Modeling $\delta^{18}O$ as an early indicator of regime shift arising from salinity stress in coastal vegetation

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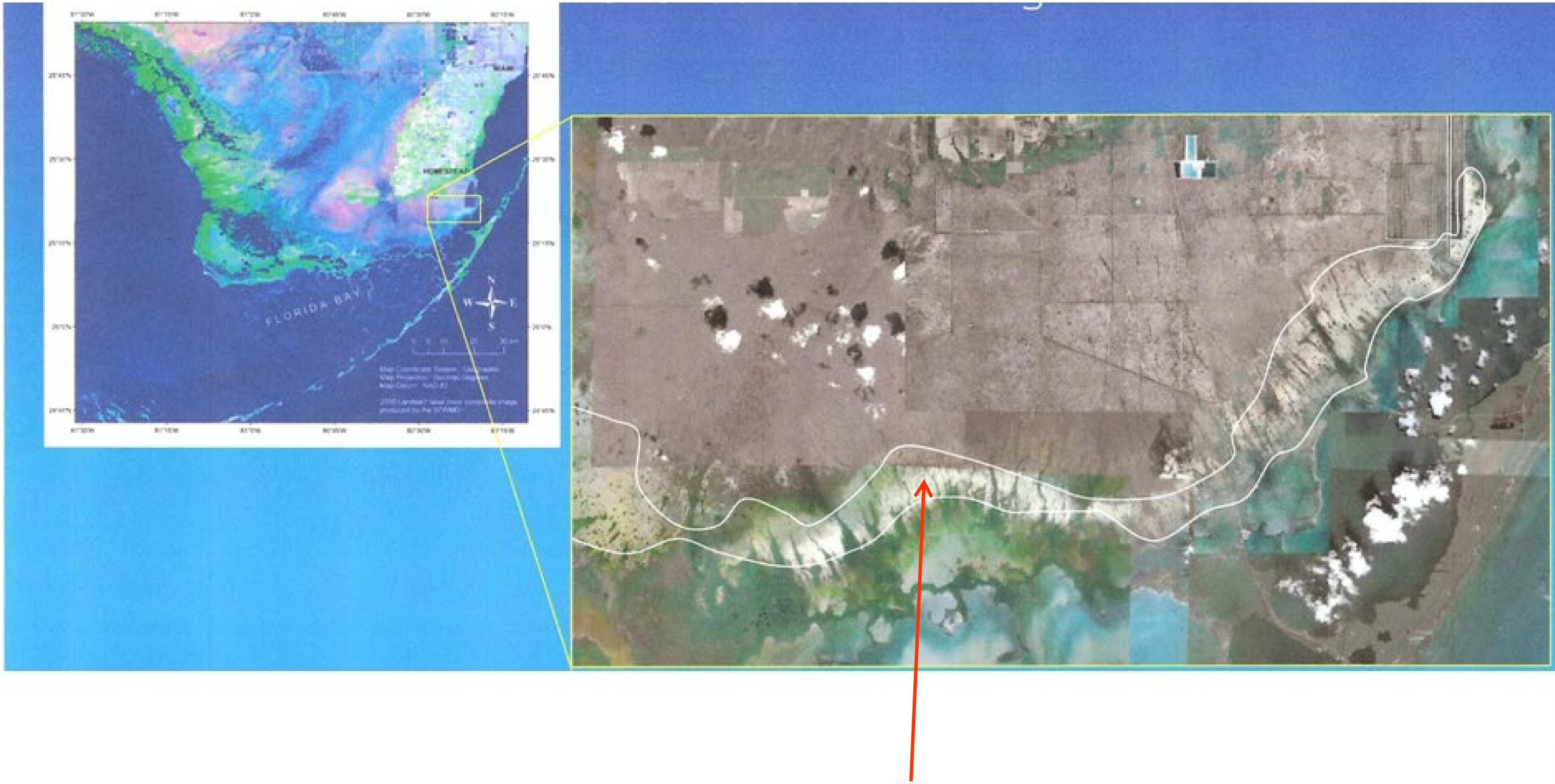
The boundary zone (ecotone) between salt-tolerant mangrove vegetation and freshwater sawgrass vegetation is moving inland.



Low productivity 'White zone' between advancing mangroves and retreating sawgrass

Slide from Michael Ross et al.

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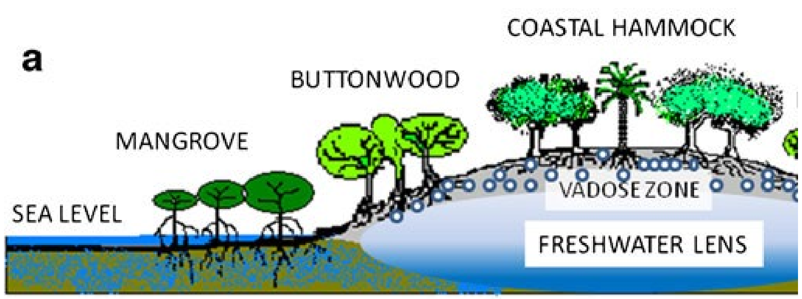
Our research has been to understand how the ecotone between mangrove and freshwater (glycophytic) vegetation (e.g., hardwood hammocks) develops, and is maintained - or may change.

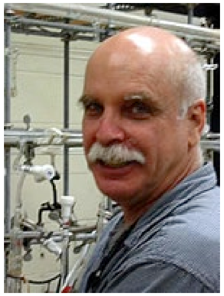
- Forming an extremely sharp (~ 1m) ecotone.

Mangroves (halophytic)

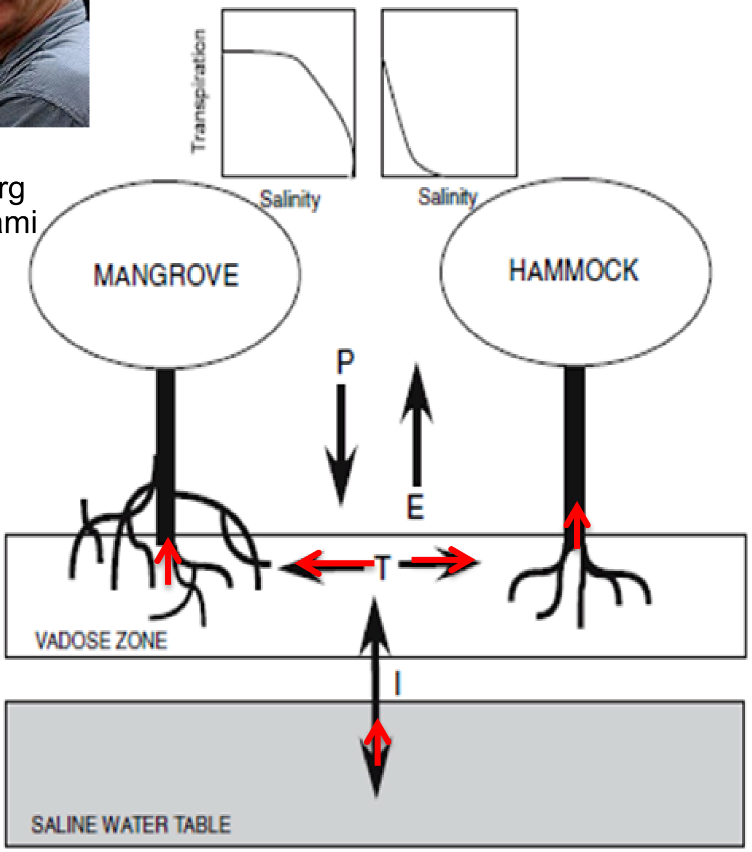
Hardwood Hammock (glychophytic)

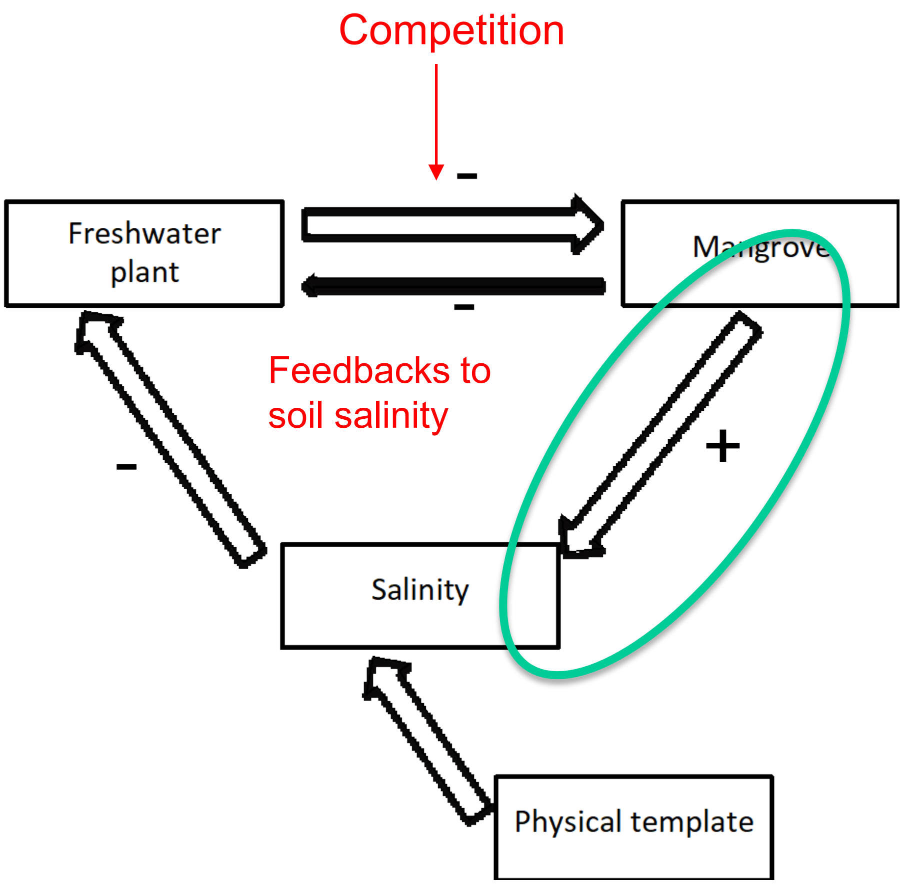


Maintenance of the typical sharp ecotone has been explained in terms of positive feedbacks between vegetation and soil salinity



Leo Sternberg U of Miami





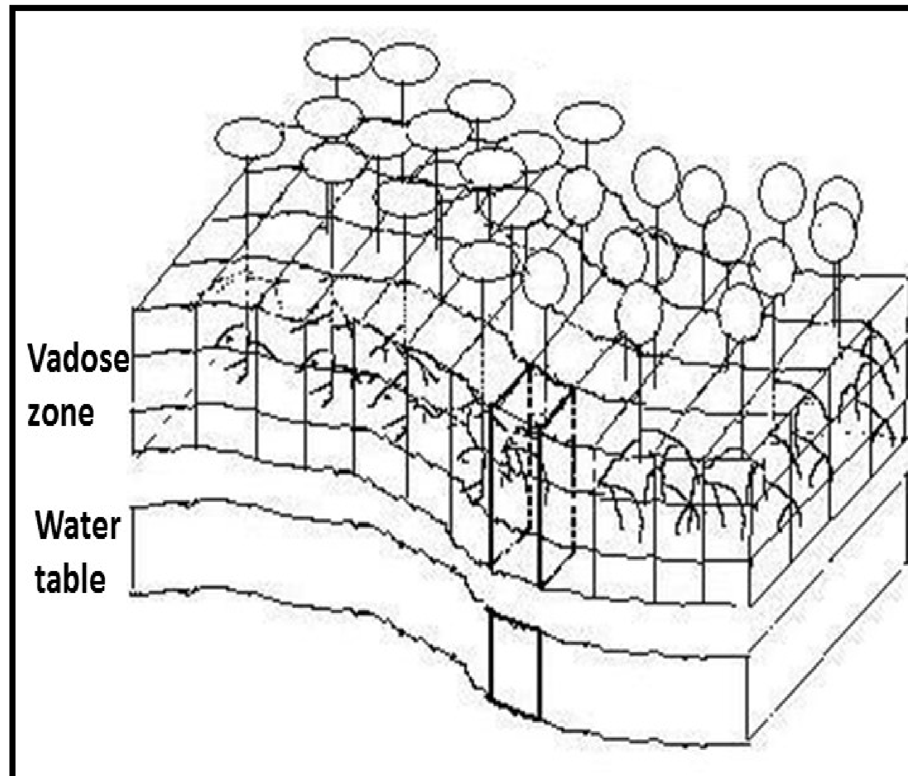
Sternberg, Teh, Ewe, Miralles-Wilhelm, DeAngelis. 2007. Ecosystems 10:648-660.

A spatially explicit model, MANHAM, was developed to simulate competition between mangroves and hardwood hammock vegetation, taking into account soil water and salinity processes.

Dr. Jiang Jiang, U. Miami, now Asst. Prof. Nanjing Forestry University

1. 100×100 grid of spatial cells, and each cell holds a seedling or a mature tree.

2. In each cell hydrology and salinity dynamics are modeled.



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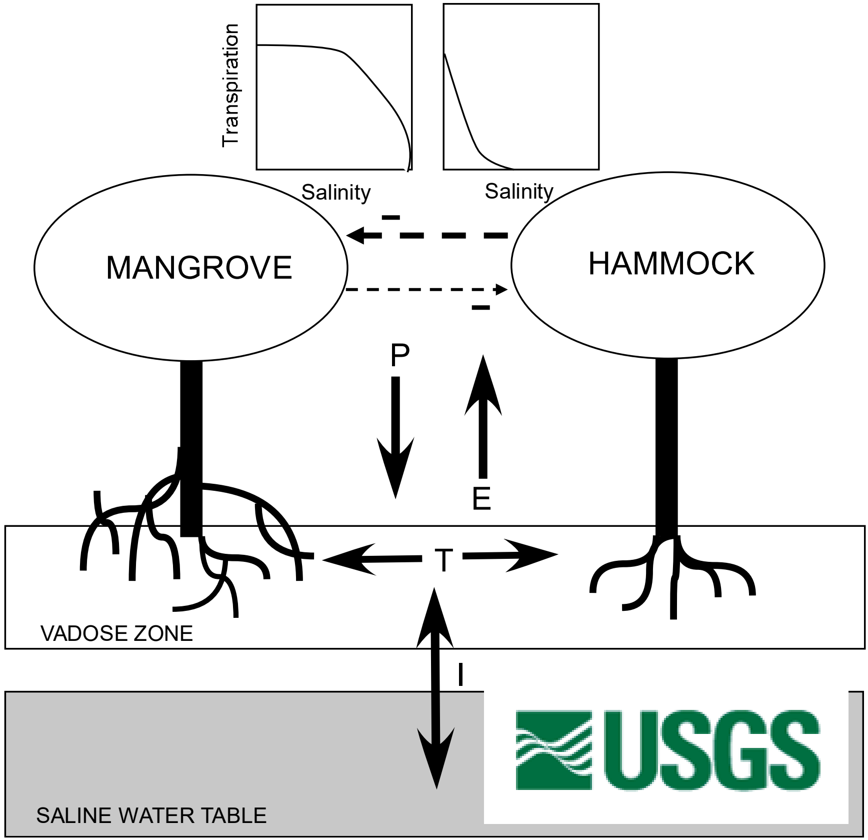
Simulations with MANHAM predicted formation of a sharp ecotone between halophytic and glycophytic vegetation

- 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 Precipitation, Transpiration, Infiltration, and Tides, with Seasonality.
- Simulates vegetation dynamics.
- Competing vegetation types with different salinity tolerances.



Teh, S. Y., D. L. DeAngelis, L. S. L. Sternberg, F. R. Miralles-Wilhelm, T. J. Smith, and H.-L. Koh. 2008. *Ecological Modelling* 213:2

MANHAM also revealed that storm surges may move the ecotone inland by pushing sea water far inland and causing regime shifts.

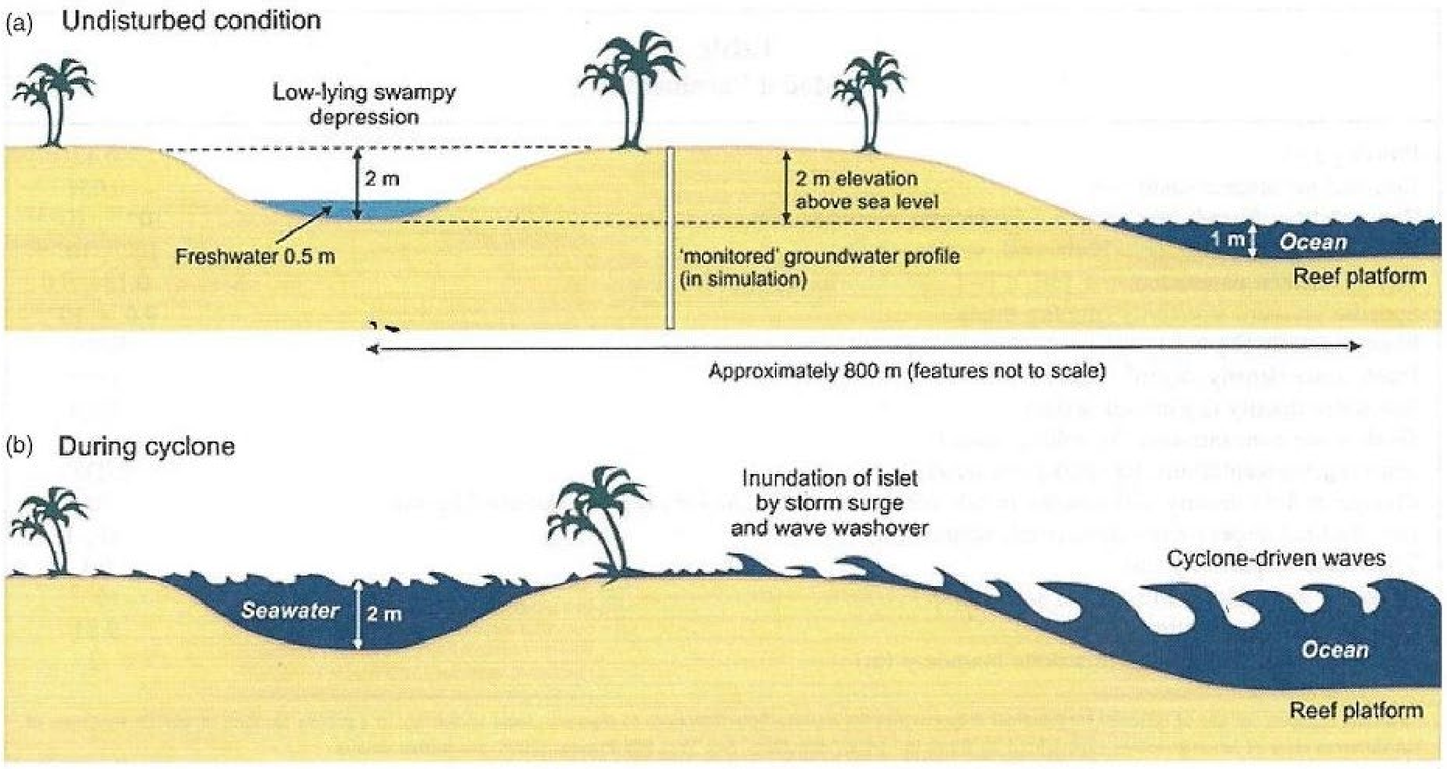
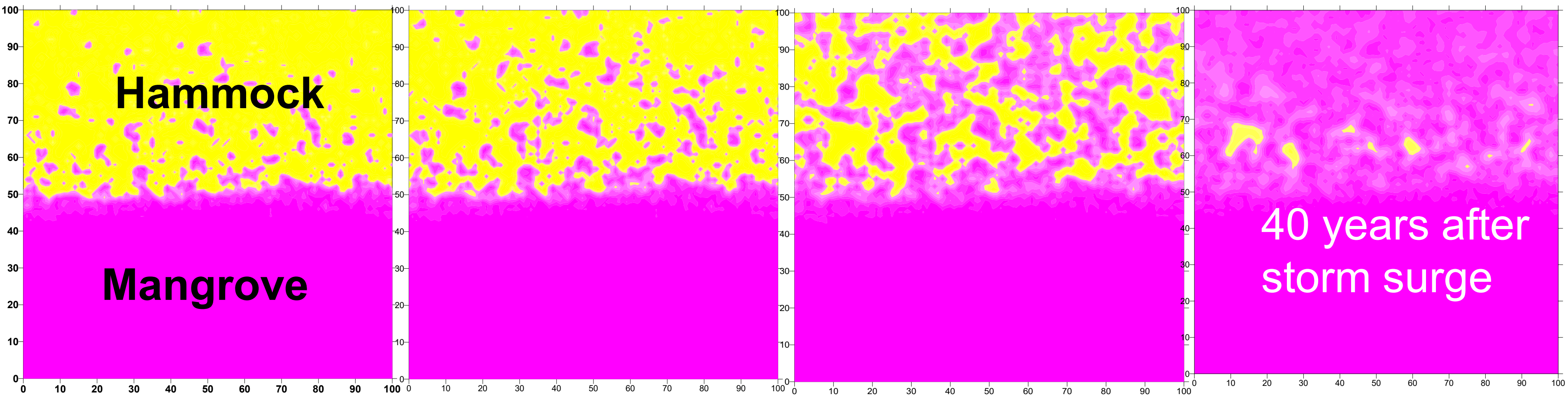


Figure from Chui and Terry, *Groundwater* (2011) doi: 10.1111/j.1745-6584.2011.00860.x

This simulation shows of landward movement of mangroves into former hammock following a storm surge



But to improve the hydrology/salinity aspects of the model we upgraded MANHAM by coupling to USGS's SUTRA groundwater model.

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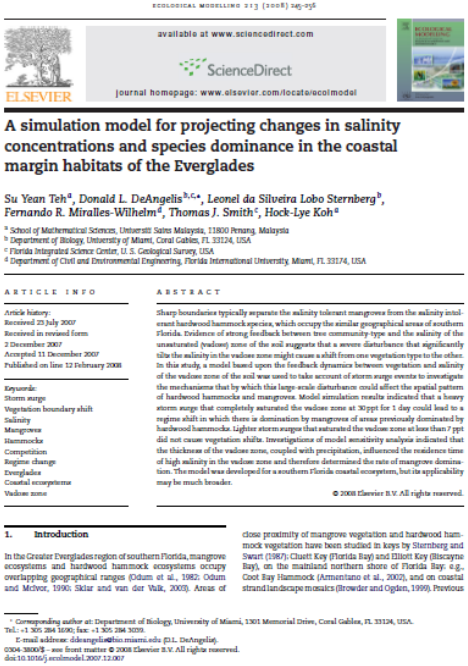
MANham + suTRA = MANTRA

- 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 on a coastal area or small island, containing zones of freshwater and halophytic vegetation.



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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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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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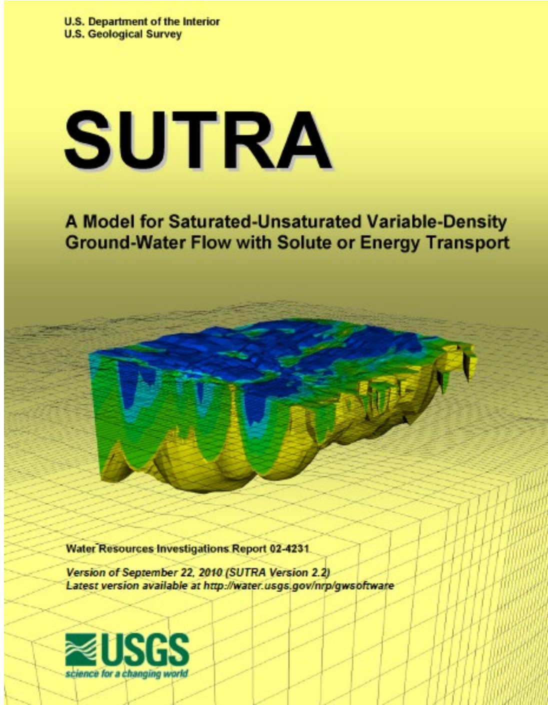
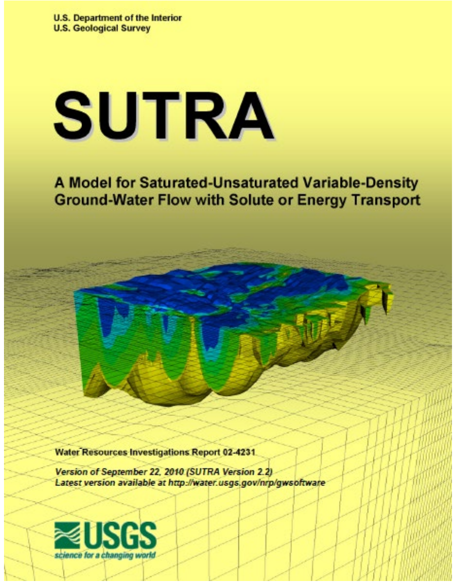


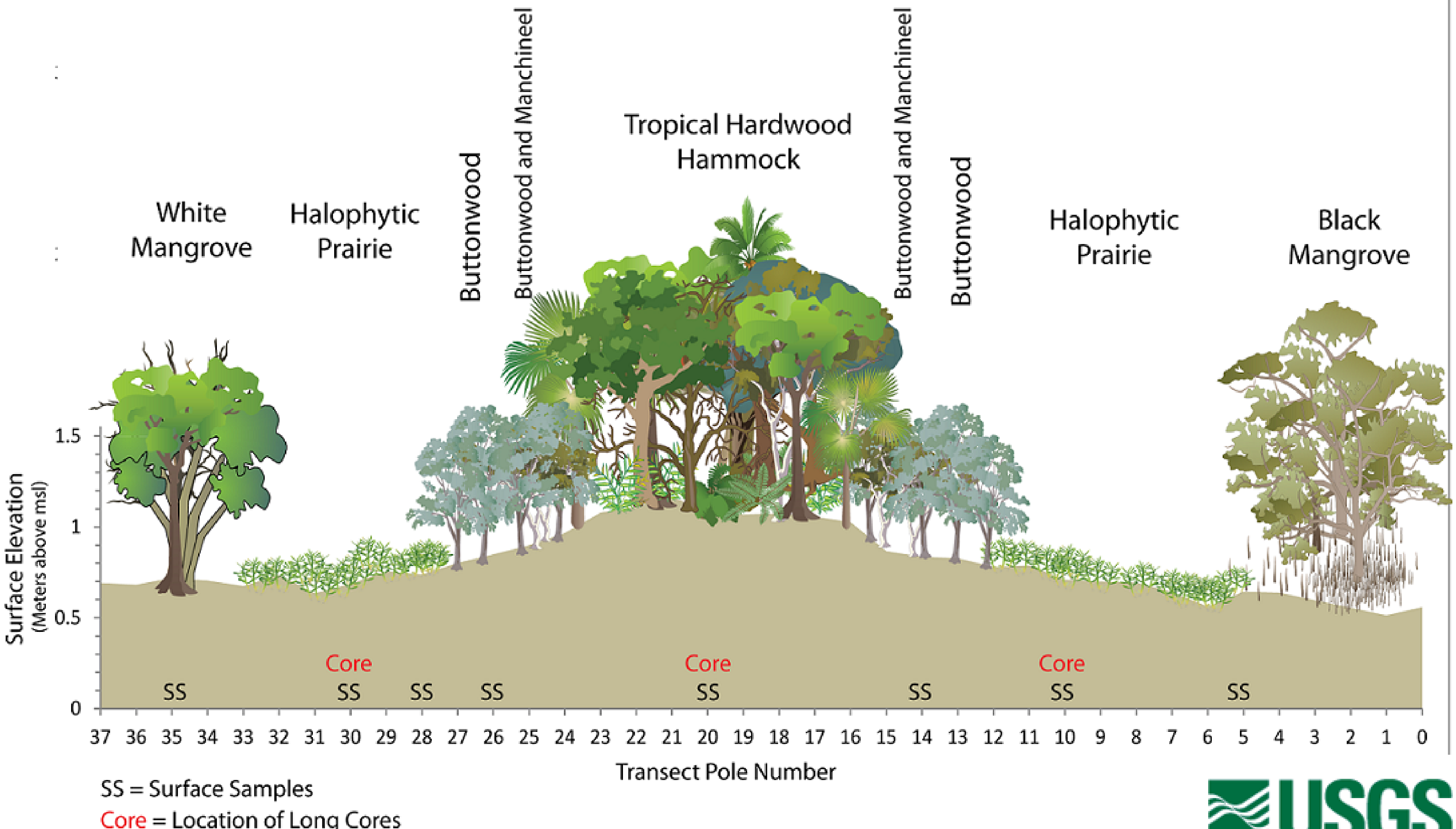
SUTRA

- Simulates fluid movement and the transport of either energy or dissolved substances in a subsurface environment;
  - Fluid density-dependent saturated-unsaturated ground-water flow.
  - Transport of a solute (salinity) in the ground water.

Voss CI, Provost AM (2010) (Version of September 22, 2010), SUTRA, A model for saturated-unsaturated variable-density ground-water flow with solute or energy transport, U.S. Geological Survey Water-Resources Investigations Report 02-4231, US Geological Survey, Reston, VA, 291 p.



We used MANTRA to make specific prediction of regime shift of Coot Bay Hammock in the Everglades following hurricane and storm surge (Teh et al. 2015).



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MANTRA Simulation Results

- Three conditions are necessary for a hammock to undergo a regime shift leading to a mangrove community:
  i. sufficiently severe damage to the existing hammock to open gaps to allow growth of invading seedlings,
  ii. a large input of salinity persisting for a long enough period of time to favor growth of mangrove seedlings in competition remaining freshwater vegetation, and,
  iii. an input of enough mangrove seedlings to allow mangroves to be present in sufficient number to influence the future soil salinity.

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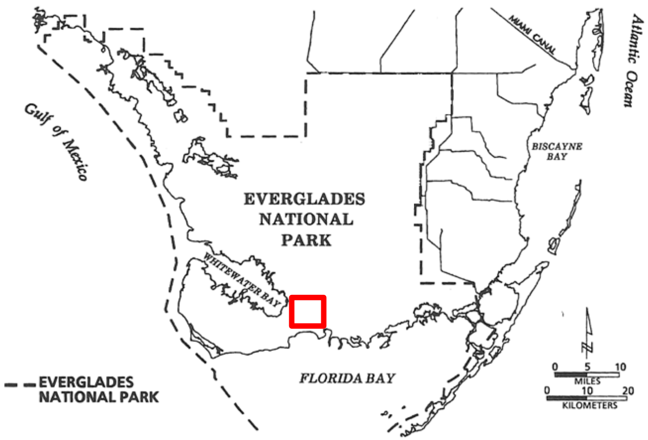
We can now test the prediction of MANTRA for Coot Bay Hammock



Much of the Coot Bay Hammock was hit and badly damaged by Hurricane Irma (September 2017) and its storm surge. Therefore, it will be possible to test the prediction of the model that some of this hammock may convert to halophytic vegetation.

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Developing an ‘early warning system’ of regime shift

Our current goal is to make precise predictions of when salinity stress due to SLR or storm surge is strong enough to lead to an eventual ‘regime shift’ from glycophytic to halophytic vegetation.

But both soil salinity around vegetation and early signs of salinity stress are hard to measure. A proxy is needed.

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$\delta^{18}O$: A Salinity Stress Indicator

- $\delta^{18}O$ in tree stem water can be used as a proxy for salinity stress.

- $\delta^{18}O$ is an appropriate indicator because:
  1. The $\delta^{18}O$ value of water is indicative of its salinity in South Florida and other places.
  2. Plants do not discriminate against $H_2{}^{18}O$ during water uptake although they discriminate against salt.

- $\therefore$ $\delta^{18}O$ will tend to increase in tree stem water when the soil conditions become more saline, even though the salt ions are excluded from the tree roots

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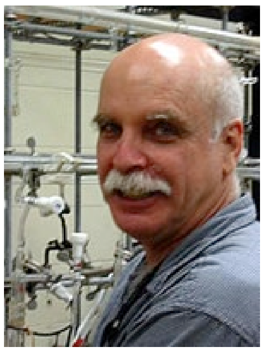
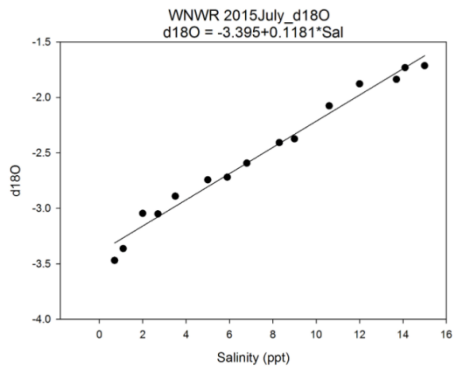
This has been further corroborated in field work by Prof. Leo Sternberg and Dr. Lu Zhai

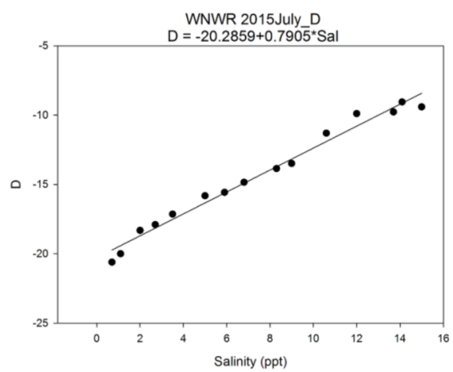
Salinity correlates with ¹⁸0 in water, and can easily be measured in tree stemwater

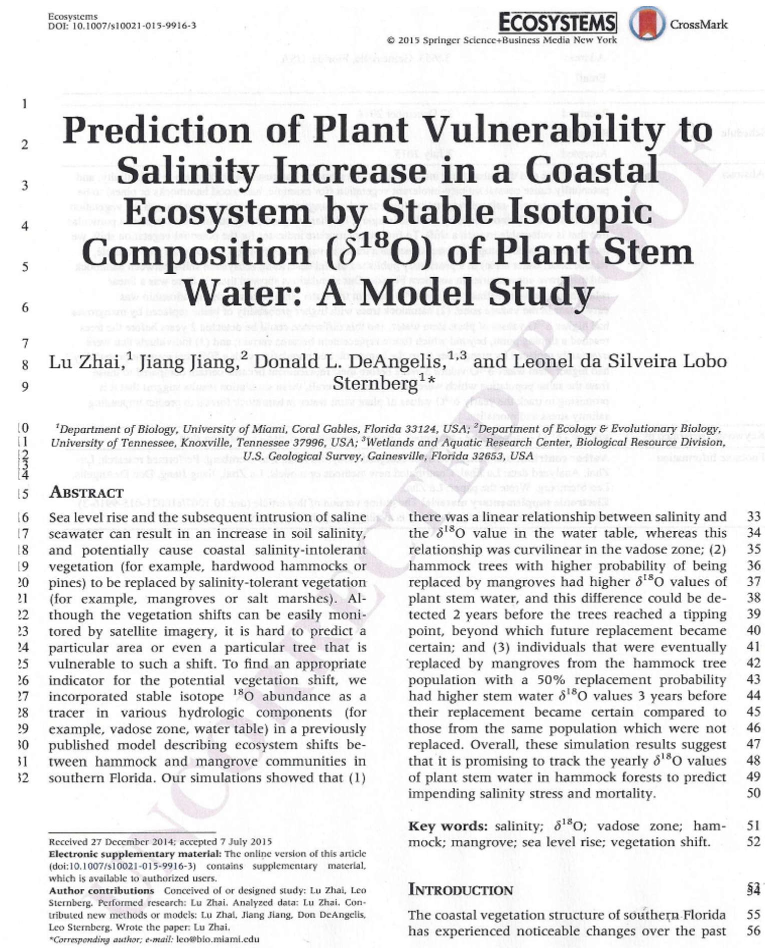


Prof. Leo Sternberg,U. Miami

Lu Zhai, grad student, U. Miami, now Los Alamos







Ecosystems
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ECOSYSTEMS

CrossMark

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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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.

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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.

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Introduction

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

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Based on field information, a spatially explicit ABM was developed: MANTRA-O18 simulation code, incorporating δ^{18}O in MANTRA

Prof. Su Yean Teh, Science University of Malaysia

Hydrogeology Journal
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PAPER

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Modeling δ^{18}O as an early indicator of regime shift arising from salinity stress in coastal vegetation

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Abstract
In many important coastal habitats, a combination of increasing soil salinization due to sea level rise, reduced precipitation and storm surges may induce regime shift from salinity-intolerant glycophytic vegetation to salinity-tolerant halophytic species. Early detection of regime shift due to salinity stress in vegetation may facilitate conservation efforts. It has been shown that the ^{18}O value of water in the xylem of trees can be used as a surrogate for salinity in the rooting zone of plants. Coupling measured δ^{18}O values in the tree xylem with simulated δ^{18}O values in trees and salinity in the vadose zone can be used to investigate competitive responses of glycophytic versus halophytic trees. MANTRA-O18 simulations suggest that the impacts of salinization on diminishing the resilience of salinity-intolerant trees can be detected up to 25 years before the glycophytic trees are threatened with regime shift to halophytic species. This early detection provides critical lead time and valuable information and insights useful for planning adaptation strategy to mitigate against the adverse impacts of sea level rise and climate change.

Keywords Sea level rise · Storm surge · MANTRA-O18 · Numerical modeling · Stable isotopes

Introduction

Coastal vegetation regime shift

Landward invasion of salinity-tolerant (halophytic) mangroves at the expense of salinity-intolerant (glycophytic) freshwater vegetation has been the subject of fascinating literature discussion on coastal ecosystems (e.g., Nicholls and Cazenave 2010; Ross et al. 1994, 2000, 2009; Saha et al. 2011a). Such regime shifts between mangroves and freshwater vegetation may be gradual (Doyle and Girod 1997; Krauss et al. 2011), as a consequence of gradual sea level rise (SLR); however, there may be rapid regime shifts (Baldwin and Mendelssohn 1998), due to large salinity pulses in the vadose zones of freshwater vegetation habitats, caused by intense storm surge overwash (Steyer et al. 2010) covering extensive area. A combination of SLR and frequent storm surges presents the most severe threats to coastal fresh groundwater and vegetation, as might be the case for low-lying southern Florida, or other regions of southeastern United States. Mechanisms of positive feedback help sustain resilience of coastal resources and maintain the separate zonation of halophytic and glycophytic vegetation types. Halophytic vegetation tends to promote high local soil salinity, while glycophytic vegetation has the tendency to maintain low soil salinity conditions (Jiang et al. 2016; Sternberg et al. 2007). This feedback promotes resilience of glycophytic coastal vegetation against regime shift to halophytic vegetation. Regime shift can potentially be induced by coastal disturbances such as persistent SLR and frequent storm sur
large pulses of high soil salinity from stor

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10040-019-01930-3) contains supplementary material, which is available to authorized users.

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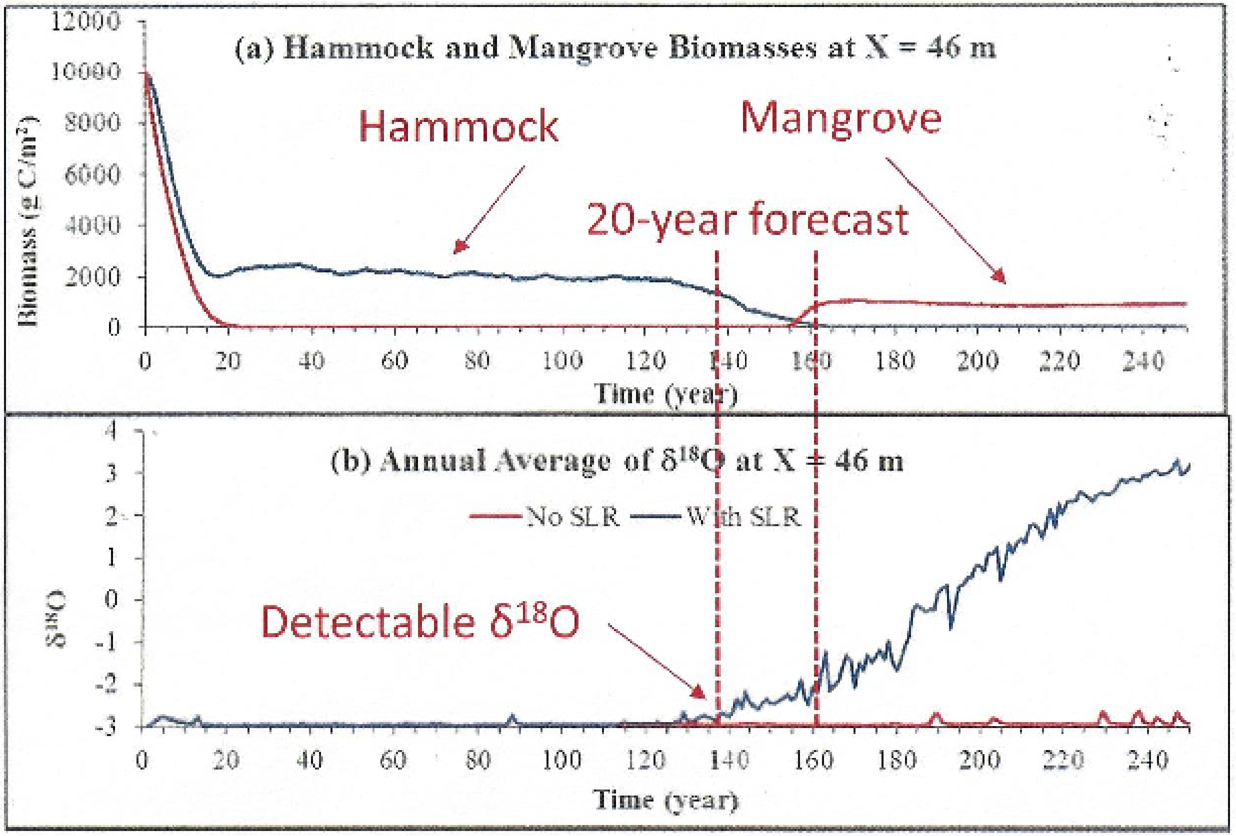
MANTRA-O18 Provides an Early Warning System for Vegetation Change

MANTRA-O18 allows predicting inevitable regime shift, due to positive feedback initiation, about 20 years in advance.



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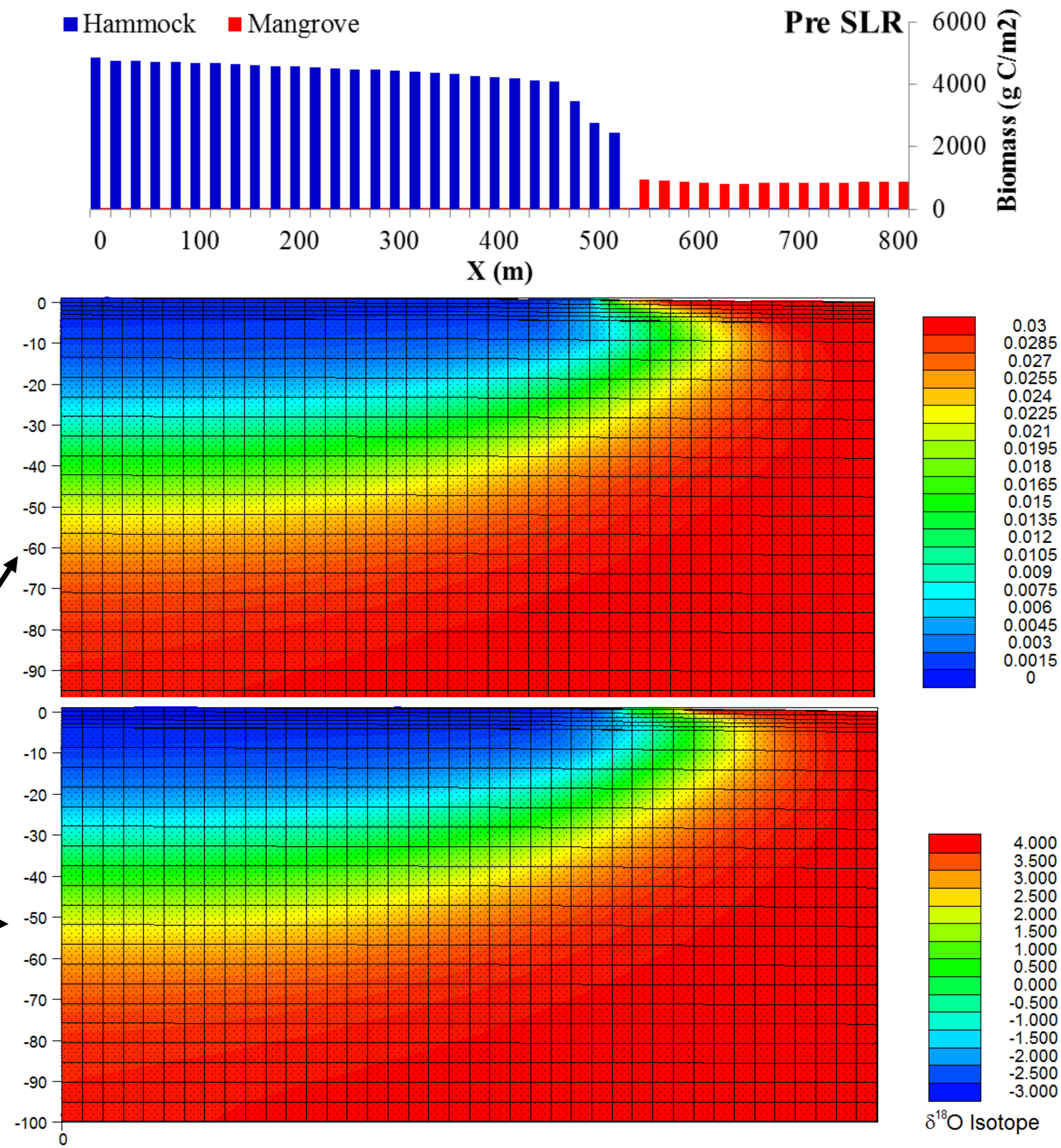
Predicting the $\delta^{18}O$ profile along with the salinity profile through time will be useful.

The following slides shows an example simulation of the effects of sea level rise on both vegetation and salinity profiles using MANTRA-O18.

MANTRA simulates both the changes in mangrove and hammock cover and the salinity and $\delta^{18}O$ fields in the ground water and vadose zone

Salinity

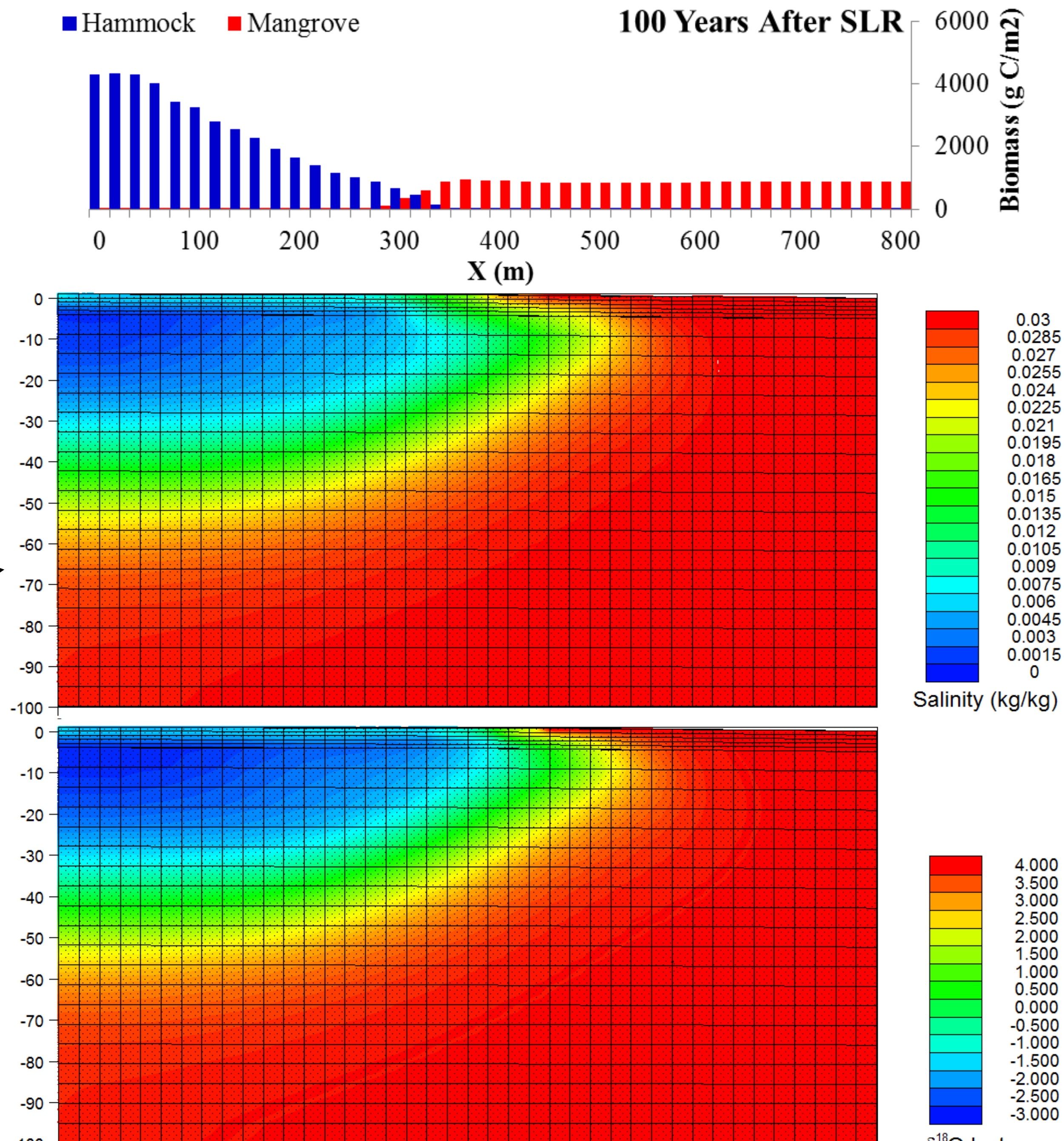
$\delta^{18}O$



After some period of sea level rise

Salinity
(red = 0.03)

$\delta^{18}O$



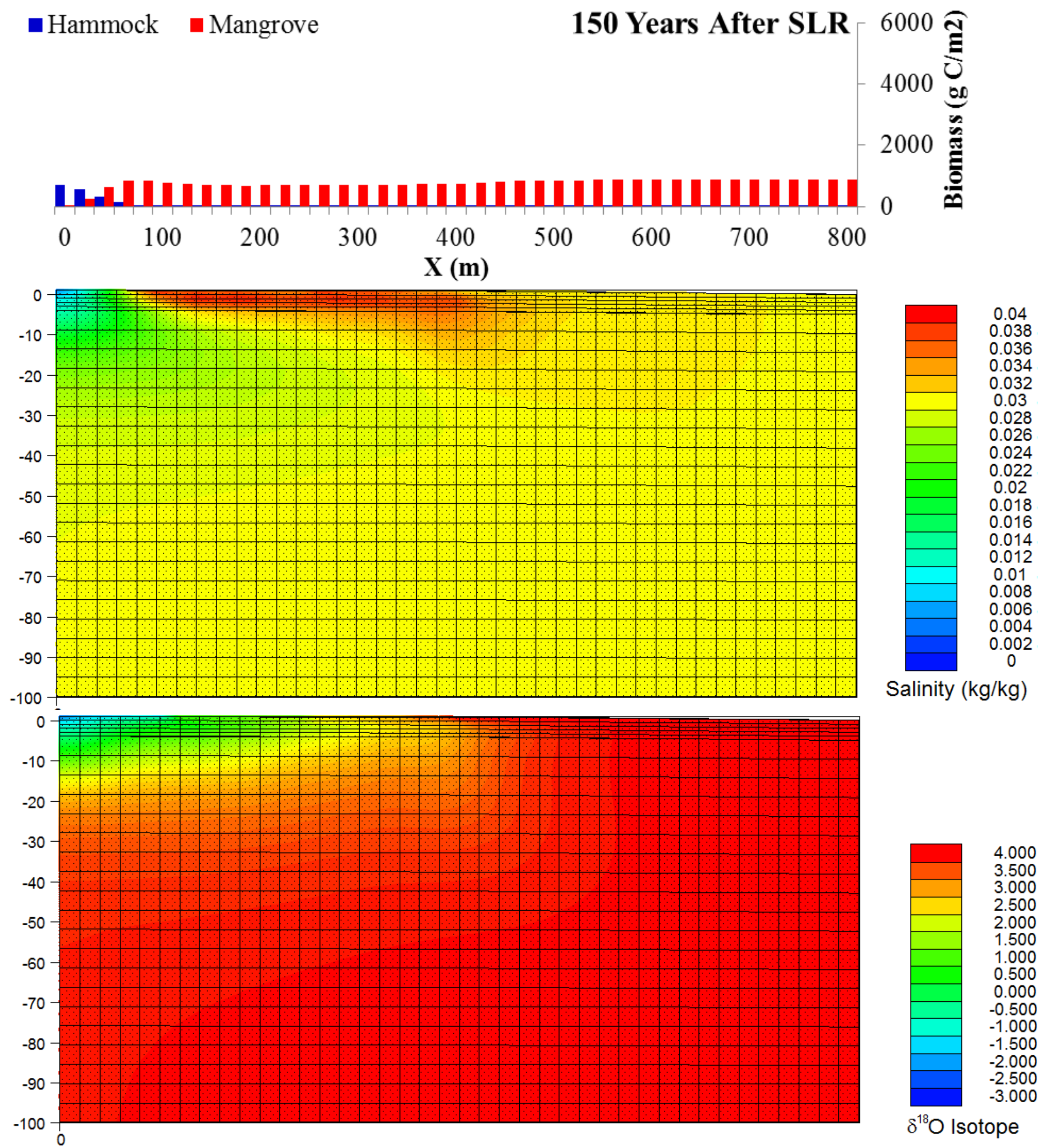
Further sea level rise.

Salinity

Note: Yellow is now 0.03, red is 0.04 due to high concentration in vadose zone

δ[18]O

There is no high concentration in vadose zone due to pland uptake



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Conclusions

- We demonstrated, using modeling, the formation of sharp halophyte/glycophyte boundary and showed potential for regime shifts from storm surges.
- MANTRA, hydrology-salinity-vegetation competition model, was used to make predictions for hurricane/storm surge related regime shift for a specific location, which can now be tested.
- We showed that stable isotopes in combination with MANTRA-O18 will provide a methodology of early prediction of regime shifts to halophytic vegetation, more than a decade in advance.

We appreciate funding from the **Greater Everglades Priority Ecosystem Science (GEPES)** Program

Thank you for your attention.

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