A coupled vegetation competition and groundwater simulation model to study the effects of sea level rise and storm surges on coastal vegetation

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Why this topic is important

Sea level rise (SLR) and risk of greater storm surges make it essential to

1. Understand the factors influencing the possibility of coastal vegetation change due to SLR and storm surges

2. Project possible future scenarios

3. Develop methodologies for early prediction of possible ‘regime shifts’ in vegetation.

Outline

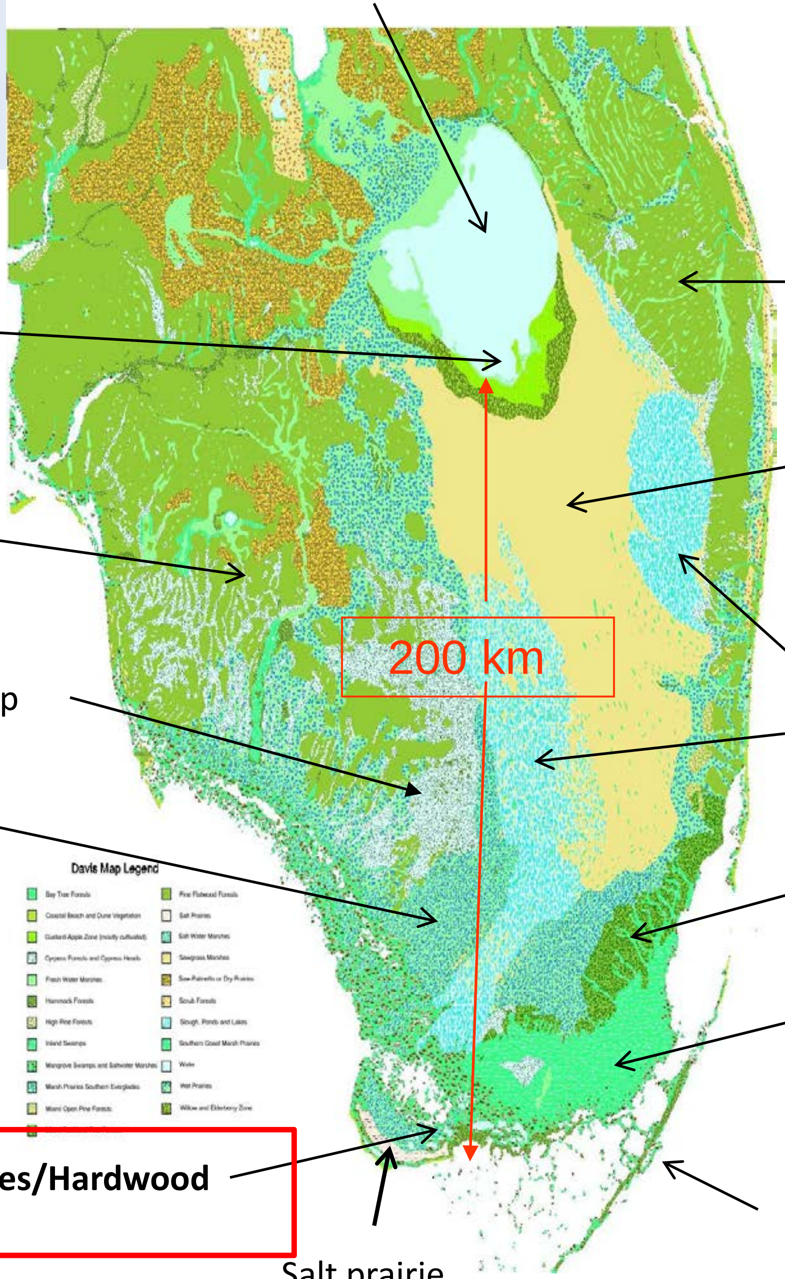
- Describe Everglades coastal vegetation halophyte/glycophyte ecotone

- MANHAM model for understanding ecotone formation and resilience to storm surge effects.

- MANTRA specific simulations of sea level rise and storm surge effects.

- Development of 'early warning' methodology for SLR and storm surge induced regime shifts - which might allow mitigation.

The Greater Everglades is a large subtropical wetland in southern Florida.



Lake Okeechobee

Elevation above sea level – about 6 meters (3 cm per km)

Pine flatwood

Sawgrass marsh

Saw palmetto, dry prairie

Cypress swamp

Slough, lakes

Marsh prairie

Pine rockland

Coast marsh prairie

Mixed Mangroves/Hardwood Hammocks

Salt prairie

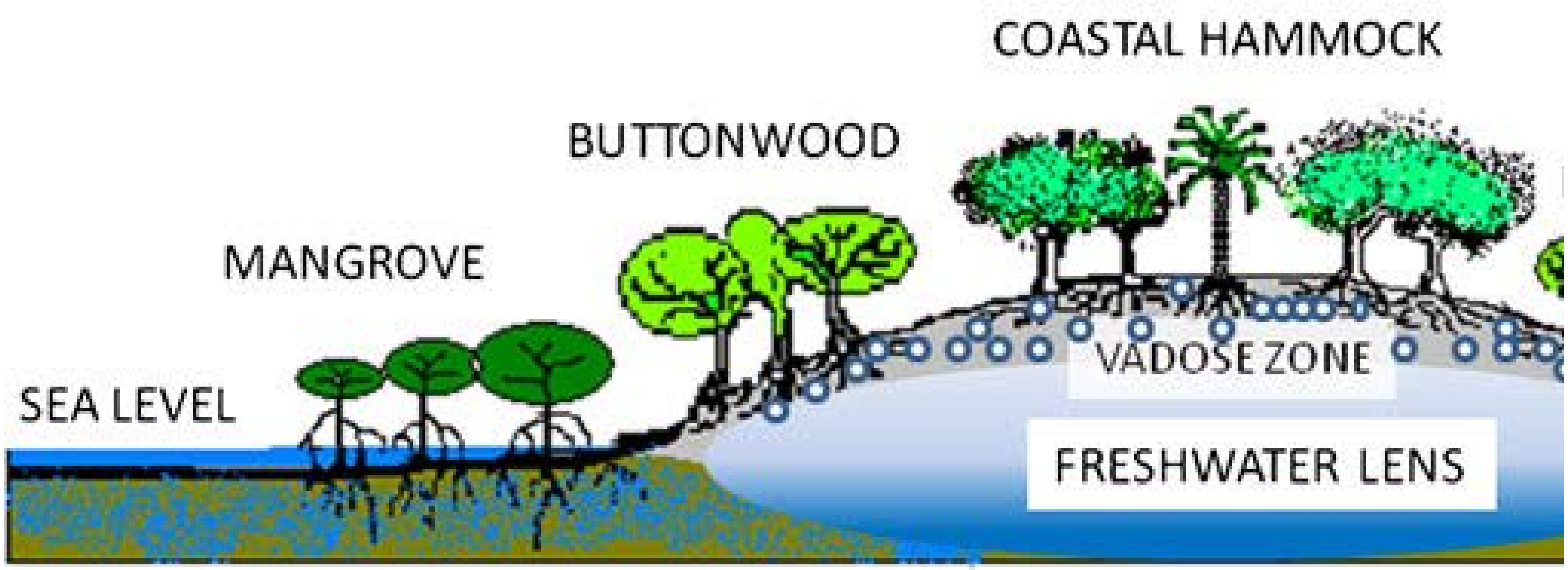
Upper Fl

Mangrove and tropical hardwood hammocks are two types of Everglades vegetation that overlap in geographic area

Mangroves (halophytic)

Hardwood Hammock (glychophytic)

Hammocks occur at slightly elevations (centimeters difference) and at lower underlying groundwater salinity



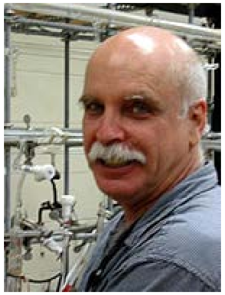
Decreasing groundwater salinity →

Everglades mangroves form extremely sharp (~ 1m) ecotone with freshwater vegetation types such as hardwood hammocks.

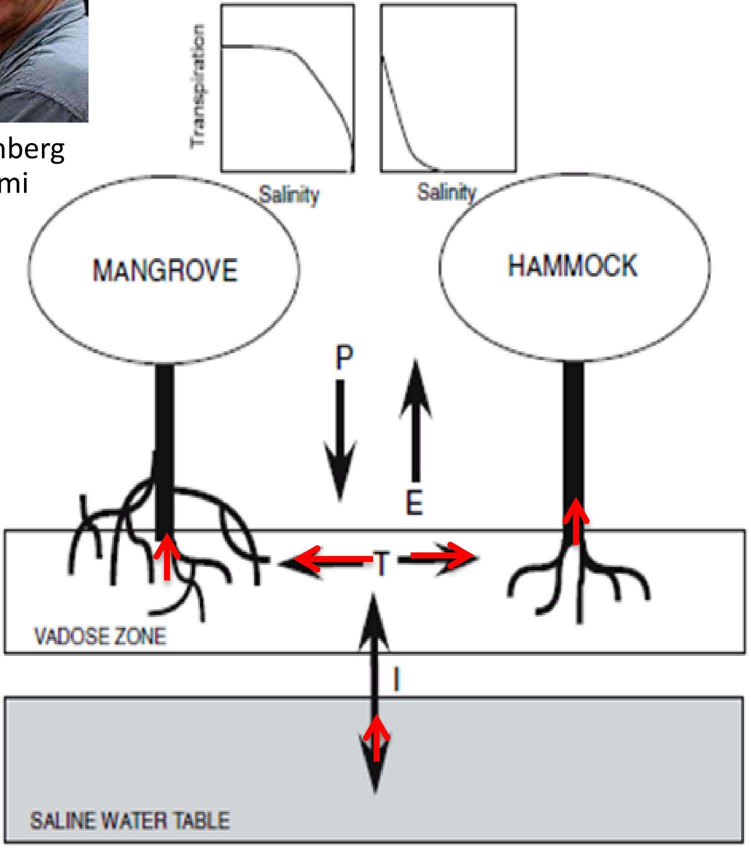
- “Ecotone”– a zone of relatively rapid change between two communities.

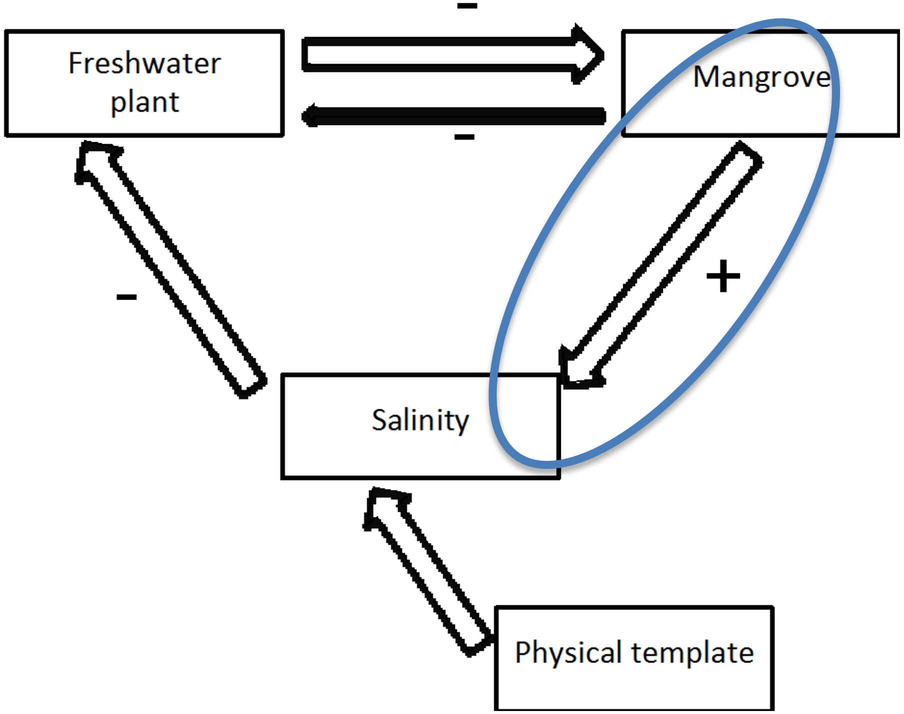
Mangrove-Hardwood Hammock Ecotone at Key Largo

Explanation of sharp ecotone in terms of positive feedbacks between vegetation and soil salinity maintain a sharp boundary



Leo Sternberg
U of Miami





Freshwater plant

Mangrove

Salinity

Physical template

Sternberg, L. et al 2007, Ecosystems

MANHAM Simulation Model

Coupled hydrology, salinity and vegetation competition

To examine this on a model landscape, a cellular automata simulation model was developed: MANHAM simulation code.

(Teh et al. 2008)

Prof. Su Yean The, Science University of Malaysia

ECOLOGICAL MODELLING 213 (2008) 245–256

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A simulation model for projecting changes in salinity concentrations and species dominance in the coastal margin habitats of the Everglades

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Coastal ecosystems
Vadose zone

ABSTRACT

Sharp boundaries typically separate the salinity tolerant mangroves from the salinity intolerant hardwood hammock species, which occupy the similar geographical areas of southern Florida. Evidence of strong feedback between tree community-type and the salinity of the unsaturated (vadose) zone of the soil suggests that a severe disturbance that significantly tilts the salinity in the vadose zone might cause a shift from one vegetation type to the other. In this study, a model based upon the feedback dynamics between vegetation and salinity of the vadose zone of the soil was used to take account of storm surge events to investigate the mechanisms that by which this large-scale disturbance could affect the spatial pattern of hardwood hammocks and mangroves. Model simulation results indicated that a heavy storm surge that completely saturated the vadose zone at 30 ppt for 1 day could lead to a regime shift in which there is domination by mangroves of areas previously dominated by hardwood hammocks. Lighter storm surges that saturated the vadose zone at less than 7 ppt did not cause vegetation shifts. Investigations of model sensitivity analysis indicated that the thickness of the vadose zone, coupled with precipitation, influenced the residence time of high salinity in the vadose zone and therefore determined the rate of mangrove domination. The model was developed for a southern Florida coastal ecosystem, but its applicability may be much broader.

1. Introduction

In the Greater Everglades region of southern Florida, mangrove ecosystems and hardwood hammock ecosystems occupy overlapping geographical ranges (Odum et al., 1982; Odum and McIvor, 1990; Sklar and van der Valk, 2003). Areas of close proximity of mangrove vegetation and hardwood hammock vegetation have been studied in keys by Sternberg and Swart (1987); Cluett Key (Florida Bay) and Elliott Key (Biscayne Bay), on the mainland northern shore of Florida Bay; e.g., Coot Bay Hammock (Armentano et al., 2002), and on coastal strand landscape mosaics (Browder and Ogden, 1999). Previous

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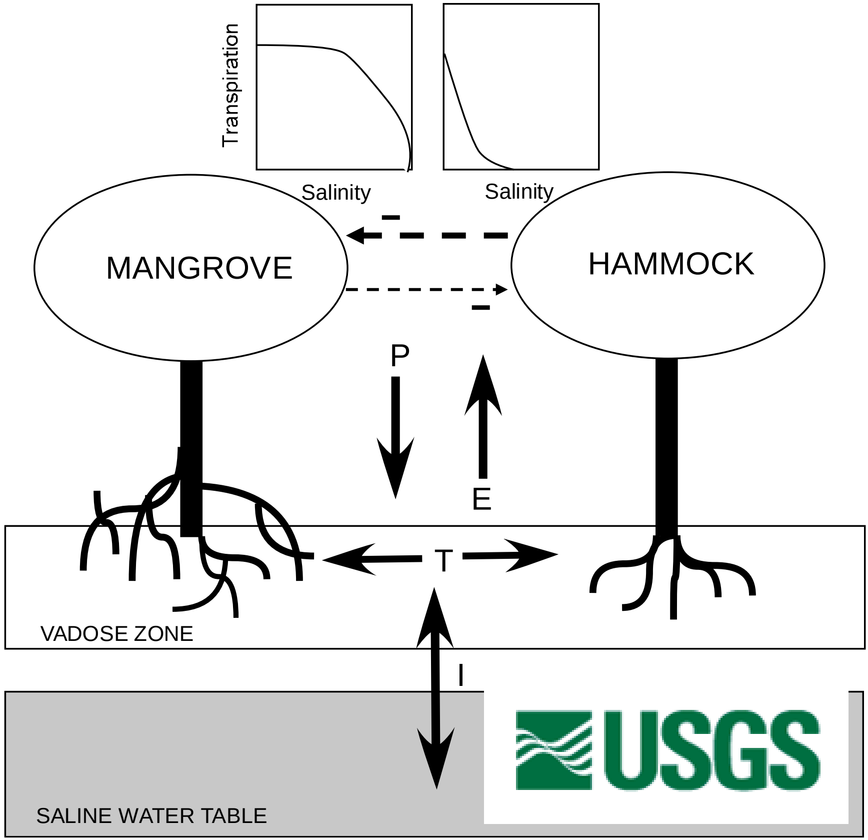
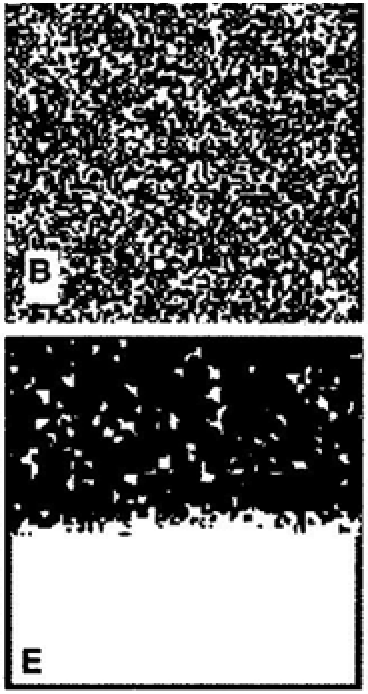
MANHAM

- MANgrove and Hardwood HAMmock Competition Model;
- Simulate interaction of vegetation with hydrology and salinity dynamics in the vadose zone
- Models water flow and salinity in the vadose zone, which depends on P, E, T, I
- Simulates vegetation dynamics
- Competing vegetation types with different tolerance level to salinity.



In MANHAM, an initially uniformly mixed hardwood hammock and mangrove vegetation will sort out along the groundwater salinity gradient, depending on initial distribution. The boundary is fairly resilient to disturbance.



Initial distribution of mangrove cells and hardwood hammock cells

High elevation (and lower groundwater salinity)

Low elevation

Distribution of mangrove and hardwood hammock cells after 50 years – Stable ecotone that is relatively resilient

Hammock

Mangrove

However, simulations with MANHAM revealed the possibility of a regime shift following a sufficiently large storm surge carrying water far inland.

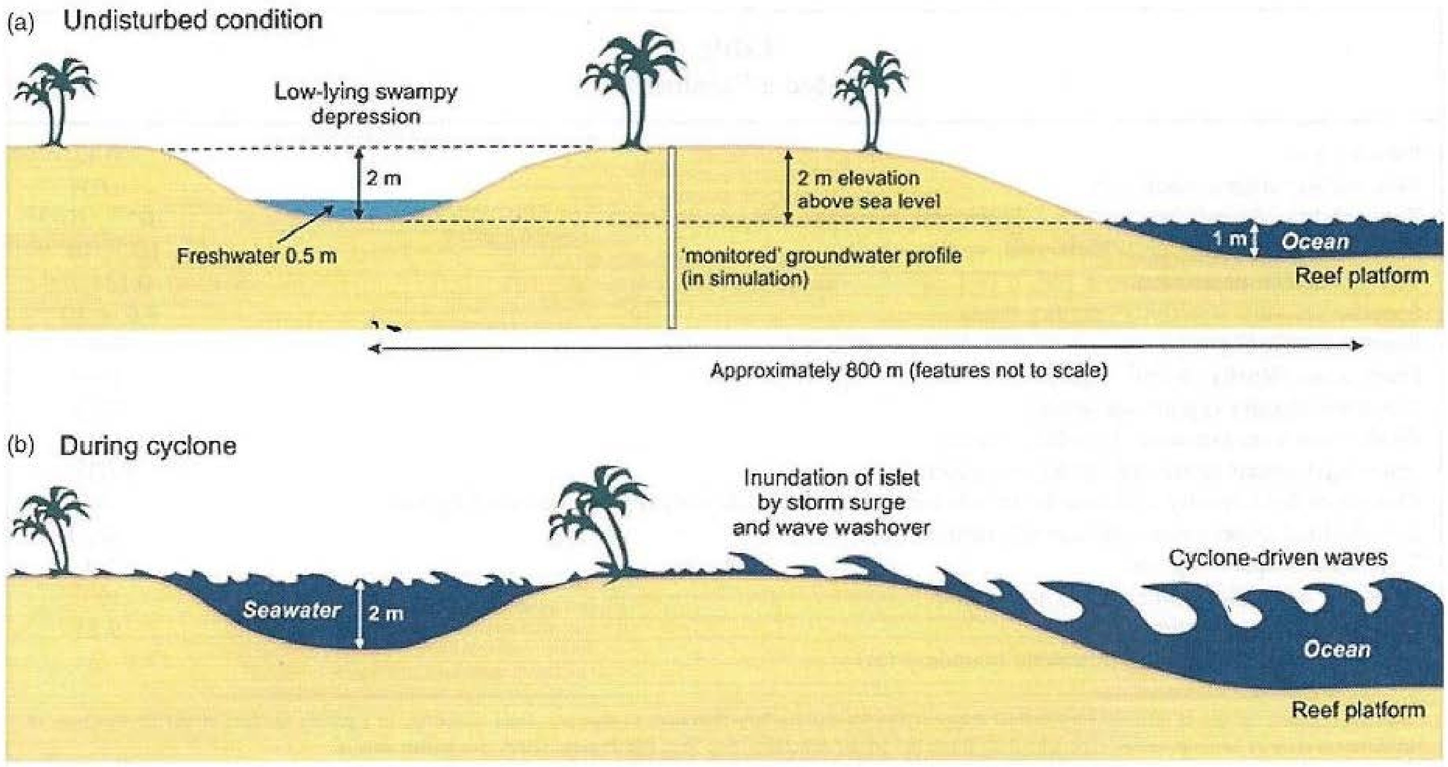


Figure from Chui and Terry, *Groundwater* (2011) doi: 10.1111/j.1745-6584.2011.00860.x

Storm surge overwash may cause long-term vegetation change due to salinity saturation of the soil; i.e., a regime shift.

Responses of atoll freshwater lenses to storm-surge overwash in the Northern Cook Islands

James P. Terry · Anthony C. Falkland

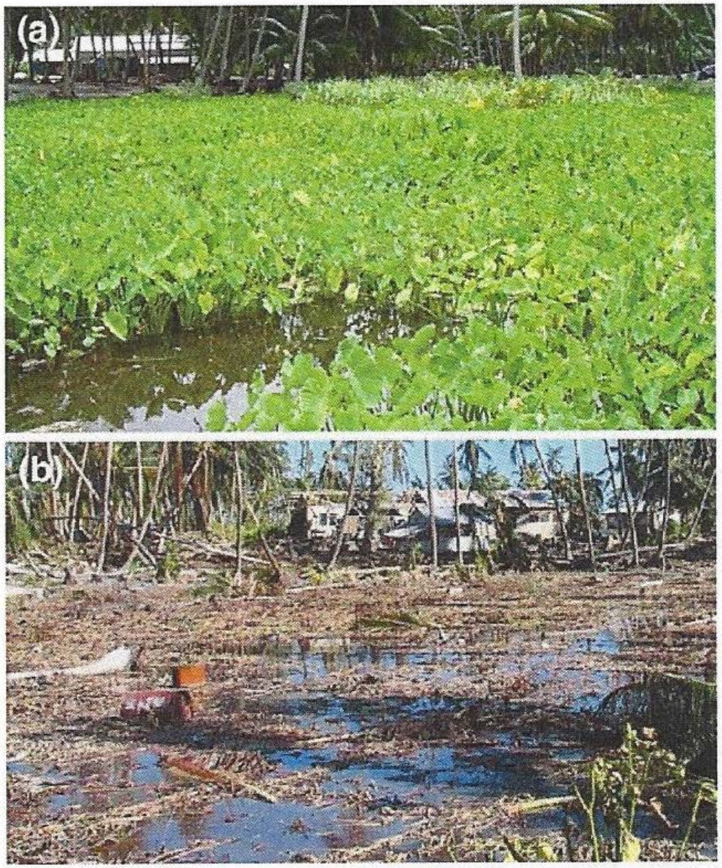


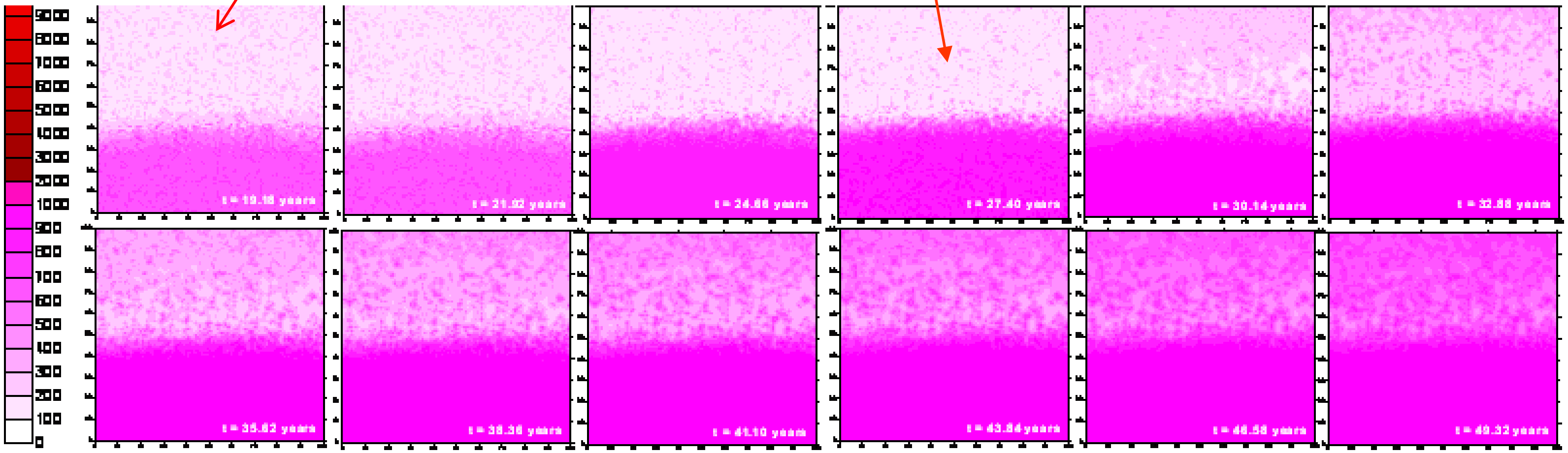
Fig. 3 Central swamp **a** with healthy taro plantation (the principal subsistence crop) on Wale islet in early 2005 and **b** seawater stagnating in the same location several days after the storm-surge overwash caused by Cyclone Percy in early March 2005. Photo credits: A. Falkland and Douglas Clark

Hydrogeology Journal (2010) 18: 749–759

MANHAM simulations show a regime shift from hardwood hammock (white zone in top of figure) to mangroves (magenta) following a simulated storm surge.

Hardwood hammock vegetation here, with some mangrove seedlings

27.4 years into simulation ; storm surge occurs



Darker magenta is higher mangrove density

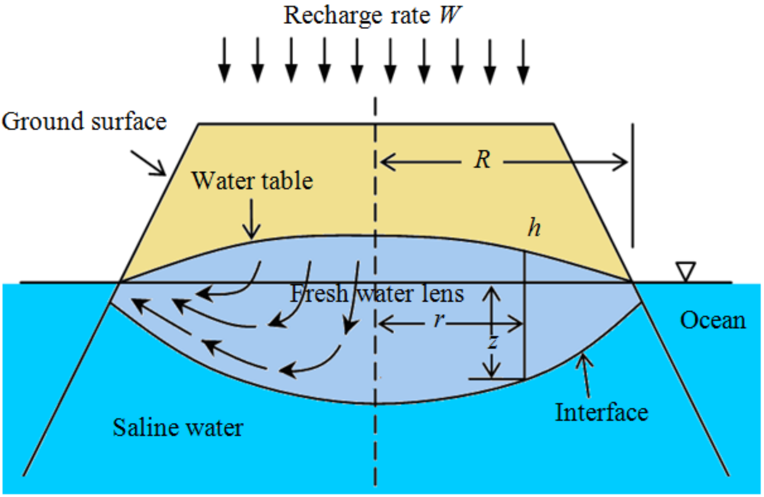
50 ye

SY Teh, DL DeAngelis, T. J. Smith, L. Sternberg, F. Miralles-Wilhelm, HL Koh. Ecological Modelling 2008

USGS science for a changing world

MANHAM Limitations

- Simulates the vadose zone as a uniform compartment;
- Does not model underlying groundwater dynamics;
- Does not consider freshwater lens , which is an important constituent of the water balance for the overlying vegetation through transpiration and plays a key role on the salinity balance as well;
- Assumes the groundwater is a constant boundary condition.

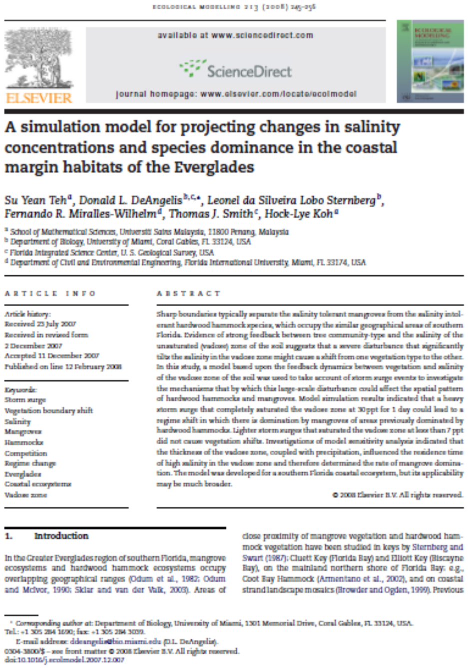


MANTRA = MANham + suTRA Simulation Model

Coupling vegetation from MANHAM with hydrology and salinity of SUTRA

MANham + suTRA = MANTRA

- Revises the MANHAM model by combining it with the USGS's SUTRA model;
- To better simulate the possible effects of gradual SLR, short- and long-term effects of a single or a sequence of overwash events.



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A simulation model for projecting changes in salinity concentrations and species dominance in the coastal margin habitats of the Everglades

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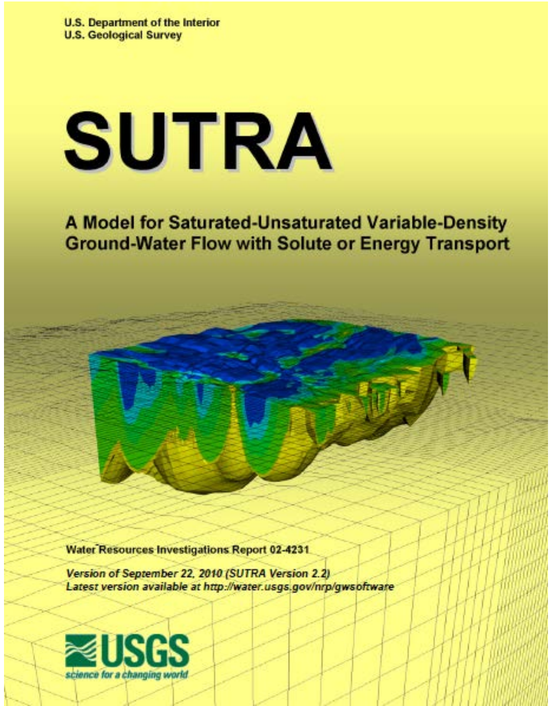

U.S. Department of the Interior
U.S. Geological Survey

SUTRA

A Model for Saturated-Unsaturated Variable-Density Ground-Water Flow with Solute or Energy Transport

Water-Resources Investigations Report 02-4231

Version of September 22, 2010 (SUTRA Version 2.2)
Latest version available at http://water.usgs.gov/nrp/gwsoftware

USGS
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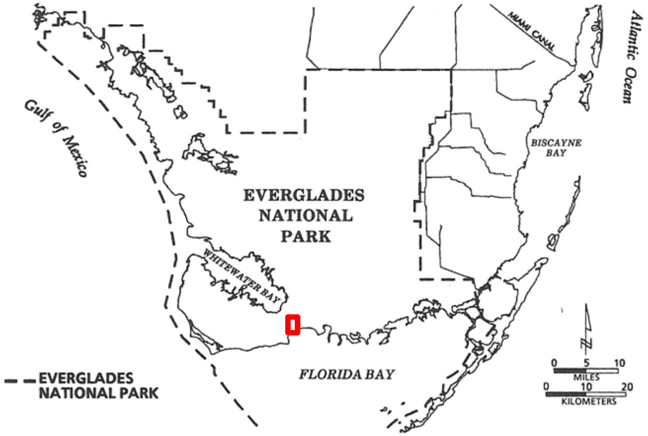
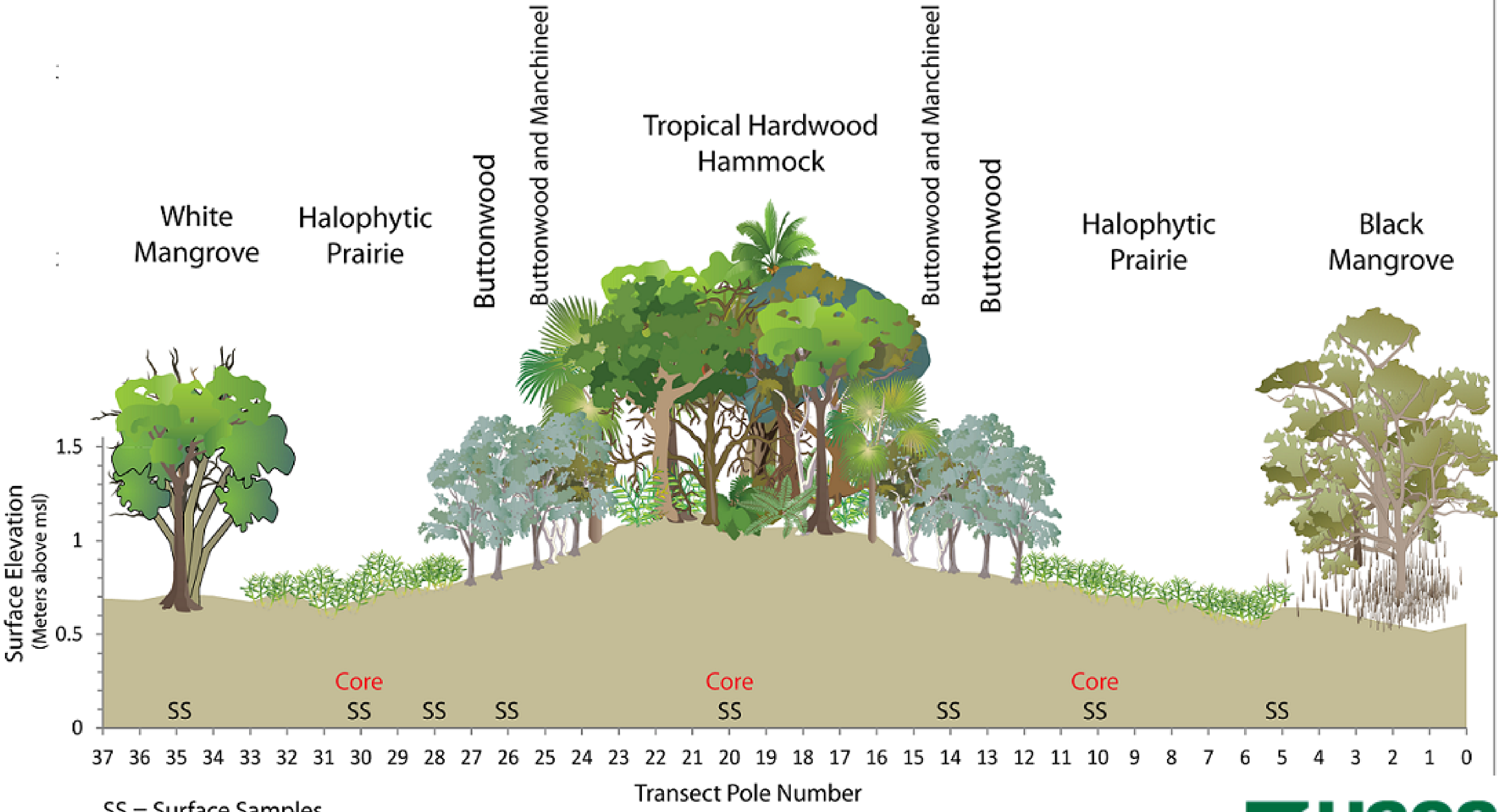
Applying MANTRA on a Study Transect – Coot Bay Hammock



Simulations of Wilma and Andrew type storm surges by MANTRA indicate little chance of a regime shift of this hammock.

Therefore, to determine what is needed to cause a regime shift, we performed scenarios where heavy damage to the hammock occurred, or subsequent drought.

West-to-east transect of about 400 m across the Coot Bay Hammock showing the sharp gradations between vegetation types



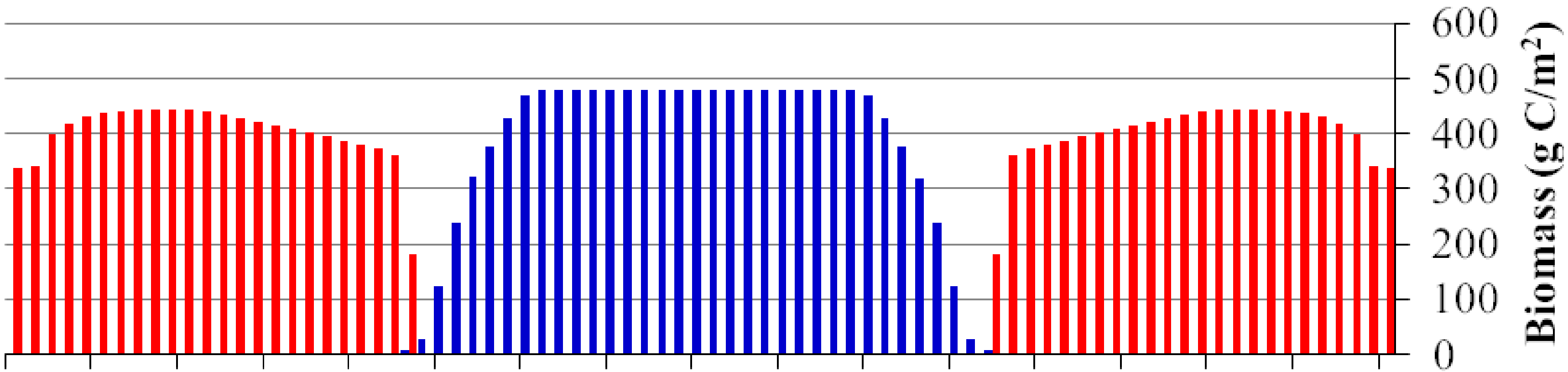
SS = Surface Samples

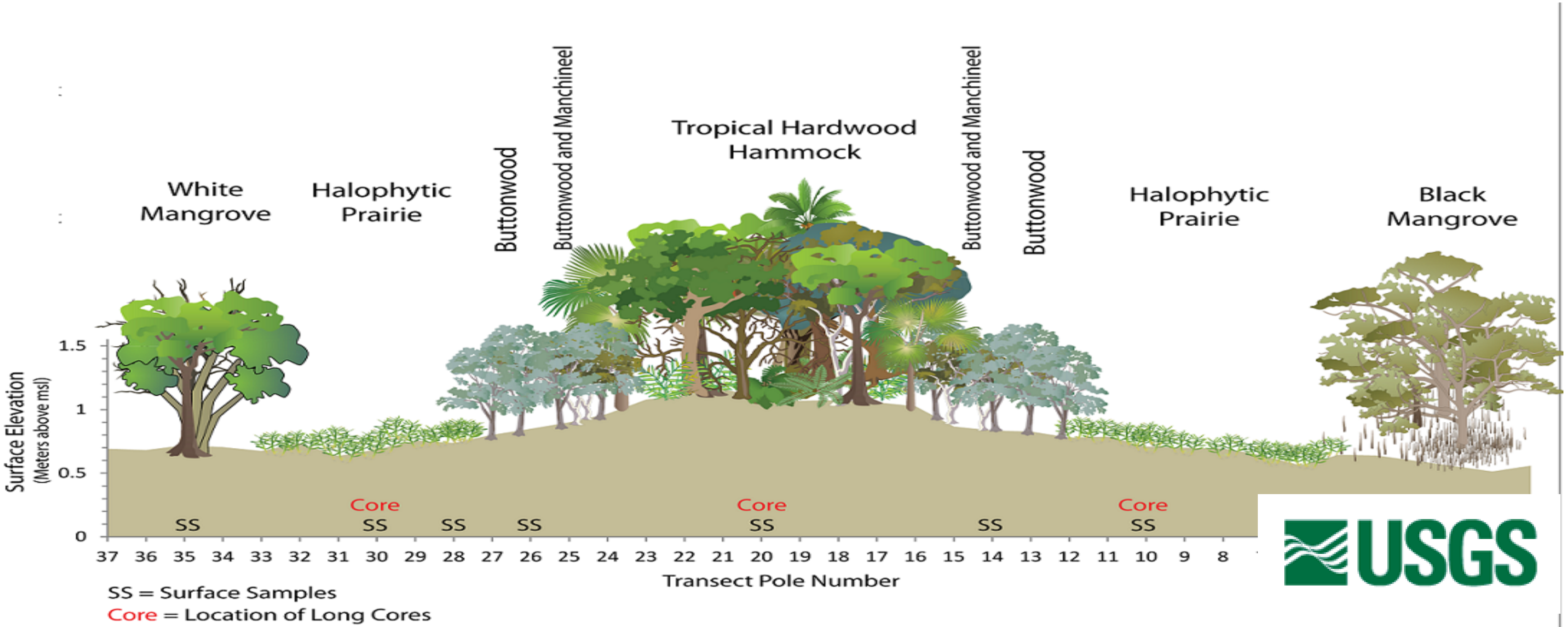
Core = Location of Long Cores

Model Simulations

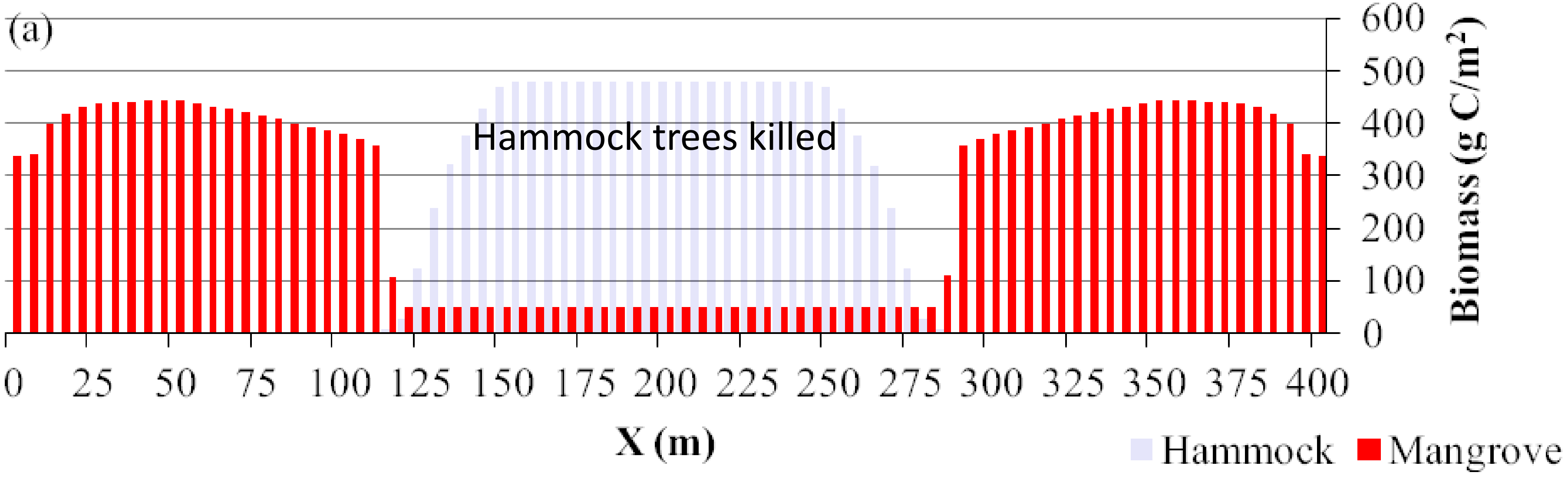
1. Existing Conditions (Scenario 1)
    - Aim: To calibrate the model to produce simulated results that are consistent with the observed data,i.e., that a sharp boundary occurs.
2. Storm Surges (Scenarios 2 and 3).
    - Scenario 2: Assume the storm inflicted heavy damage to the hardwood hammock trees.
    - Scenario 3: Moderate damage but the storm surge was followed by a severe four-year drought.

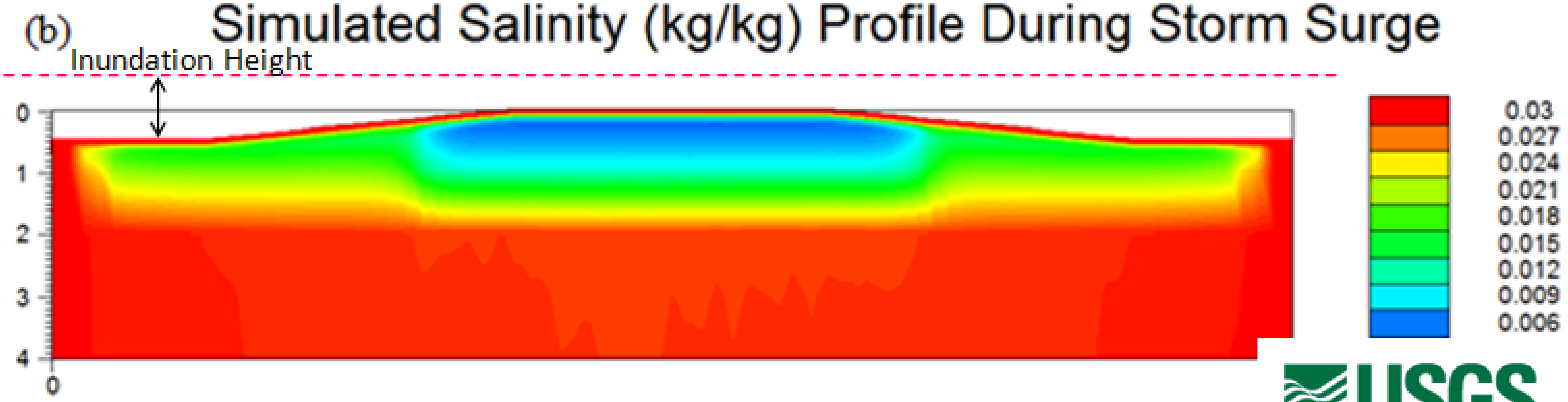
Existing Conditions





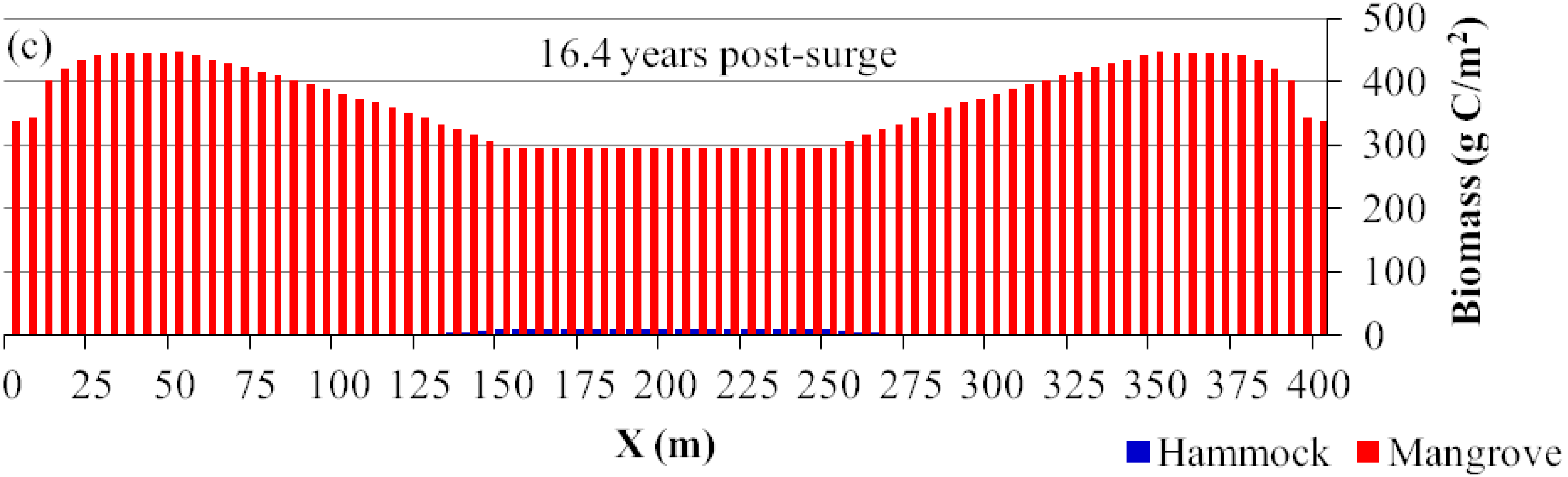
Storm Surge – Heavy Damage





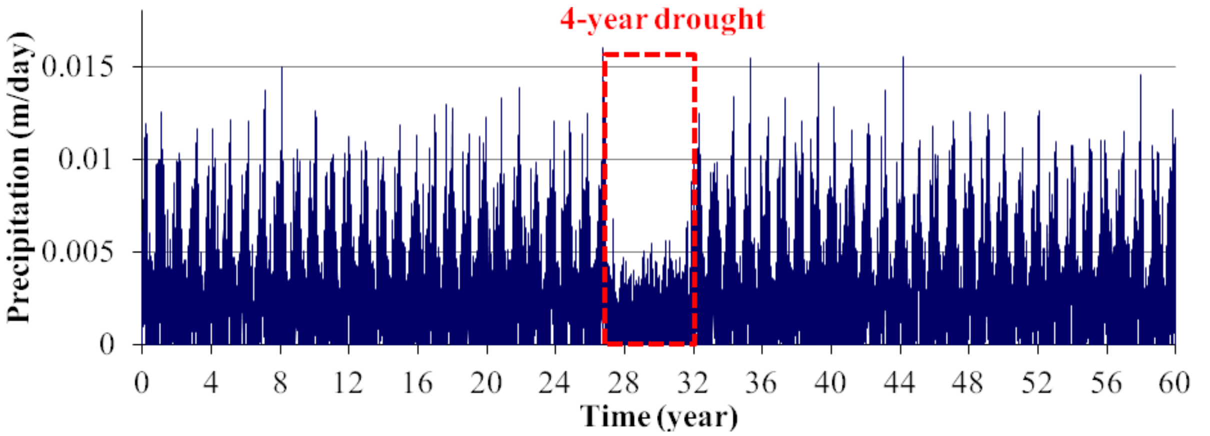
USGS

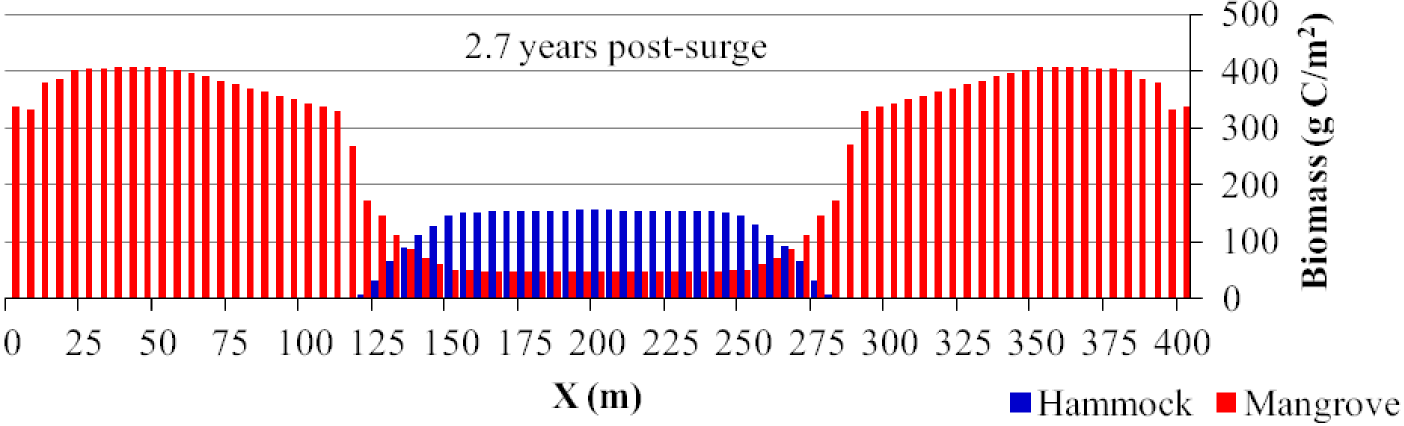
Storm Surge with Heavy Damage: 16 years later

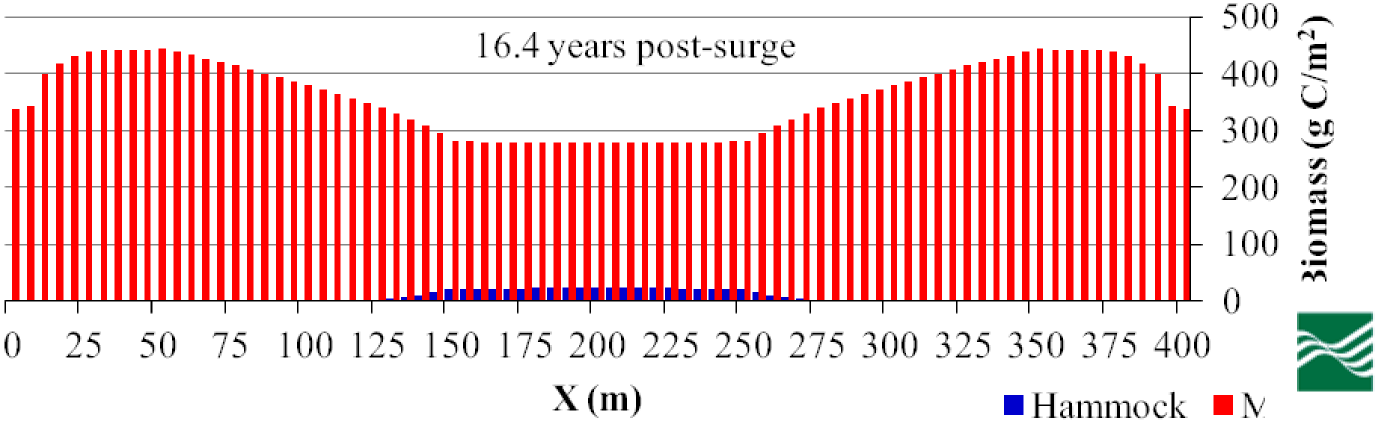


This is typical heavy damage to hardwood hammock →

Storm Surge – Moderate Damage with Drought







Development of ‘early warning’ methodology

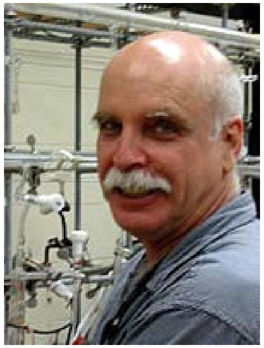
Stable isotope measurement provides a tool for prediction

Using modeling plus stable isotopes for early earning of regime shifts

- MANTRA and MANHAM will be used as part of an approach to early warning of salinity stress near the ‘tipping point’ in trees. Work being done by Prof. Leo Sternberg and grad student Lu Zhai.

- $\delta^{13}C$ in tree leaves measures stress and $\delta^{18}O$ in tree stemwater is a measure of salinity. Both will be incorporated in MANTRA and MANHAM.

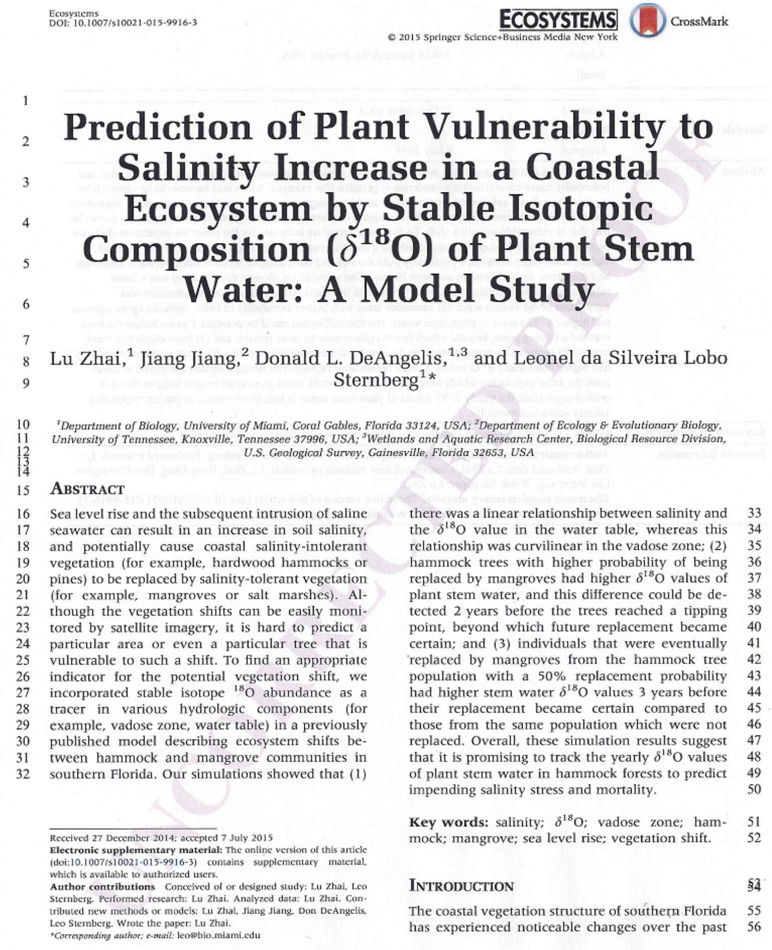
Correlation between $\delta^{13}C$ and $\delta^{18}O$ would indicate that salinity is causing the stress. Combined with model simulations, this provides an early detection of tipping point



Prof. Leo Sternberg,U. Miami

Lu Zhai, grad student, U. Miami

Salinity correlates with $^{18}0$ in water, and can easily be measured in tree stemwater.



Ecosystems
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ECOSYSTEMS

Prediction of Plant Vulnerability to Salinity Increase in a Coastal Ecosystem by Stable Isotopic Composition ($\delta^{18}O$) of Plant Stem Water: A Model Study

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[1]Department of Biology, University of Miami, Coral Gables, Florida 33124, USA; [2]Department of Ecology & Evolutionary Biology, University of Tennessee, Knoxville, Tennessee 37996, USA; [3]Wetlands and Aquatic Research Center, Biological Resource Division, U.S. Geological Survey, Gainesville, Florida 32653, USA

ABSTRACT

Sea level rise and the subsequent intrusion of saline seawater can result in an increase in soil salinity, and potentially cause coastal salinity-intolerant vegetation (for example, hardwood hammocks or pines) to be replaced by salinity-tolerant vegetation (for example, mangroves or salt marshes). Although the vegetation shifts can be easily monitored by satellite imagery, it is hard to predict a particular area or even a particular tree that is vulnerable to such a shift. To find an appropriate indicator for the potential vegetation shift, we incorporated stable isotope ^{18}O abundance as a tracer in various hydrologic components (for example, vadose zone, water table) in a previously published model describing ecosystem shifts between hammock and mangrove communities in southern Florida. Our simulations showed that (1) there was a linear relationship between salinity and the $\delta^{18}O$ value in the water table, whereas this relationship was curvilinear in the vadose zone; (2) hammock trees with higher probability of being replaced by mangroves had higher $\delta^{18}O$ values of plant stem water, and this difference could be detected 2 years before the trees reached a tipping point, beyond which future replacement became certain; and (3) individuals that were eventually replaced by mangroves from the hammock tree population with a 50% replacement probability had higher stem water $\delta^{18}O$ values 3 years before their replacement became certain compared to those from the same population which were not replaced. Overall, these simulation results suggest that it is promising to track the yearly $\delta^{18}O$ values of plant stem water in hammock forests to predict impending salinity stress and mortality.

Key words: salinity; $\delta^{18}O$; vadose zone; hammock; mangrove; sea level rise; vegetation shift.

INTRODUCTION

The coastal vegetation structure of southern Florida has experienced noticeable changes over the past

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Author contributions Conceived of or designed study: Lu Zhai, Leo Sternberg. Performed research: Lu Zhai. Analyzed data: Lu Zhai. Contributed new methods or models: Lu Zhai, Jiang Jiang, Don DeAngelis, Leo Sternberg. Wrote the paper: Lu Zhai.

Corresponding author; e-mail: leo@bio.miami.edu

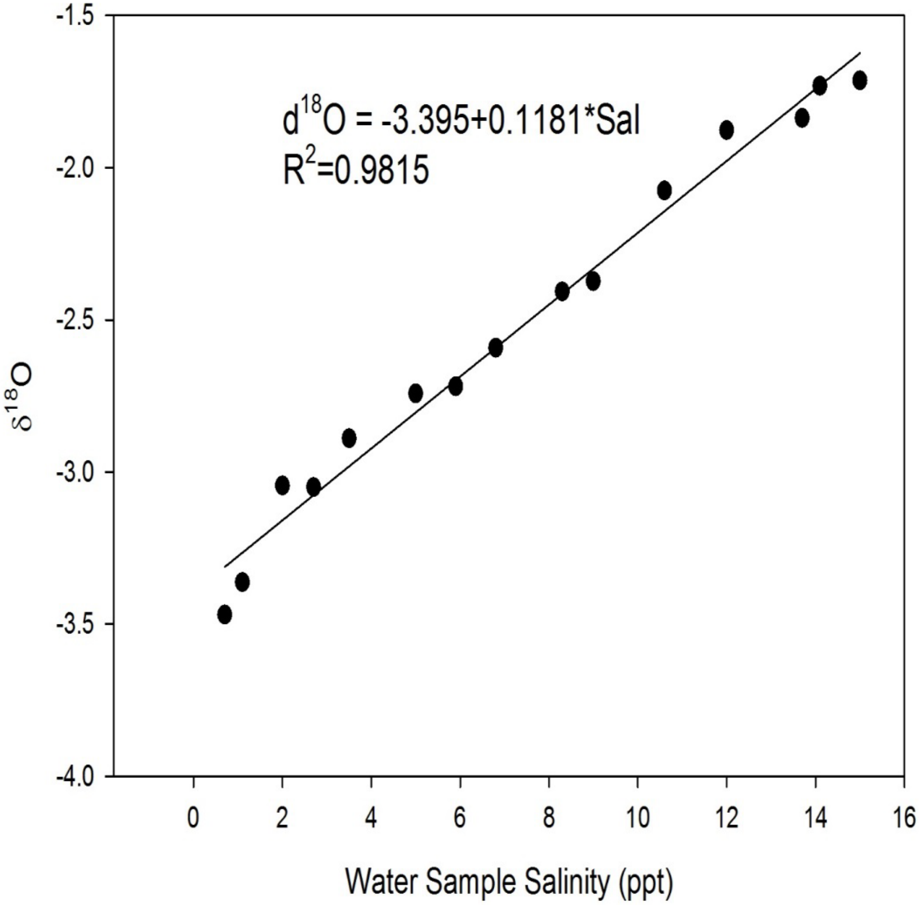
Study Sites

1. Waccamaw National Wildlife Refuge
Spartina marsh,
Cypress stands.

2. Sugar Loaf Wildlife Preserve
Mangroves,
buttonwoods,
hardwood hammocks, pines

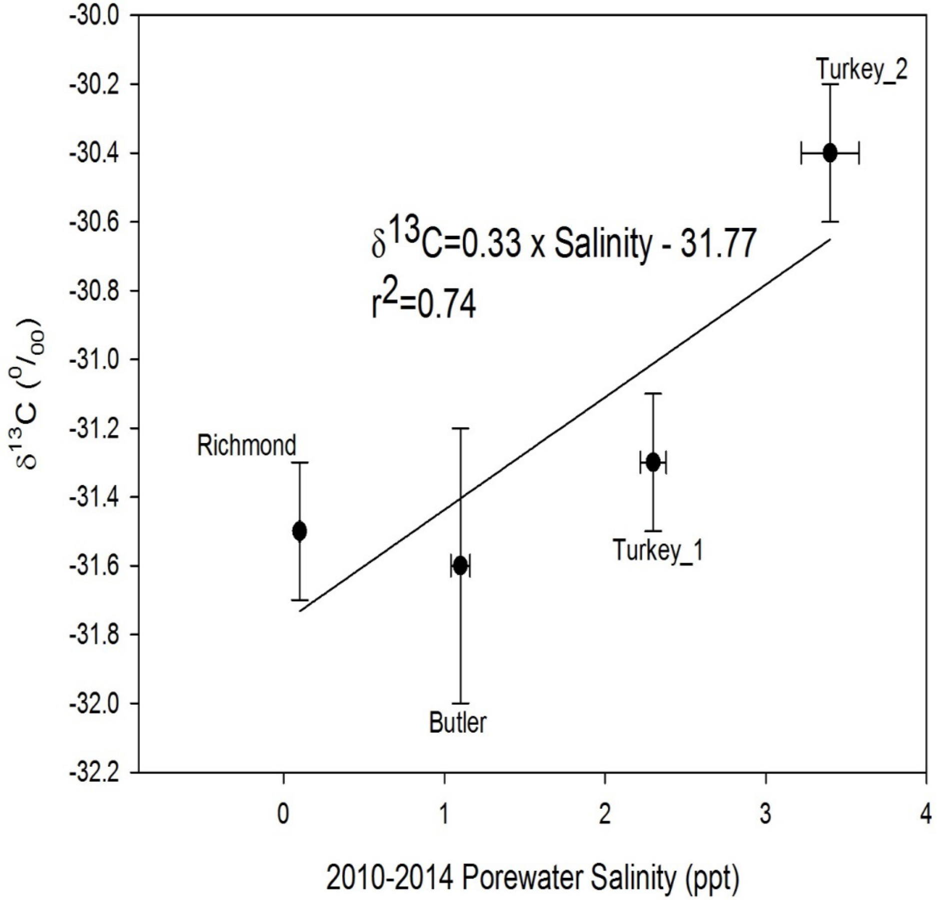
Water Samples from Waccamaw River

July 2015



$\delta^{18}O$ → the plant salt stress

Leaf samples of Myrtle
March 2016



$\delta^{13}C$ → the plant salt stress

Conclusions

- MANHAM demonstrated the formation of sharp halophyte/glycophyte boundary and showed potential for regime shifts from storm surges.

- MANTRA was used to make a detailed hydrology-salinity-vegetation competition model to examine resilience of coastal freshwater vegetation to storm surges.

- Use of stable isotopes in combination with MANHAM and MANTRA will provide a methodology of early prediction of regime shifts to halophytic vegetation, which can allow mitigation.