BEFORE THE GHOSTS APPEAR: IDENTIFYING THE EFFECTS OF CHRONIC SALTWATER INTRUSION ON COASTAL FLOODPLAIN SWAMPS USING REMOTE SENSING

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²Environmental Engineering Sciences, University of Florida
The Take-Home Message

• Remote-sensing (RS) data can be used to identify saltwater-stressed coastal floodplain swamps...

• Outcomes easier to detect than process

• RS can be used for monitoring and exploration...coupled with local knowledge
The Coastal Wetland Mosaic

- Coastal margins are inhabited by a mosaic of different wetland types
- Abiotic gradients strongly drive ecosystem structure and function
  - Hydroperiod, salinity, nutrients

( Oliver-Cabrera and Wdowinski 2016)
Coastal Floodplain Swamps (CFS)

- Coastal floodplain swamps (CFS) prevalent coastal ecosystem in SE USA
- CFS provide $25,681 \text{ ha}^{-1} \text{ yr}^{-1}$ worth of ecosystem services (Costanza 2014;)
  - Nutrient removal, storm surge attenuation, and carbon sequestration (Blair et al. 2015)
- Landscape position $\rightarrow$ vulnerable to saltwater intrusion (SWI) (Krauss et al. 2009)
Sea Level Rise and Saltwater Intrusion

- Sea level rise represents a significant stressor to CFS.
- Current rates of SLR outpace CFS soil accretion (Craft 2012).
- Saltwater intrusion is a well documented threat to CFS (Middleton et al. 2015).

(Craft 2012)
Coastal Floodplain Swamps and Salinization

- CFS species have limited tolerance to salinity (Pezeshki et al. 1987)
- Chronic SWI can lead to a shift in community structure and function (White and Kaplan 2017)
- CFS will be converted to salt marsh or open water in the long-term (Brinson et al. 1995)
- Need for a region-wide approach to understand the effects of SWI on CFS ecology
Mainstream Attention to “Ghost Forests”

“Ghost forests”: What they are and why they’re becoming more common
Body of Work on CFS and Salinization

Response of baldcypress (Taxodium distichum L. var. Distichum) to increases in flooding salinity in Louisiana’s Mississippi River deltaic plain

Authors: S. R. Pezeshki, R. D. DeLaune, W. H. Patrick

GROWTH AND NUTRITION OF BALDCYPRESS FAMILIES PLANTED UNDER VARYING SALINITY REGIMES IN LOUISIANA, USA

Ken W. Krausz, Jim L. Chambers, James A. Allen, David M. Sotelo Jr., Antonio S. DeSoto

Identification of salt tolerant baldcypress (Taxodium distichum (L.) Rich) for planting in coastal areas

Authors: William H. Connor, L. Wayne Inabinette

Interaction of flooding and salinity stress on baldcypress (Taxodium distichum) (L.) Rich

James A. Allen, S. Reza Pezeshki, Jim L. Chambers

Selection for Salt Tolerance in Tidal Freshwater Swamp Species: Advances Using Baldcypress as a Model for Restoration

Authors: Ken W. Krausz, Jim L. Chambers, David Creech

Tidal Freshwater Swamps of the Southeastern United States: Effects of Land Use, Hurricanes, Sea-level Rise, and Climate Change

Authors: Thomas W. Doyle, Calvin P. O’Neal, Marcia P. Melder, Andrew S. From, Monica H. Palka

Degradation of Baldcypress–Water Tupelo Swamp to Marsh and Open Water in Southeastern Louisiana, U.S.A.: An Irreversible Trajectory?

Gary P. Shaffer, William B. Wood, Susanne S. Hoeppner, Thais E. Perkins, Jason Zoller, and Demetra Kandalepas

SEASONAL PATTERNS OF RIVER CONNECTIVITY AND SALWATER INTRUSION IN TIDAL FRESHWATER FORESTED WETLANDS

Christopher J. Anderson, B. Graeme Lockaby

Flooding and saltwater intrusion: Potential effects on survival and productivity of wetland forests along the U.S. Gulf Coast


Disentangling the effects of drought, salinity, and sulfate on baldcypress growth in a coastal plain restored wetland

Amanda S. Powell, Lonnie Jackson, Marcelo Artón

Groundwater salinity in a floodplain forest impacted by saltwater intrusion

Authors: David A. Kaplan, R. B. Nebel, Rafael Muñoz-Carpena

Effects of Hurricane Katrina on the forest structure of Taxodium distichum swamps of the Gulf Coast, USA

Authors: Beth A. Middleton
Challenges of Traditional/Field Methods

- Time
- Cost
- Permit Required
- Interest

(Strayer et al. 1986, Franklin 1989, Lovett et al. 2007)
Detecting Vegetative Change Using Remote Sensing


• **Enhanced vegetation index (EVI)**
  • Sensitive to high biomass (Huete et al. 2002)
  • Corrects for aerosol scattering and background soil

• Variety of RS tools available: Google Earth Engine (GEE) is fast, free, and user-friendly.

\[
EVI = G \times \frac{(NIR - RED)}{(NIR + C1 \times RED - C2 \times Blue + L)}
\]
Overarching Research Question

Can remote sensing data be used to track the long-term impacts of saltwater intrusion on coastal floodplain swamps?
Welcome to the Swamp, We Got Mud and Knees

- Mixture of **needle** and **broadleaf** canopy
  - *Taxodium distichum, Nyssa spp., Fraxinus spp.*
    (Brinson et al. 1980)

- Characterized by **yearly leaf senescence**
  - Varies with abiotic factors (i.e. flooding, temperature, salinity stress)

- Groundcover vegetation is **rare**, and **sparse** when present (Huenneke and Sharitz 1986)

- Canopy species have limited salinity tolerance
Idealized Difference In CFS Health

Summer Canopy

Upstream

Downstream
Idealized Difference In CFS Health

Summer Canopy

Upstream

Summer Understory

Downstream
Idealized Difference In CFS Health

Upstream
- Summer Canopy
- Summer Understory
- Winter Understory

Downstream
- Summer Understory
- Winter Understory
Expected Differences in EVI

Long-term Trends

Average Year

EVI Distribution
Expected Differences in EVI

Long-term Trends

Average Year

EVI Distribution

EVI Distribution
Hypotheses – $H_1$: Magnitude and Distribution

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Rationale</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{1A}$: $\bar{X}<em>{EVI</em>{alt}} &lt; EVI_{fresh}$</td>
<td>Lower EVI at SWI sites may indicate the presence of a stressor</td>
<td>MWU</td>
</tr>
<tr>
<td>$H_{1B}$: $X_{-} - EVI_{alt} \neq EVI_{fresh}$</td>
<td>Differences in distribution imply changes to phenological patterns</td>
<td>KS</td>
</tr>
</tbody>
</table>

The symbols $\bar{X}$ and $X_{-}$ represent median and standard deviation, respectively. Statistical techniques and test used in this study are abbreviated as follows: Mann-Whitney U (MWU), Kolmogorov-Smirnov (KS), Linear Regression (LR), and Mann-Kendall (MK).
Hypotheses – $H_2$: Long-term Trends

Table 1. A suite of hypothesis developed to help identify the effects of SWI on CFS using remote sensing

<table>
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<tr>
<td>$H_{2A}$: Slope EVI_{st} &lt; 0</td>
<td>Negative slope at stressed sites likely driven by SWI induced stress</td>
<td>LR, MK</td>
</tr>
<tr>
<td>$H_{2B}$: Slope EVI_{trend} &lt; 0</td>
<td>A declining trend indicates a long-term change in EVI</td>
<td>LR, MK</td>
</tr>
<tr>
<td>$H_{2C}$: Slope EVI_{D,U} &lt; 0</td>
<td>The ratio accounts for shared regional stressors, meaning a declining slope indicates local stressor is affecting the stressed site</td>
<td>LR, MK</td>
</tr>
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</table>

Years

EVI

Upstream

Downstream

The symbols $\bar{X}$ and $\times$ represent median and standard deviation, respectively. Statistical techniques and test used in this study are abbreviated as follows: Mann-Whitney U (MWU), Kolmogorov-Smirnov (KS), Linear Regression (LR), and Mann-Kendall (MK).
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<tr>
<td>$H_{3a}$: $\bar{X}$ EVI$<em>{0.5}$ &lt; EVI$</em>{0.6}$</td>
<td>Lower growing season EVI can indicate effect of SWI stress on peak biomass/productivity</td>
<td>MWU</td>
</tr>
<tr>
<td>$H_{3b}$: $\bar{X}$ EVI$<em>{0.6}$ &gt; EVI$</em>{0.5}$</td>
<td>Higher dormant seasons EVI may indicate the presence of salt-tolerant canopy and herbaceous species (Succession)</td>
<td>MWU</td>
</tr>
<tr>
<td>$H_{3c}$: $\bar{X}$ EVI$<em>{0.5}$ &lt; EVI$</em>{0.6}$</td>
<td>Lower G:D ratio implies a decrease in seasonal variation (Phenological change)</td>
<td>MWU</td>
</tr>
<tr>
<td>$H_{3d}$: Slope EVI$_{0.5}$ &lt; 0</td>
<td>A declining slope indicates a chronic stressor is present</td>
<td>LR, MK</td>
</tr>
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Site Selection – Long-term Salinity/Veg Monitoring

Neches SE Louisiana Big Bend Suwannee
Remote Sensing Workflow

**RS Data**
- MODIS Terra
  - 500m Surface Reflectance

**Masking**
- Clouds, cloud shadows, and incomplete pixels

**Calculations**
- EVI is calculated per pixel and averaged across the ROI

**Daily EVI**
- Graph showing EVI over time from 2000 to 2015.
Were the Hypotheses Supported?

- 52.8% support across all sites
- Support varied across regions
  - Suwannee and Big Bend >50%
  - SE Louisiana and Neches <50%
- Subset of “best-performing” hypotheses more supported across all regions

### Table 3. Results of hypothesis testing in each region

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<tr>
<th>Hypothesis</th>
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<th>Neches</th>
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<tr>
<td>$H_{1A}$: $\bar{X} \text{EVI}<em>{\text{sat}} &lt; \text{EVI}</em>{\text{fresh}}$</td>
<td>True</td>
<td>True</td>
<td>False</td>
<td>True</td>
<td>75*</td>
</tr>
<tr>
<td>$H_{1B}$: $X \sim \text{EVI}<em>{\text{sat}} \neq \text{EVI}</em>{\text{fresh}}$</td>
<td>True</td>
<td>True</td>
<td>True</td>
<td>True</td>
<td>100*</td>
</tr>
<tr>
<td>$H_{2A}$: Slope $\text{EVI}_{\text{sat}} &lt; 0$</td>
<td>True</td>
<td>False</td>
<td>False</td>
<td>False</td>
<td>25</td>
</tr>
<tr>
<td>$H_{2B}$: Slope $\text{EVI}_{\text{rest,}S} &lt; 0$</td>
<td>True</td>
<td>False</td>
<td>False</td>
<td>False</td>
<td>25</td>
</tr>
<tr>
<td>$H_{2C}$: Slope $\text{EVI}_{D,U} &lt; 0$</td>
<td>True</td>
<td>False</td>
<td>False</td>
<td>False</td>
<td>50</td>
</tr>
<tr>
<td>$H_{3A}$: $\bar{X} \text{EVI}<em>{G,5} &lt; \text{EVI}</em>{G,F}$</td>
<td>True</td>
<td>True</td>
<td>False</td>
<td>True</td>
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<tr>
<td>$H_{3B}$: $\bar{X} \text{EVI}<em>{D,5} &gt; \text{EVI}</em>{D,F}$</td>
<td>False</td>
<td>True</td>
<td>True</td>
<td>False</td>
<td>50</td>
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<tr>
<td>$H_{3C}$: $\bar{X} \text{EVI}<em>{G,D,5} &lt; \text{EVI}</em>{G,D,F}$</td>
<td>True</td>
<td>True</td>
<td>True</td>
<td>False</td>
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<tr>
<td>$H_{3D}$: Slope $\text{EVI}_{G,D,5} &lt; 0$</td>
<td>False</td>
<td>False</td>
<td>False</td>
<td>False</td>
<td>0</td>
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**All Correct (%)**
- 78
- 56
- 33
- 44
- 52.8

**Best Performing (%)**
- 100
- 100
- 50
- 75
- 81.3

*Best performing hypotheses (*) were supported ≥ 75% across sites*
Why Were Certain Hypotheses Supported?

- Best-performing hypotheses relied on differences in summary statistics

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<td>True</td>
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<td>$H_{1B}$: $X \sim \text{EVI}<em>{\text{sh}} \neq \text{EVI}</em>{\text{sh}}$</td>
<td>True</td>
<td>True</td>
<td>True</td>
<td>True</td>
<td>100*</td>
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<tr>
<td>$H_{2A}$: $\bar{X} \text{EVI}<em>{G,8} &lt; \text{EVI}</em>{G,F}$</td>
<td>True</td>
<td>True</td>
<td>False</td>
<td>True</td>
<td>75*</td>
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<tr>
<td>$H_{2C}$: $\bar{X} \text{EVI}<em>{G,D,8} &lt; \text{EVI}</em>{G,D,F}$</td>
<td>True</td>
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Why Were Certain Hypotheses Supported?

- Best-performing hypotheses relied on differences in summary statistics
- 5 of 9 hypotheses had low support
  - Slow pace of change and interannual variation challenges detection

![Graph showing EVI levels in Neches River before and after drought](image)

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<td>H_{2A}: Slope EVI_{ah} &lt; 0</td>
<td>True</td>
<td>False</td>
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<td>False</td>
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<tr>
<td>H_{2B}: Slope EVI_{Pre,D} &lt; 0</td>
<td>True</td>
<td>False</td>
<td>False</td>
<td>False</td>
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<tr>
<td>H_{2C}: Slope EVI_{D,U} &lt; 0</td>
<td>True</td>
<td>False</td>
<td>False</td>
<td>True</td>
<td>50</td>
</tr>
<tr>
<td>H_{3B}: \bar{X} EVI_{D,S} &gt; EVI_{D,F}</td>
<td>False</td>
<td>True</td>
<td>True</td>
<td>False</td>
<td>50</td>
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<tr>
<td>H_{3D}: Slope EVI_{G,D,S} &lt; 0</td>
<td>False</td>
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• Best-performing hypotheses relied on differences in **summary statistics**

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  o Slow pace of change and interannual variation challenges detection

• Detecting process vs. outcome?

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<tr>
<td>H\textsubscript{2A}: Slope EVI\textsubscript{inh} &lt; 0</td>
<td>True</td>
<td>False</td>
<td>False</td>
<td>False</td>
<td>25</td>
</tr>
<tr>
<td>H\textsubscript{3B}: Slope EVI\textsubscript{trend,S} &lt; 0</td>
<td>True</td>
<td>False</td>
<td>False</td>
<td>False</td>
<td>25</td>
</tr>
<tr>
<td>H\textsubscript{3C}: Slope EVI\textsubscript{D,U} &lt; 0</td>
<td>True</td>
<td>False</td>
<td>False</td>
<td>True</td>
<td>50</td>
</tr>
<tr>
<td>H\textsubscript{3B}: EVI\textsubscript{D,S} &gt; EVI\textsubscript{D,F}</td>
<td>False</td>
<td>True</td>
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<td>H\textsubscript{3D}: Slope EVI\textsubscript{D,D,S} &lt; 0</td>
<td>False</td>
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Recall: Expected Differences in EVI

Distribution

Average Year

Long-term Trends

- Upstream
- Downstream

Density

EVI

EVI

EVI

Year

Years
Observed Differences in EVI Across All Sites

- Downstream slope = 3.34e-07, p-value = 0.9
- Upstream slope = -5.2e-07, p-value = 0.89
Technical and Methodological Considerations

• Sampling rate
  o MODIS period of record too short?
  o Landsat temporal resolution too low?
• Smaller pixel size would help capture smaller sites
• Local knowledge needed to contextualize results

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Landsat</th>
<th>MODIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral resolution</td>
<td>7 bands</td>
<td>36 bands</td>
</tr>
<tr>
<td>Pixel size</td>
<td>30 m</td>
<td>250, 500 or 1000 m</td>
</tr>
<tr>
<td>Scene width</td>
<td>185 km</td>
<td>2330 km</td>
</tr>
<tr>
<td>Image frequency</td>
<td>16 days</td>
<td>Twice daily</td>
</tr>
<tr>
<td>Corrections</td>
<td>None</td>
<td>Surface reflectance</td>
</tr>
</tbody>
</table>
Take Home Messages

• RS data can be used to identify chronic, low level SWI-stress in CFS
• Ecologically motivated hypotheses: some "work" better...
• SWI outcomes easier to detect than process
Next Steps – Supervised Classification

- Map extent/health of CFS across the Northern Gulf of Mexico and the South Atlantic Coast
  - Preliminary results using supervised classification
  - Challenges arise from the lack of uniformity at stressed sites
Thank you! Questions?

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David Kaplan, dkaplan@ufl.edu
H1A: Compares Median EVI Value

- Reduction in primary production via SWI is well-documented
- Chronic stress will lead to consistent lower production/biomass
- EVI value will/do reflect that trend
- Lack of Support in SE Louisiana
  - Proliferation of *Triadica sebifera*
  - Highly hydrologically altered

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<tr>
<td>H1A: ( \mu_{\text{sv}} &lt; \mu_{\text{bb}} )</td>
<td>True</td>
<td>True</td>
<td>False</td>
<td>True</td>
<td>75*</td>
</tr>
<tr>
<td>H1B: ( X \sim \text{EVI}<em>{\text{sv}} \neq \text{EVI}</em>{\text{bb}} )</td>
<td>True</td>
<td>True</td>
<td>True</td>
<td>True</td>
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<tr>
<td>H3A: ( \mu_{\text{G,S}} &lt; \mu_{\text{G,F}} )</td>
<td>True</td>
<td>True</td>
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<td>True</td>
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<td>H3B: ( \mu_{\text{G,D,S}} &lt; \mu_{\text{G,D,F}} )</td>
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- EVI value will/do reflect that trend
- Lack of Support in SE Louisiana
  - Proliferation of *Triadica sebifera*
  - Highly hydrologically altered
### H$_{1B}$: Compares EVI Distributions

- Demonstrates long-term changes to seasonal patterns
- Over time, stressed CFS will lose bimodality from:
  - Decreased growing season productivity
  - Increased understory biomass during the dormant season
  - Leaf emergence and senescence can shift due to SWI (Brinson et al. 1985, Pezeshki et al. 1988)

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<td>$H_{1A}$: $\mu_\text{EVI}<em>{\text{salt}} &lt; \mu</em>\text{EVI}_{\text{fresh}}$</td>
<td>True</td>
<td>True</td>
<td>False</td>
<td>True</td>
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<td>$H_{1B}$: $X \sim \text{EVI}<em>{\text{salt}} \neq \text{EVI}</em>{\text{fresh}}$</td>
<td>True</td>
<td>True</td>
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<td>$H_{3A}$: $\mu_\text{EVI}<em>{G,S} &lt; \mu</em>\text{EVI}_{G,F}$</td>
<td>True</td>
<td>True</td>
<td>False</td>
<td>True</td>
<td>75*</td>
</tr>
<tr>
<td>$H_{3C}$: $\mu_\text{EVI}<em>{G,D,S} &lt; \mu</em>\text{EVI}_{G,D,F}$</td>
<td>True</td>
<td>True</td>
<td>True</td>
<td>False</td>
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- Demonstrates long-term changes to seasonal patterns
- Over time, stressed CFS will lose bimodality from:
  - Decreased growing season productivity
  - Increased understory biomass during the dormant season
  - Leaf emergence and senescence can shift due to SWI (Brinson et al. 1985, Pezeshki et al. 1988)
H₃A: Compares Peak Growing Season Median EVI

- Highlights the effect of chronic SWI on peak primary production
- Stressed sites have consistently lower peak biomass
- Lack of support in SE Louisiana

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Suwannee</th>
<th>Big Bend</th>
<th>SE Louisiana</th>
<th>Neches</th>
<th>Correct (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₃A: μ EVIₛₑ ≤ EVIₑₑₑₑ</td>
<td>True</td>
<td>True</td>
<td>False</td>
<td>True</td>
<td>75*</td>
</tr>
<tr>
<td>H₃B: X~ EVIₛₑ ≠ EVIₑₑₑₑ</td>
<td>True</td>
<td>True</td>
<td>True</td>
<td>True</td>
<td>100*</td>
</tr>
<tr>
<td>H₃C: μ EVIₑₑₑₑ ≤ EVIₑₑₑₑ</td>
<td>True</td>
<td>True</td>
<td>False</td>
<td>True</td>
<td>75*</td>
</tr>
<tr>
<td>H₃C: μ EVIₑₑₑₑ ≤ EVIₑₑₑₑ</td>
<td>True</td>
<td>True</td>
<td>True</td>
<td>False</td>
<td>75*</td>
</tr>
</tbody>
</table>

All Correct (%) | 78 | 56 | 33 | 44 | 52.8:52.8
Best Performing (%) | 100 | 100 | 50 | 75 | 81.3

*Best performing hypotheses (≥ 75%)*
H$_3$C: Compares Median Growing:Dormant Season EVI Ratio

- Shows consistent changes to seasonal dynamics
- Lack of Support in Neches
  - Historic drought in 2010 to 2011 (Nielsen-Gammon 2012)

Table 3. Results of hypothesis testing in each region

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Suwannee</th>
<th>Big Bend</th>
<th>SE Louisiana</th>
<th>Neches</th>
<th>Correct (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$<em>{1A}$: $\mu$ EVI$</em>{sali}$ &lt; EVI$_{emb}$</td>
<td>True</td>
<td>True</td>
<td>False</td>
<td>True</td>
<td>75*</td>
</tr>
<tr>
<td>H$<em>{1B}$: $X$~ EVI$</em>{sali}$ ≠ EVI$_{fresh}$</td>
<td>True</td>
<td>True</td>
<td>True</td>
<td>True</td>
<td>100*</td>
</tr>
<tr>
<td>H$<em>{3A}$: $\mu$ EVI$</em>{G,S}$ ≤ EVI$_{G,F}$</td>
<td>True</td>
<td>True</td>
<td>False</td>
<td>True</td>
<td>75*</td>
</tr>
<tr>
<td>H$<em>{3C}$: $\mu$ EVI$</em>{G,DS}$ &lt; EVI$_{G,DF}$</td>
<td>True</td>
<td>True</td>
<td>True</td>
<td>False</td>
<td>75*</td>
</tr>
</tbody>
</table>

All Correct (%) | 78 | 56 | 33 | 44 | 52.8;52.8
Best Performing (%) | 100 | 100 | 50 | 75 | 81.3

*Best performing hypotheses ($\geq$ 75%)
H$_{3C}$: Compares Median Growing:Dormant Season EVI Ratio

- Shows consistent changes to seasonal dynamics
- Lack of Support in Neches
  - Historic drought in 2010 to 2011 (Nielsen-Gammon 2012)
H₃C: Compares Median Growing:Dormant Season EVI Ratio

• Shows consistent changes to seasonal dynamics
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