and long time periods – site-specific & general
- Coupling of marsh geomorphology model to hydrodynamic model – mechanistic feedbacks among vegetation, hydrology, and geomorphology

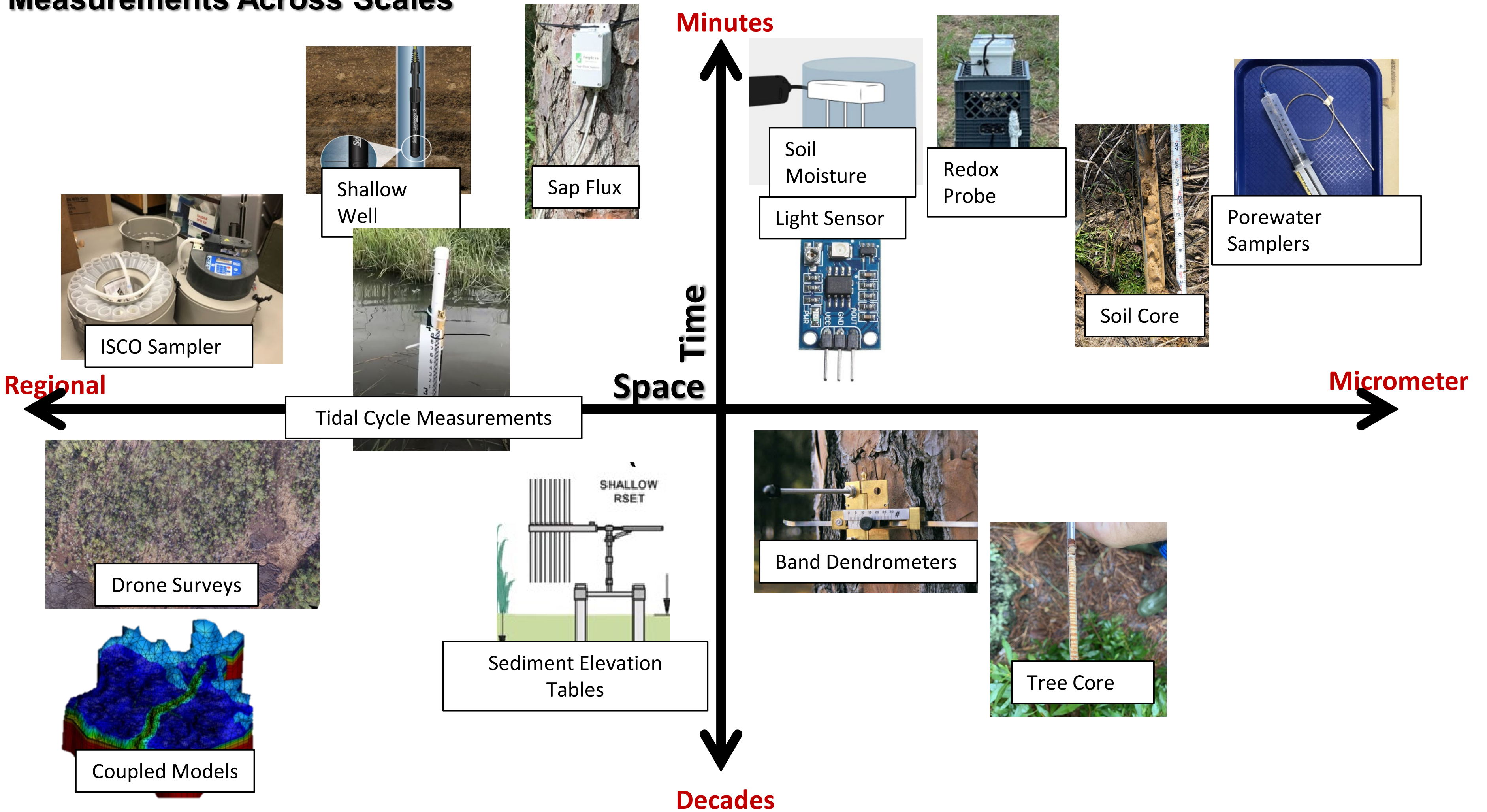
Measurement Transects



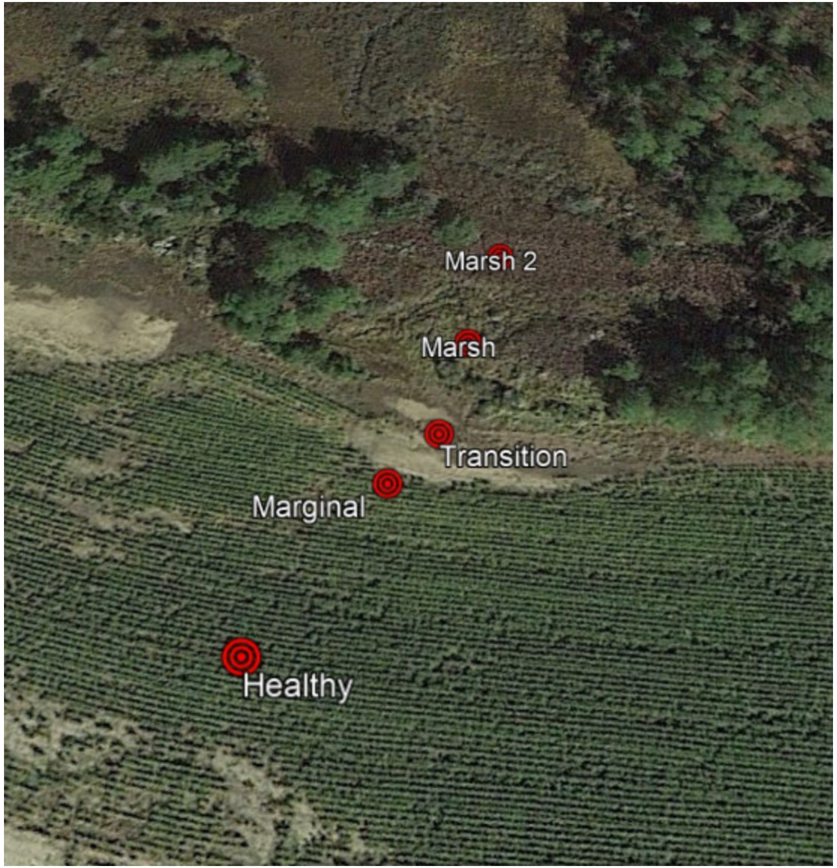

Pelican Case housing Campbell
Datalogger and 12V Battery
Porewater
Samplers/Rhizons
PVC Well
with CTD
Logger
In-Situ Redox
Probe
SET
Soil Moisture Sensors
Reference
Electrode
Fresh Groundwater
Saline Groundwater


Pelican Case housing Campbell Datalogger and 12V Battery
Porewater Samplers/Rhizons
In-Situ Redox Probe
PVC Well with CTD Logger
SET
Soil Moisture Sensors
Reference Electrode
Sap Flux Sensor
Band Dendrometer
Fresh Groundwater
Saline Groundwater

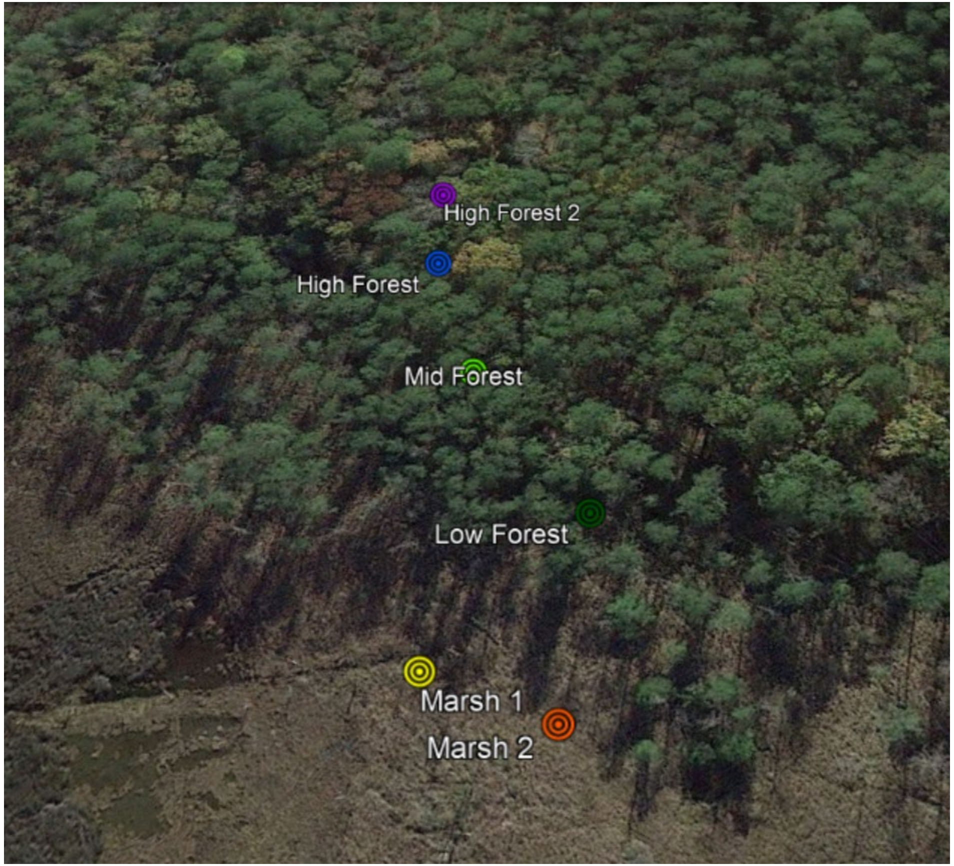
Measurements Across Scales



Maryland Agriculture



Maryland Forest



Hydrology

Michael and Fagherazzi groups

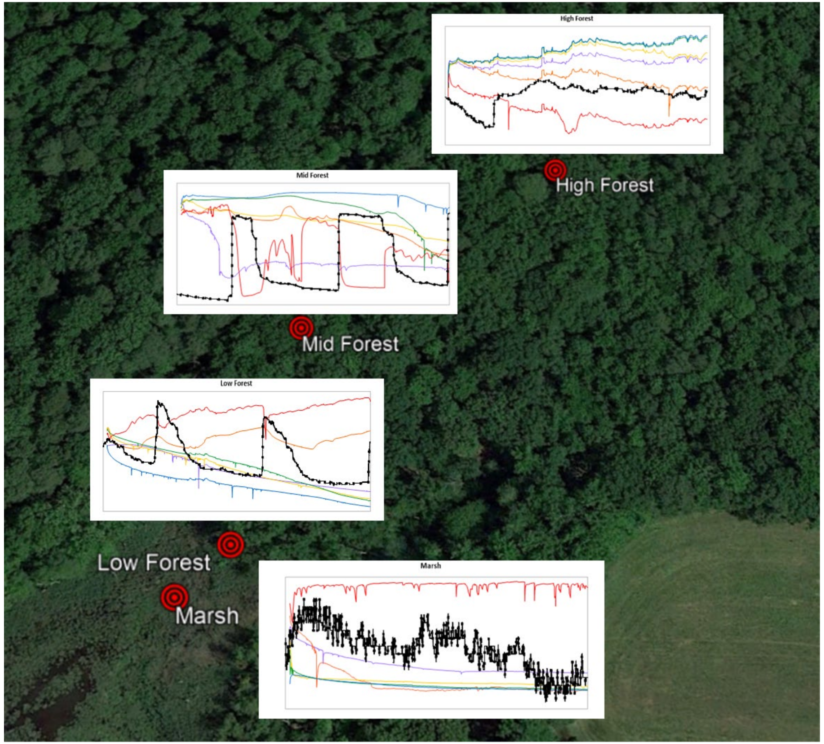
Characterize slow and fast hydrological processes and link to salinization and water table depths

Equipment	Number of Sensors	Measurement	Daily Measurements
Soil Moisture Sensors	52	Soil Temperature	4,992
	52	Soil Moisture	4,992
	52	Soil Salinity	4,992
Shallow Wells	38	Water Temperature	3,648
	38	Water Level	3,648
	38	Water Salinity	3,648
Redox Probes	96	Redox Potential	9,216

Total Daily Hydrologic Measurements Across All Sites: 35,136

→ *Large-scale data analysis*

→ *Comparisons across sites, land use, and location on the land-sea gradient*

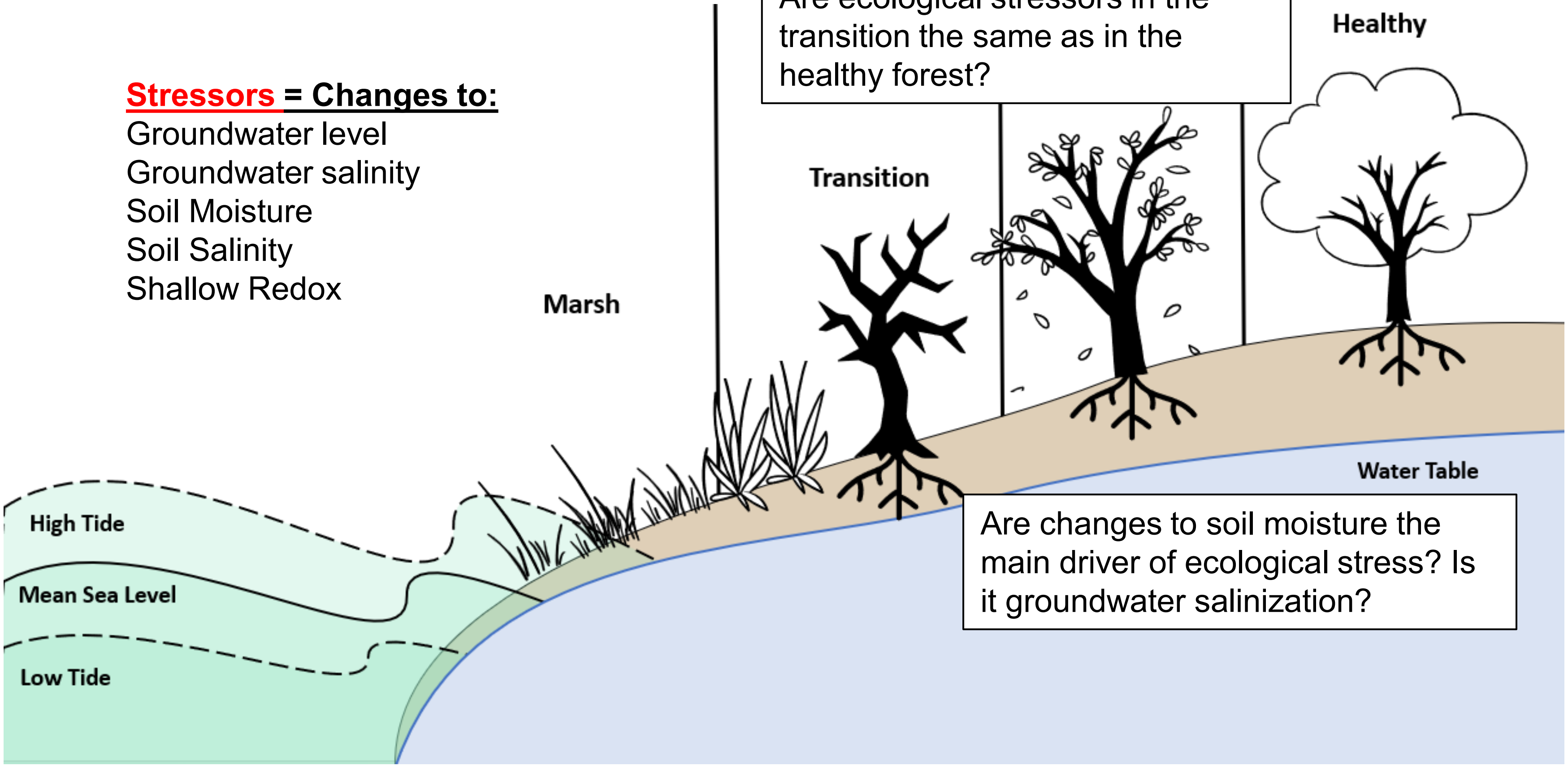


- Nordio, Frederiks, Hingst, Carr, Gedan, Michael, Kirwan, Fagherazzi, *Geophysical Research Letters*, 2022
- Nordio and Fagherazzi, *Journal of Hydrology*, 2022

How are stressors evolving over time? Do they vary across a transect? Across the sites?

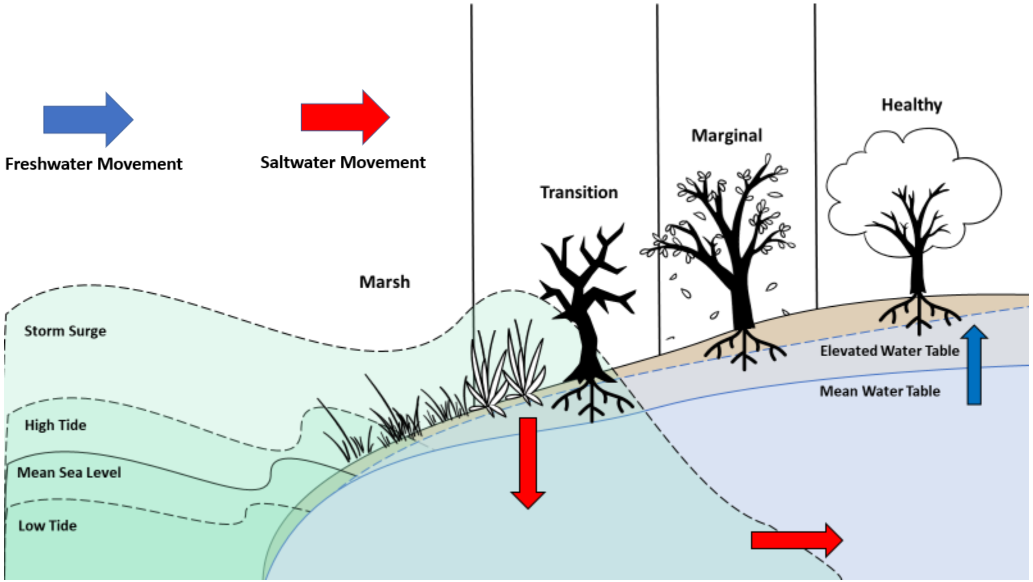
Stressors = Changes to:

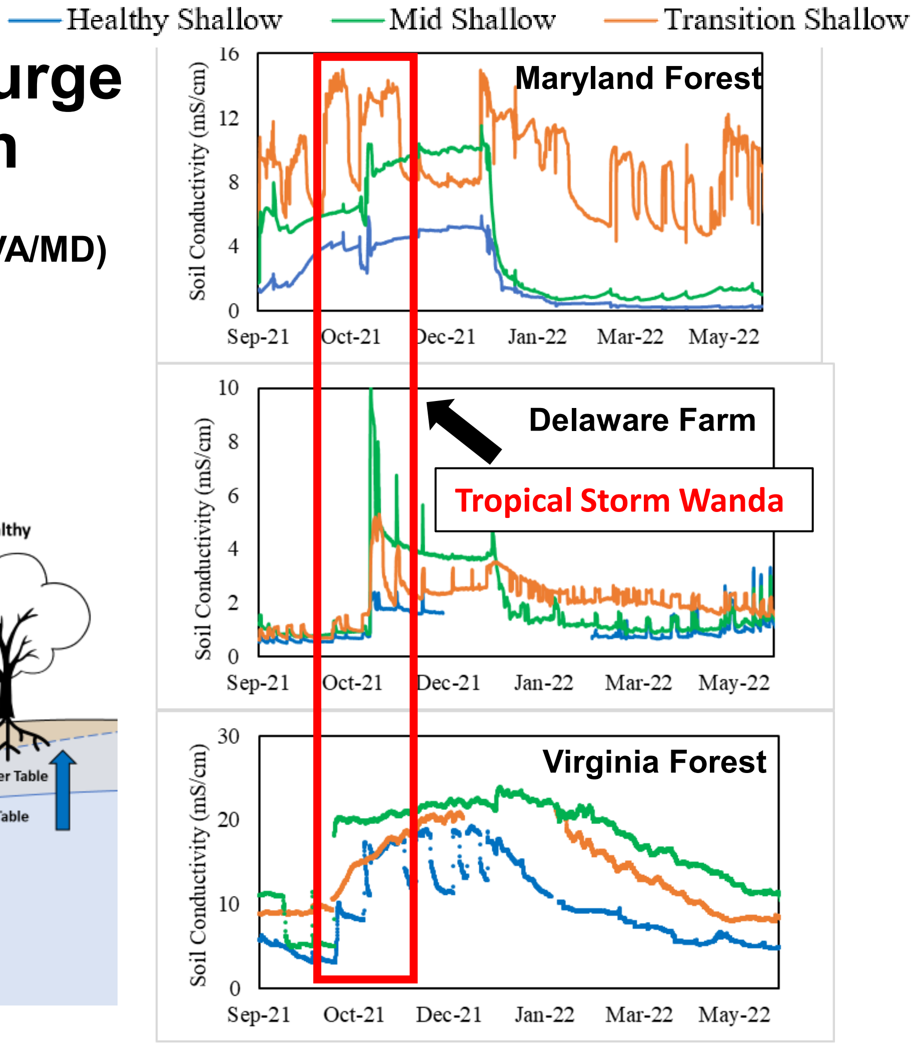
Groundwater level
Groundwater salinity
Soil Moisture
Soil Salinity
Shallow Redox



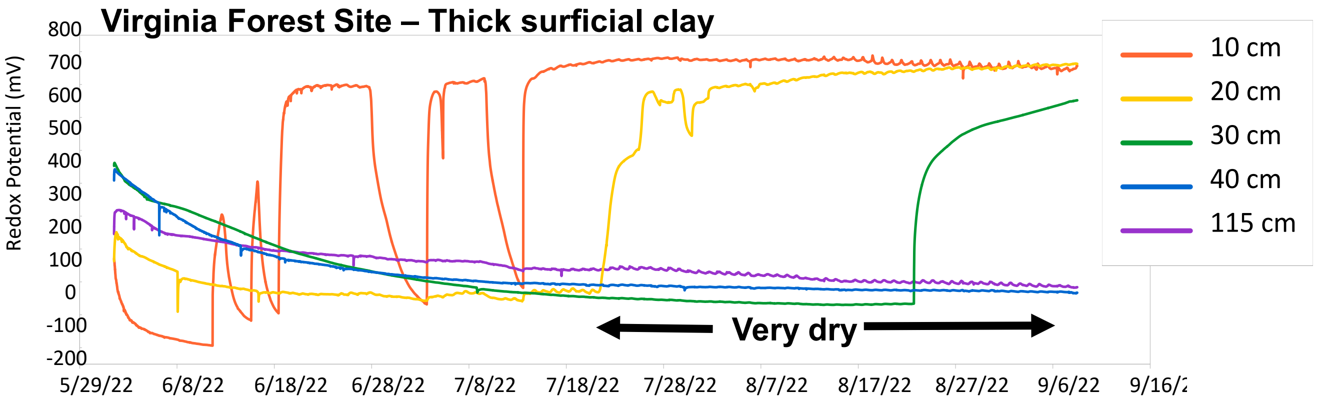
Local characteristics control surge salinization extent and duration

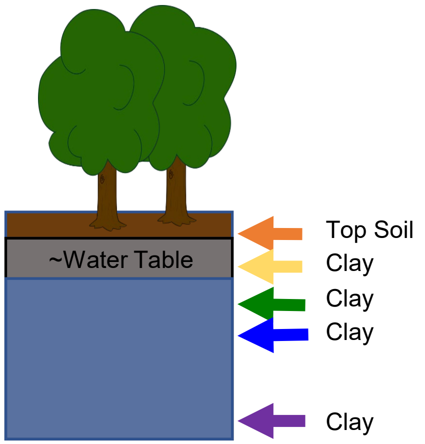
Low Elevation= Greater extent of surge up transect (VA/MD)
High Channel Salinity= Higher salinity infiltrating subsurface (VA/MD)
Low Permeability= Longer recovery time (VA)

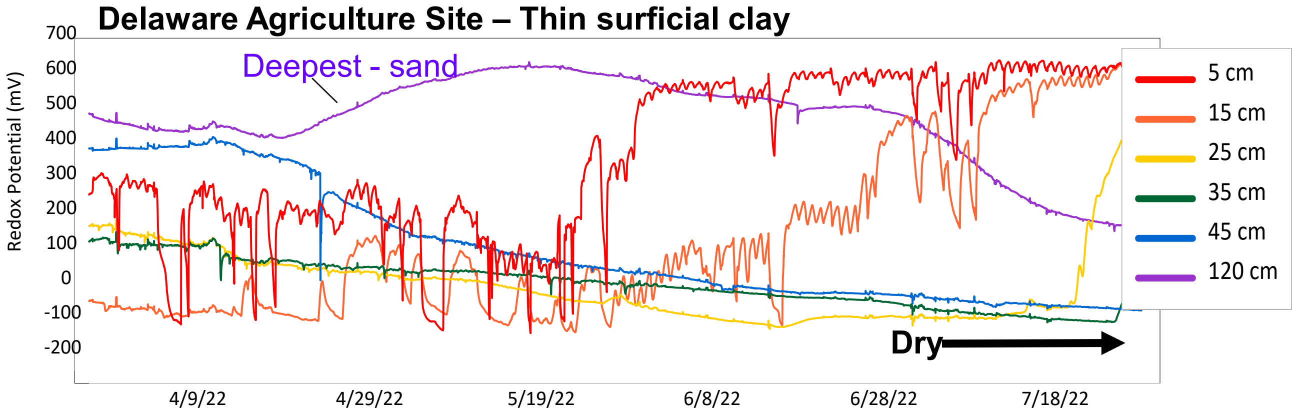


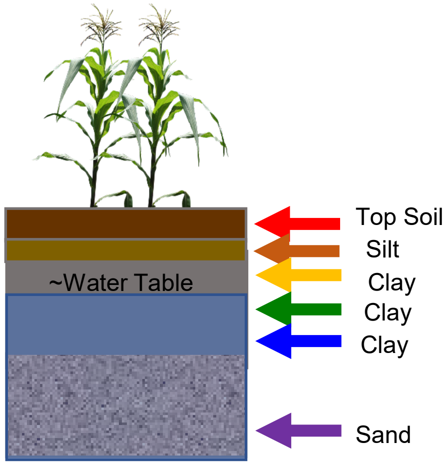


Permeability controls soil moisture which controls redox potential

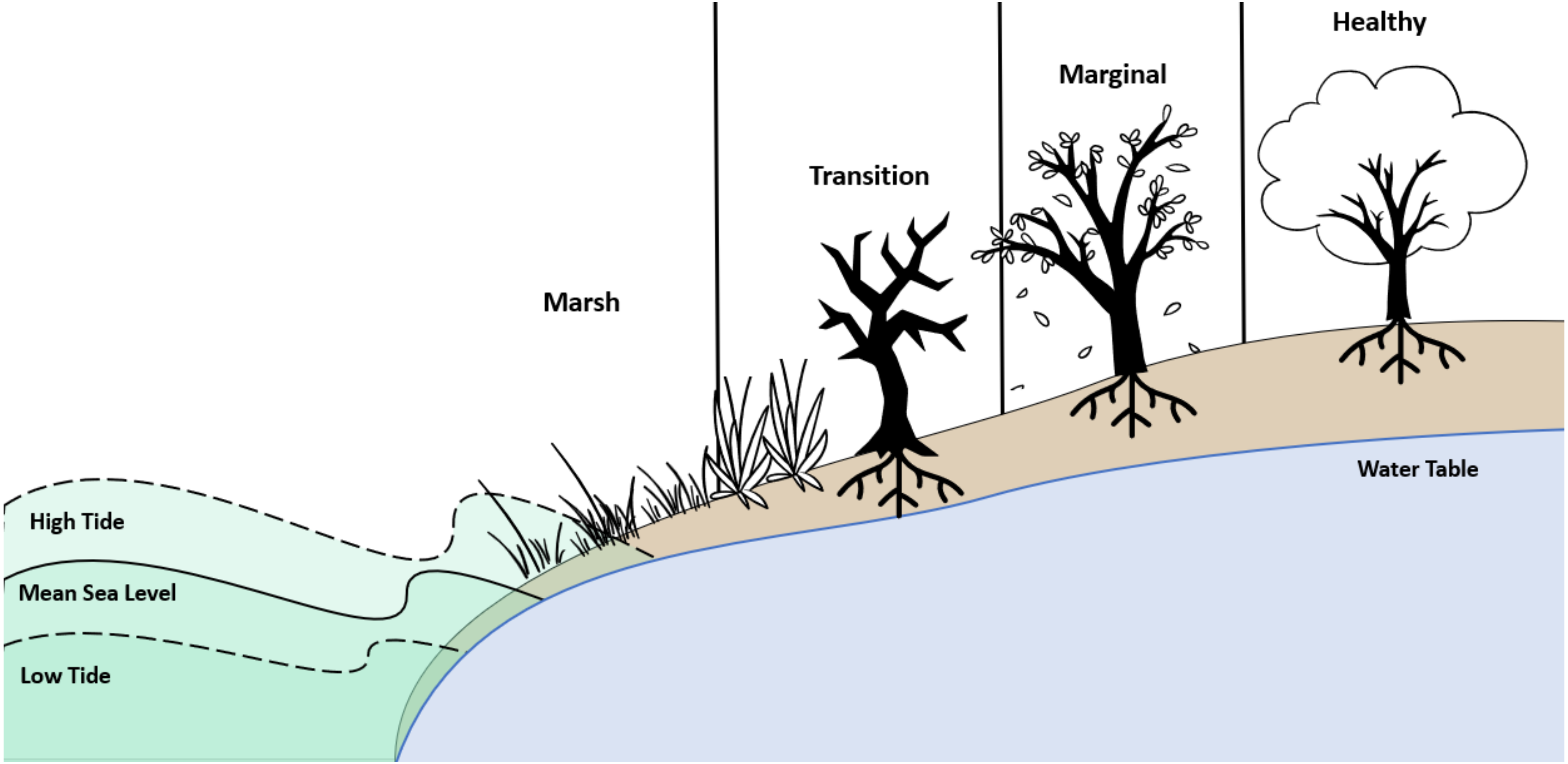






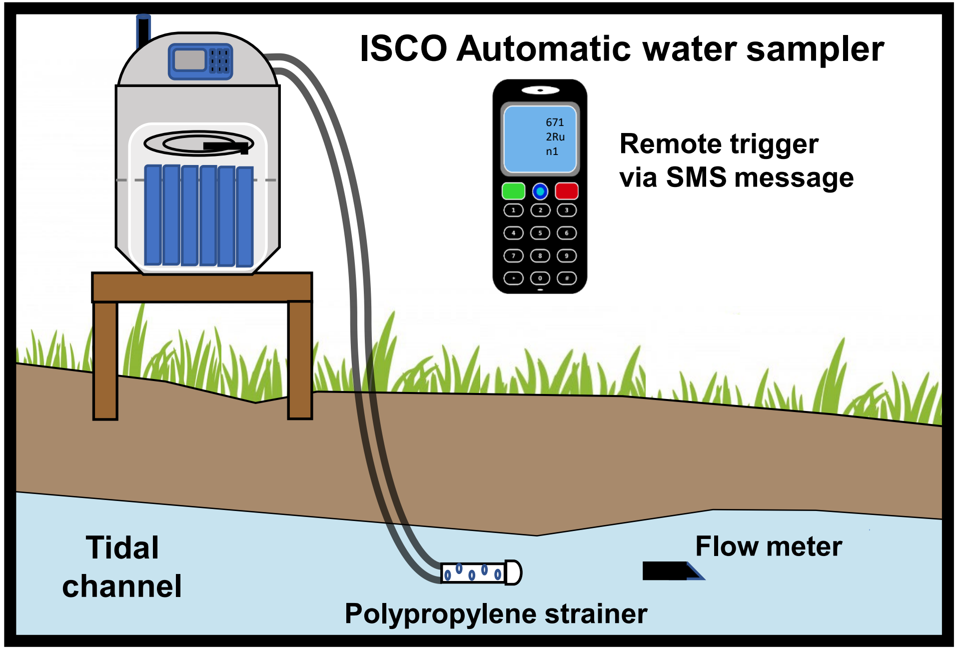


How do land-sea solute fluxes vary across sites and hydrologic events?



Solute Flux Measurements

Led by Tully & Chin Groups

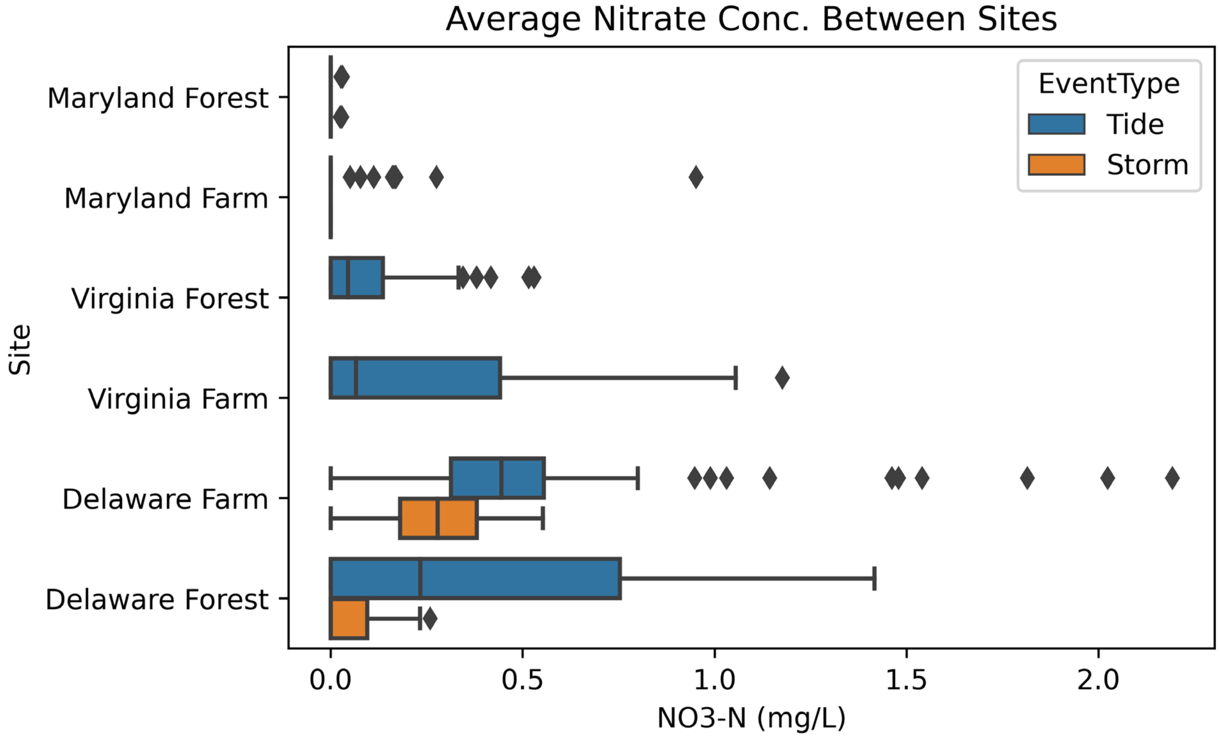


Measuring:

- Water Flux
- DOC, DIN, DON, SRP, TP, Cl, SO_4
- Fluorescence and absorbance spectroscopy

Tully group

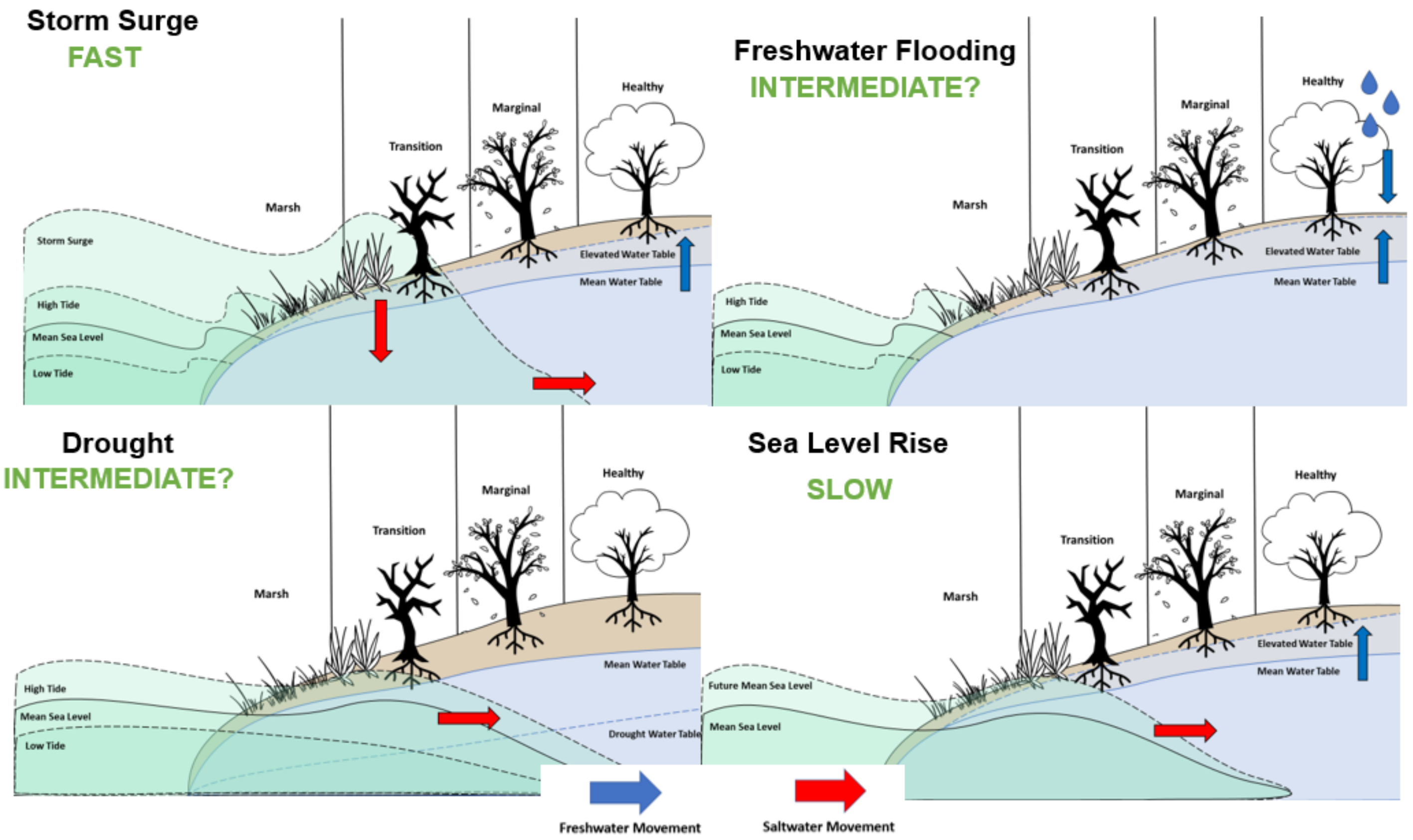
Variability in surface water chemistry across sites and events



Very low [NO3-N] in MD compared to VA and DE

*only displaying July 2022 sampling events

How do hydrologic events affect ecosystems on different timescales?



→ *Relationships between tree water use and tree growth and hydrologic conditions*

Band Dendrometers

Series 5 manual band dendrometer - photo: Forestry Suppliers

Sap Flux Sensors

SAPLINX heat pulse velocimetry sap flux sensors
Edaphic Scientific, Australia

Dendochronology

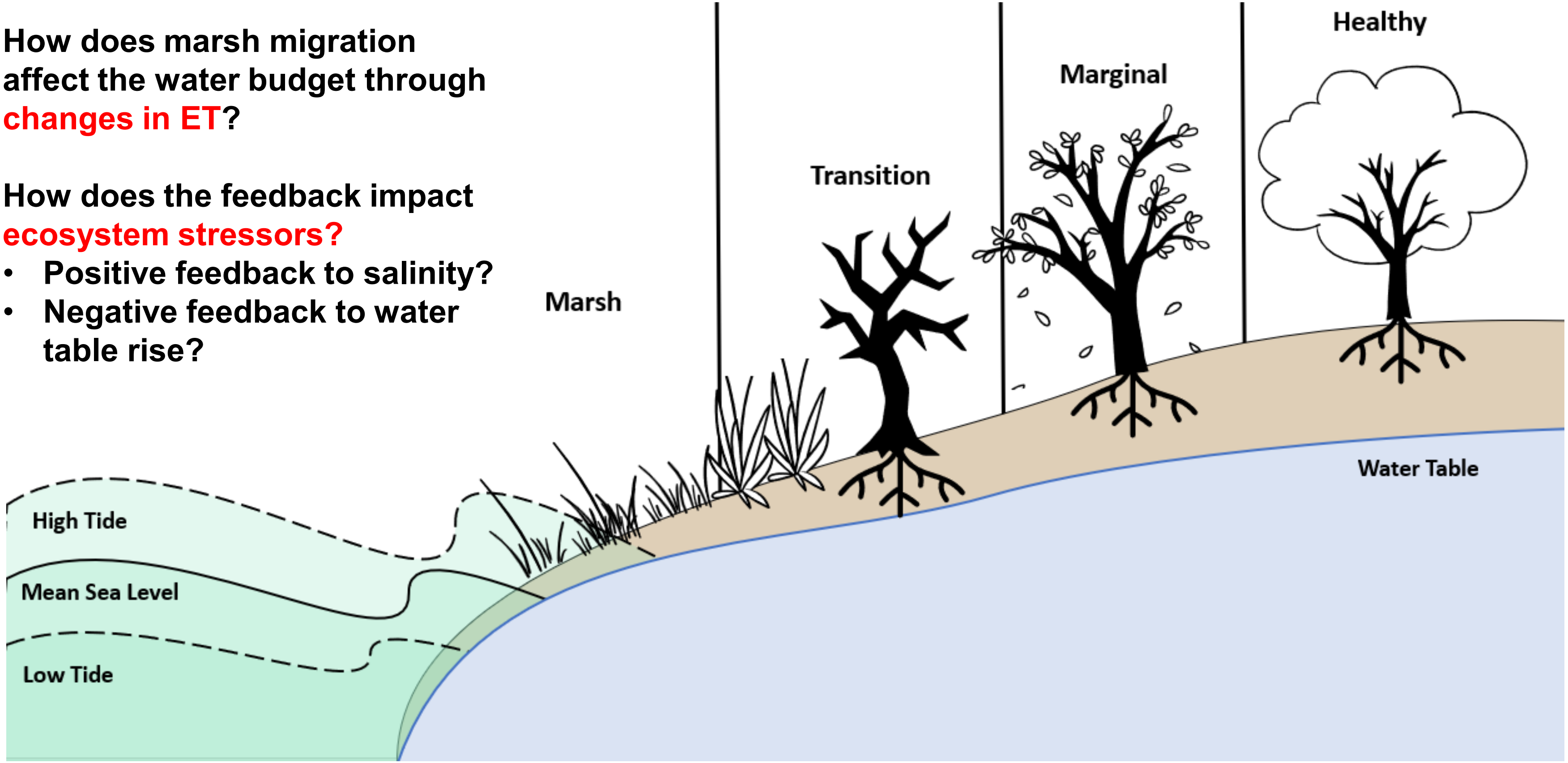
Gedan & Stotts groups

How does ecosystem change feed back to hydrology through evapotranspiration?

How does marsh migration affect the water budget through changes in ET?

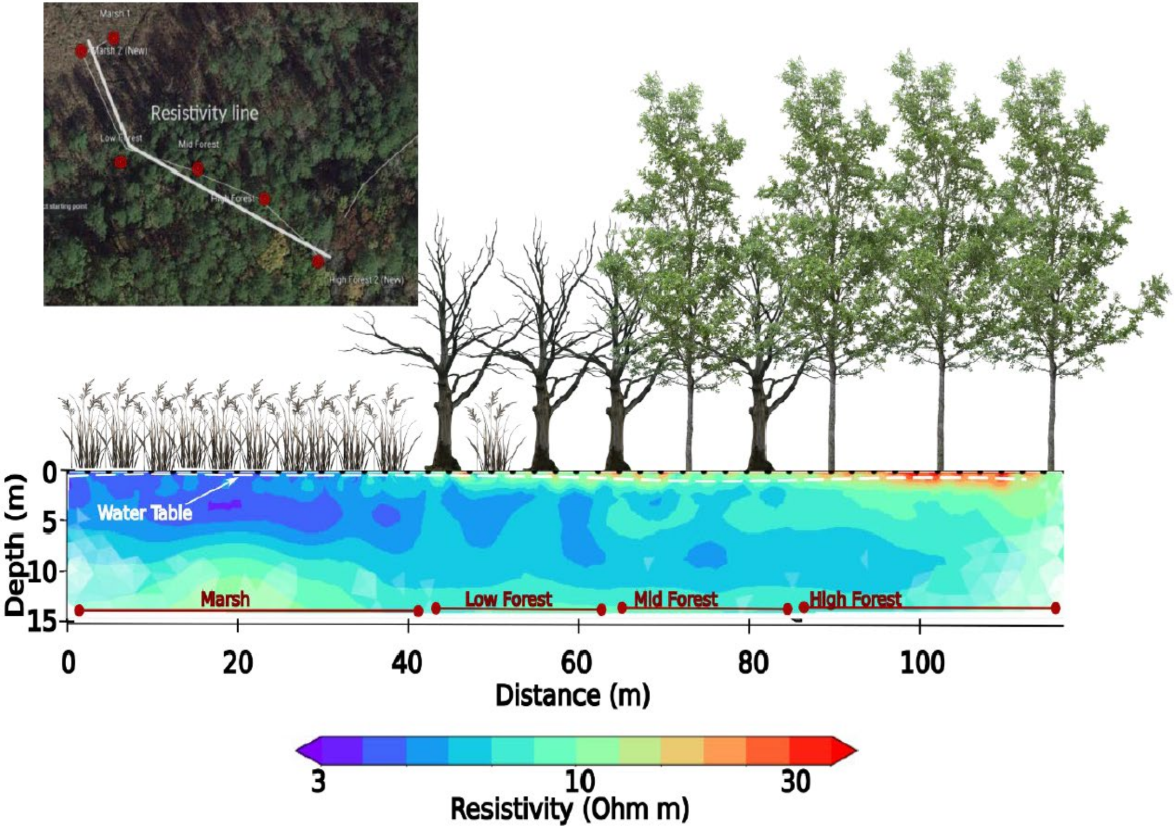
How does the feedback impact ecosystem stressors?

- **Positive feedback to salinity?**
- **Negative feedback to water table rise?**



Also on the horizon:

Geophysics: New NSF-funded project led by Lee Slater (Rutgers Newark)

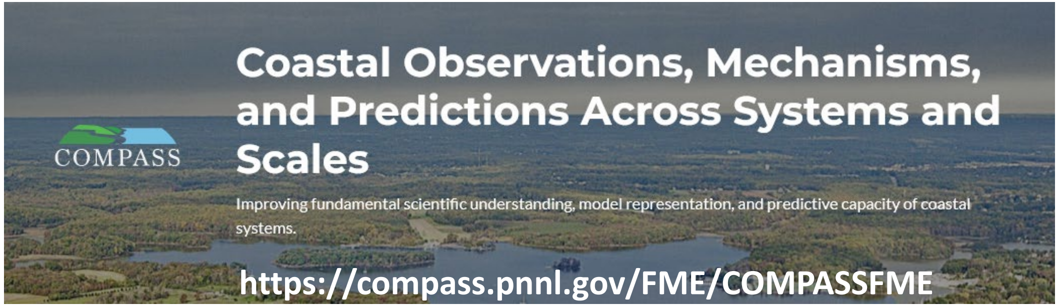


Incorporating feedbacks into dynamic models: Predicting future change

- 3D mechanistic models of flooding and salinization over short and long time periods
- Coupling of marsh geomorphology and ecology models to hydrodynamic models – mechanistic feedbacks among vegetation, hydrology, and geomorphology

ter

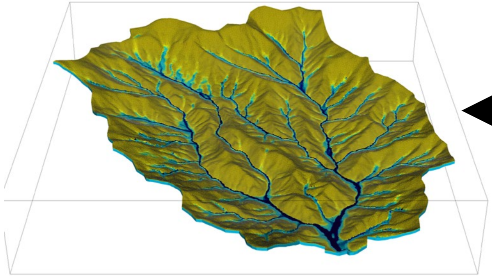
Incorporating feedbacks into dynamic models: Predicting future change

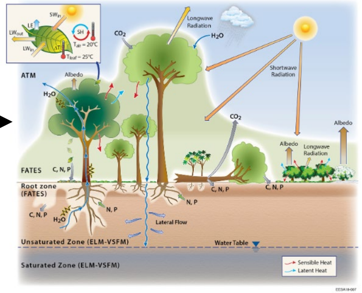


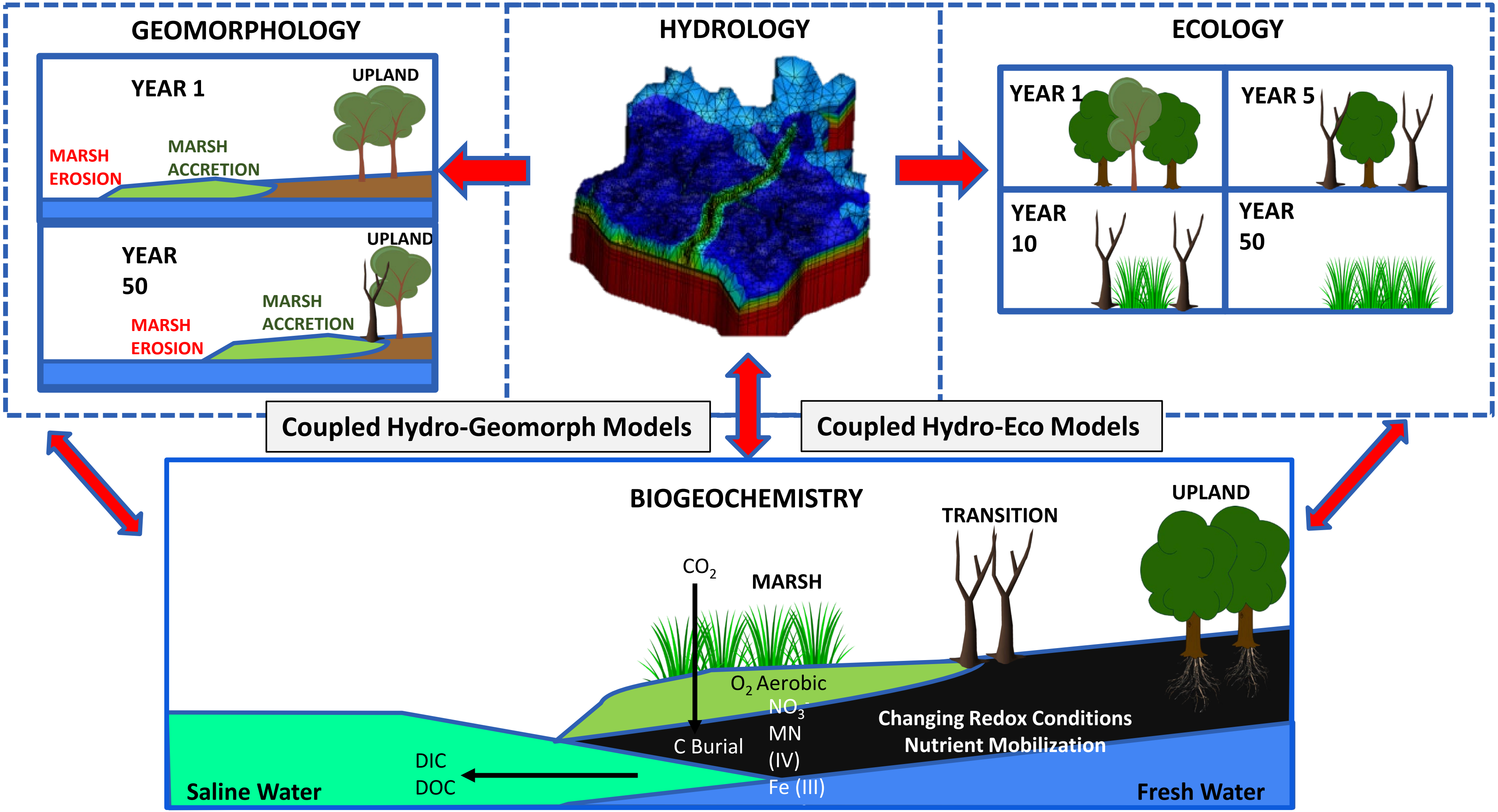
Pacific Northwest National Laboratory
Smithsonian Environmental Research Center
Los Alamos National Laboratory
The University of Toledo
Berkeley Lab
Argonne National Laboratory
Heidelberg University
Oak Ridge National Laboratory

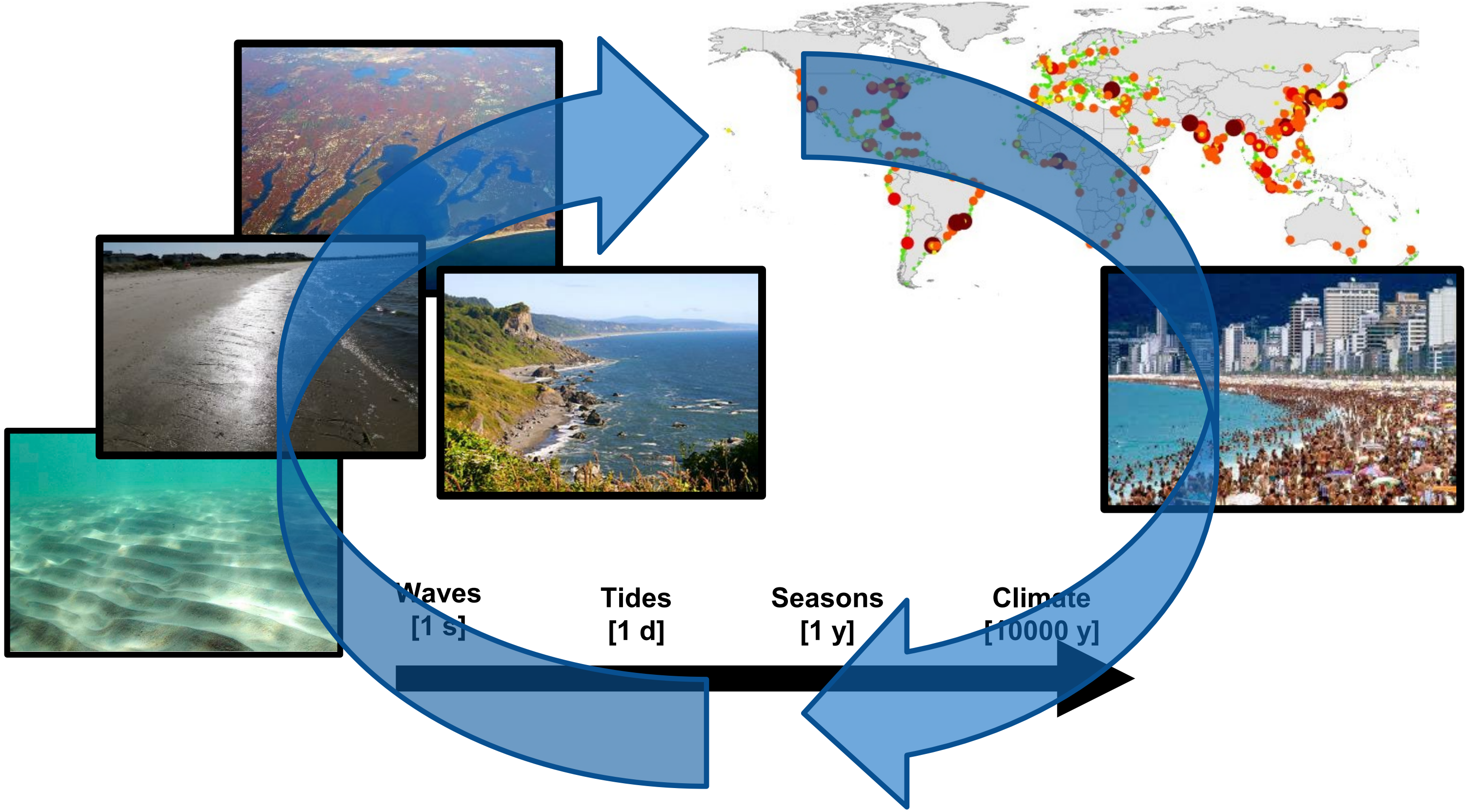
- 3D mechanistic models of flooding and salinization over short and long time periods
- Coupling of marsh geomorphology and ecology models to hydrodynamic models – mechanistic feedbacks among vegetation, hydrology, and geomorphology

With Xingyuan Chen and David Moulton:
Applying DoE's Advanced Terrestrial Simulator (ATS) coupled to the Functionally-Assembled Terrestrial Ecosystem Simulator (FATES)






GEOMORPHOLOGY
YEAR 1
UPLAND
MARSH EROSION
MARSH ACCRETION
YEAR 50
UPLAND
MARSH EROSION
MARSH ACCRETION
HYDROLOGY
ECOLOGY
YEAR 1
YEAR 5
YEAR 10
YEAR 50
Coupled Hydro-Geomorph Models
Coupled Hydro-Eco Models
BIOGEOCHEMISTRY
TRANSITION
UPLAND
CO_2
MARSH
O_2 Aerobic
NO_3^-
MN (IV)
Fe (III)
C Burial
Changing Redox Conditions
Nutrient Mobilization
DIC
DOC
Saline Water
Fresh Water



UNDERSTANDING AND MODELING LINKS & FEEDBACKS **AMONG SYSTEM COMPONENTS** ***ACROSS SCALES AND SETTINGS*** **ARE KEY TO PREDICTING THE** ***FUTURE EVOLUTION*** **OF COASTAL LANDSCAPES AND LAND-SEA FLUXES**

Coastal Critical Zone Network

https://czn.coastal.udel.edu/

Coastal Critical Zone Research Travel Awards:

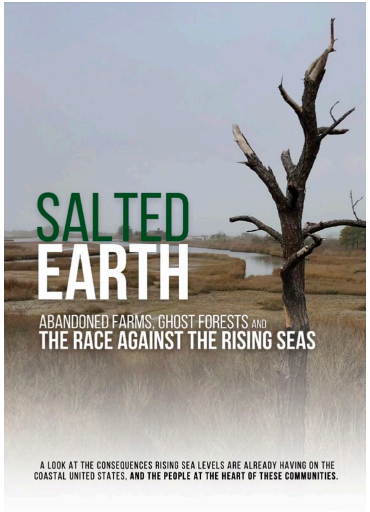
- Faculty, postdoctoral scientists, graduate students or professionals
- Laboratory, field visits, dialogue
- Travel, hotel, food cost
- For more details, visit our opportunities page on the Coastal CZN website, at https://czn.coastal.udel.edu/opportunities/ or email denin-info@udel.edu

Coastal Critical Zone Network

https://czn.coastal.udel.edu/

Also…we’re hiring a modeling postdoc!

Contact me (hmichael@udel.edu) if you’re interested!



Communicating NSF Coastal Critical Zone Research through Film

https://czn.coastal.udel.edu/salted-earth/

Thanks!

Questions
Discussion
Collaboration Ideas?