

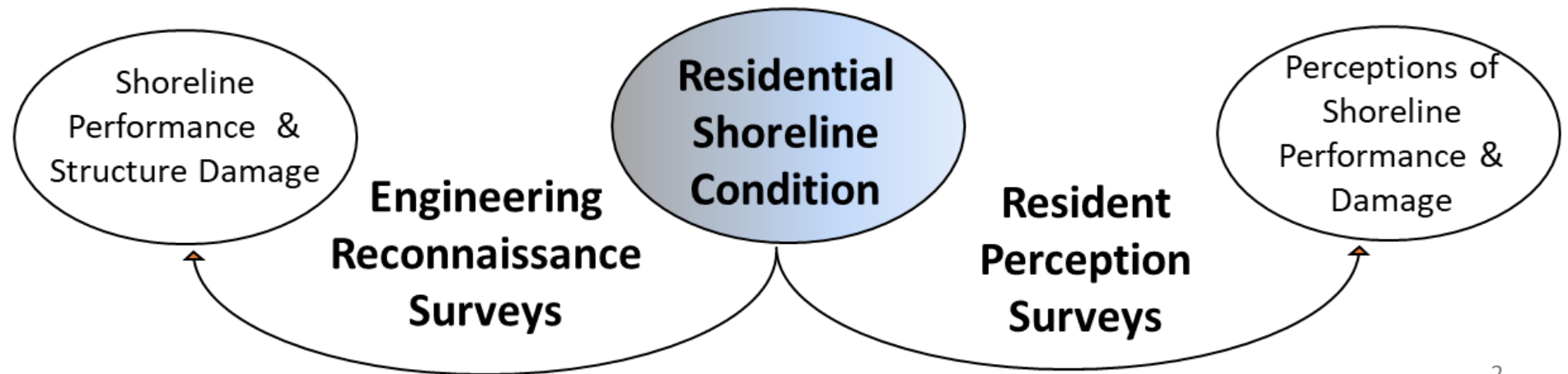
# Case Study: Interconnectivities between Shoreline Type and Structural Vulnerability

**The Role of Mangroves in Mitigating Damage due to Hurricane Irma in the Florida Keys**

Tori Tomiczek, Kelsi Furman, Brittany Webbmartin, Kiera O'Donnell, Steven Scyphers

# Outline

1. Introduction: The Florida Keys and Hurricane Irma
2. Post-Storm Reconnaissance
  - a. Shoreline Damage- Island and Parcel Scales
  - b. Structural Damage- Parcel Scale
4. Interconnectivities between Hazard, Shoreline Archetype, and Physical Damage
5. Homeowner Perceptions of Shoreline Performance
6. Ongoing Work and Next Steps
7. Conclusions



# Florida Keys: Structural Consistency, Shoreline Variability

DOC



# Hurricane Irma

Duration	30 August-16 September, 2017
Keys Landfall	Cudjoe Key, 10 September, 2017, 1310 UTC, Category 4
Central Pressure	914 mBar (min)*; 929 mBar (Keys landfall)
Wind Speeds	185 mph (maximum)**; 130 mph (Keys landfall)
Storm Surge	3 m (Florida Keys)
Effects	Catastrophic damage in Barbuda, USVI, Caribbean, middle Florida Keys, >146 deaths
US Property Damage	\$53.4 billion***

\* 2<sup>nd</sup> most intense of 2017 (behind Hurricane Maria)

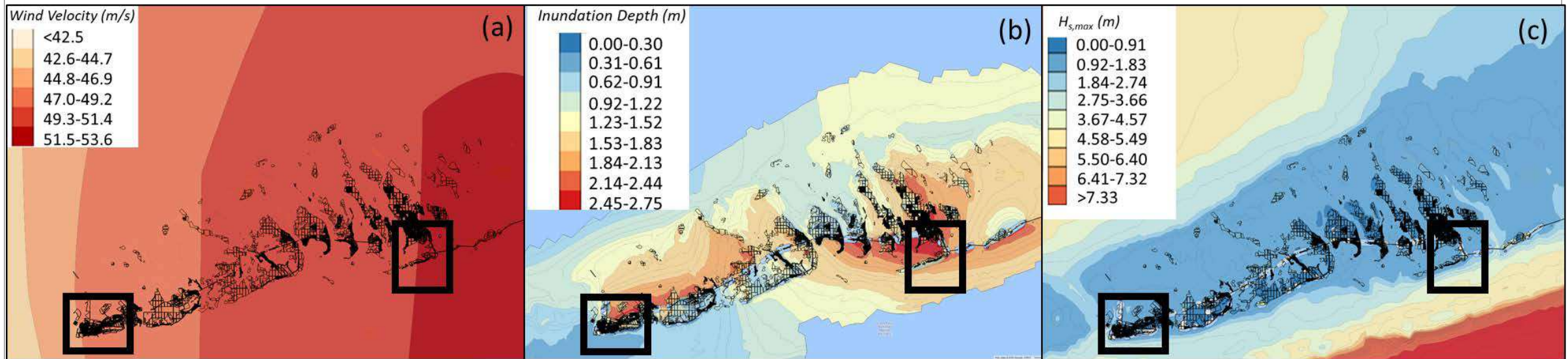
\*\* Strongest of 2017

\*\*\* 5<sup>th</sup> costliest in US History



# Hurricane Irma: Hazard Intensity Measures

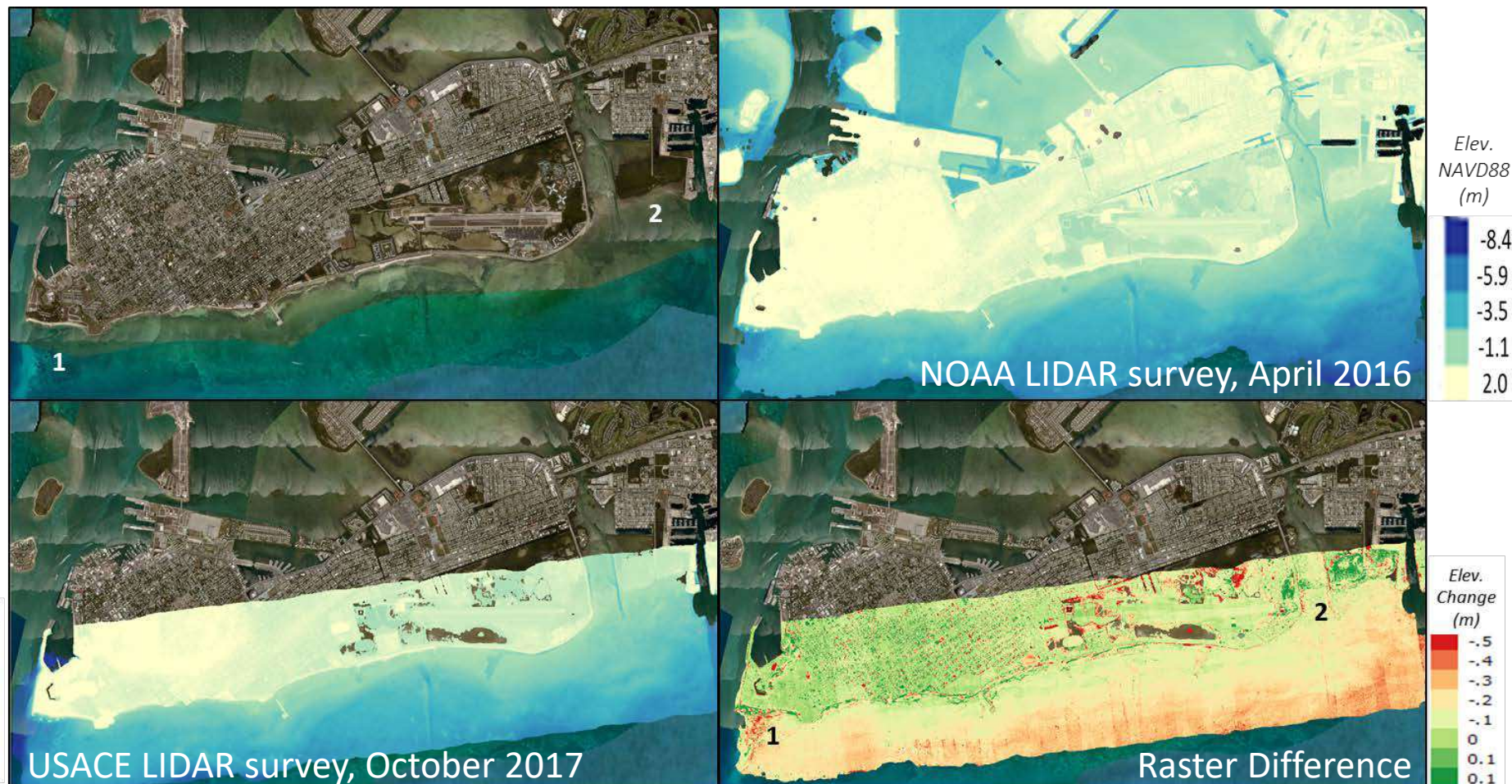
ADCIRC + SWAN storm simulation courtesy CERA (2017)



	Key West	Big Pine Key
Wind Velocity (m/s)	44.8-49.2	49.3-53.6
Inundation Depth (m)	1.23-2.14	1.53-2.75
Significant Wave Height (m)	0-1.83	0.92-2.74



# Island Scale Vulnerability





# Island Scale Vulnerability



Elev.  
Change  
(m)

**Fort Zachary  
Taylor State  
Park**



**Roosevelt  
Seawall and Cow  
Key Mangroves**

# Parcel Scale Damage Assessments



- NEU-USNA Collaborative Effort
  - July 2017- present
- Key West and Big Pine Key
- *Investigate relationship between shoreline resiliency, structural vulnerability, and shoreline management*
- **October Survey:** 263 residential structures, 332 shorelines



# Shoreline Archetypes



**Mangrove**



**Sandy Beach**



**Revetment**



**Bulkhead**

- Compiled from observations, NOAA C-CAP (2017) regional land cover classifications and USACE (1995) descriptions of shoreline structures



# Shoreline Damage



Mangrove: broken branches, loss of foliage, regrowth



Sandy Beaches: erosion



Revetment: rocks displaced



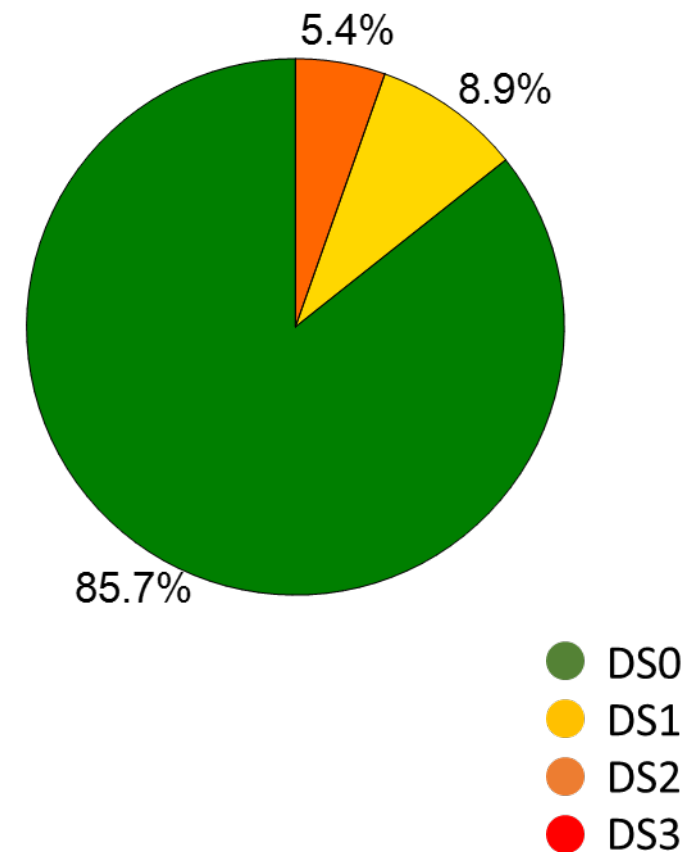
Bulkhead: cracks, undercutting, structural collapse



# Shoreline Damage Descriptions

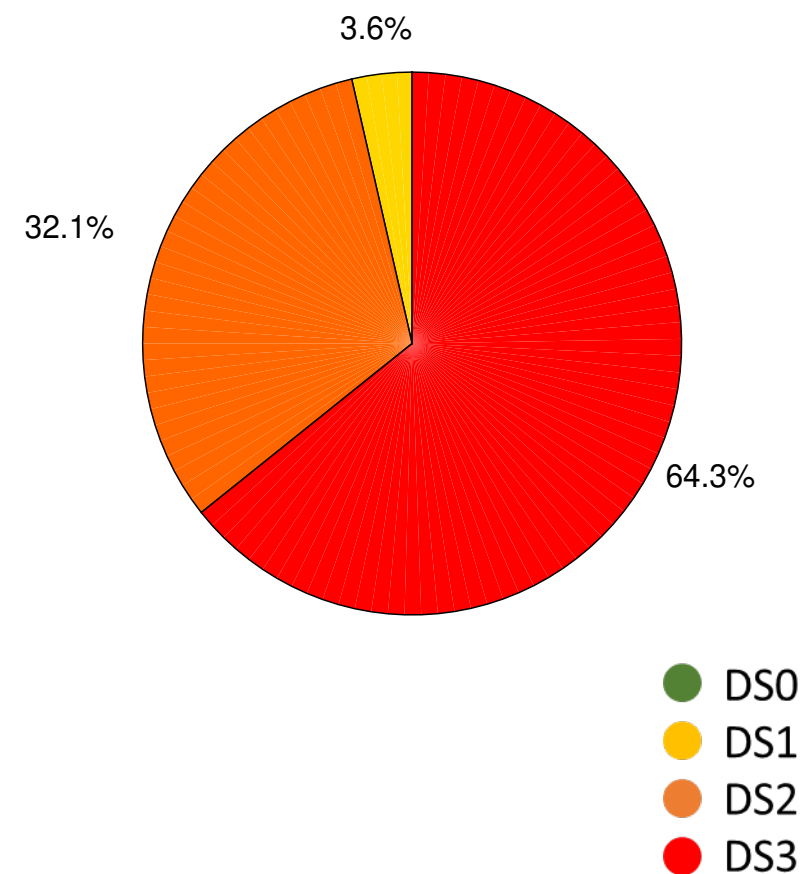
Shoreline Type	0	1	2	3
Mangrove	No Visible Damage	Aesthetic damage; loss of foliage; loss of <25% of mangrove tract in the form of dead/uprooted trees	Loss of 25-50% of mangrove tracts in the form of dead/uprooted trees	Loss of >50% of mangrove tract in form of uprooted/dead trees
Sandy Beach	No Visible Damage	Aesthetic damage; loss of <25% of vegetation/dune grasses; minor evidence of erosion	Loss of 25-50% of vegetation; significant erosion (>12" average dune height or shoreline recession per property)	Loss of >50% of vegetation; major erosion (>3' average dune height or shoreline recession per property)
Bulkhead/ Vertical Wall	No Visible Damage	Nonstructural/ aesthetic damage to components; repairs include patching concrete; repointing mortar, applying a skim coat	Failure or partial failure of structural elements including crumbling, bulging, collapsing, horizontal cracks>2" and scour>6"	Complete failure/ collapse of structure
Revetment	No Visible Damage	Nonstructural/ aesthetic damage to components; repairs include resetting fallen stones; <10% armament rocks displaced	Failure or partial failure of structural elements including crumbling, bulging, collapsing, horizontal cracks>2" and scour>6"; 10-25% armament rocks displaced	Complete failure/ collapse of structure >25% armament rocks displaced, requiring complete repair
Hybrid	No Visible Damage	Aesthetic damage; loss of <25% of vegetation; minor evidence of erosion <10% displaced rocks from sills	Loss of 25-50% of vegetation; significant erosion: >12" shoreline recession; 10-25% displaced armament rocks; partial failure of structural elements	Loss of >50% of vegetation; major erosion: >3' shoreline recession >25% displaced rocks; complete failure

# Standardized Shoreline Damage Assessments



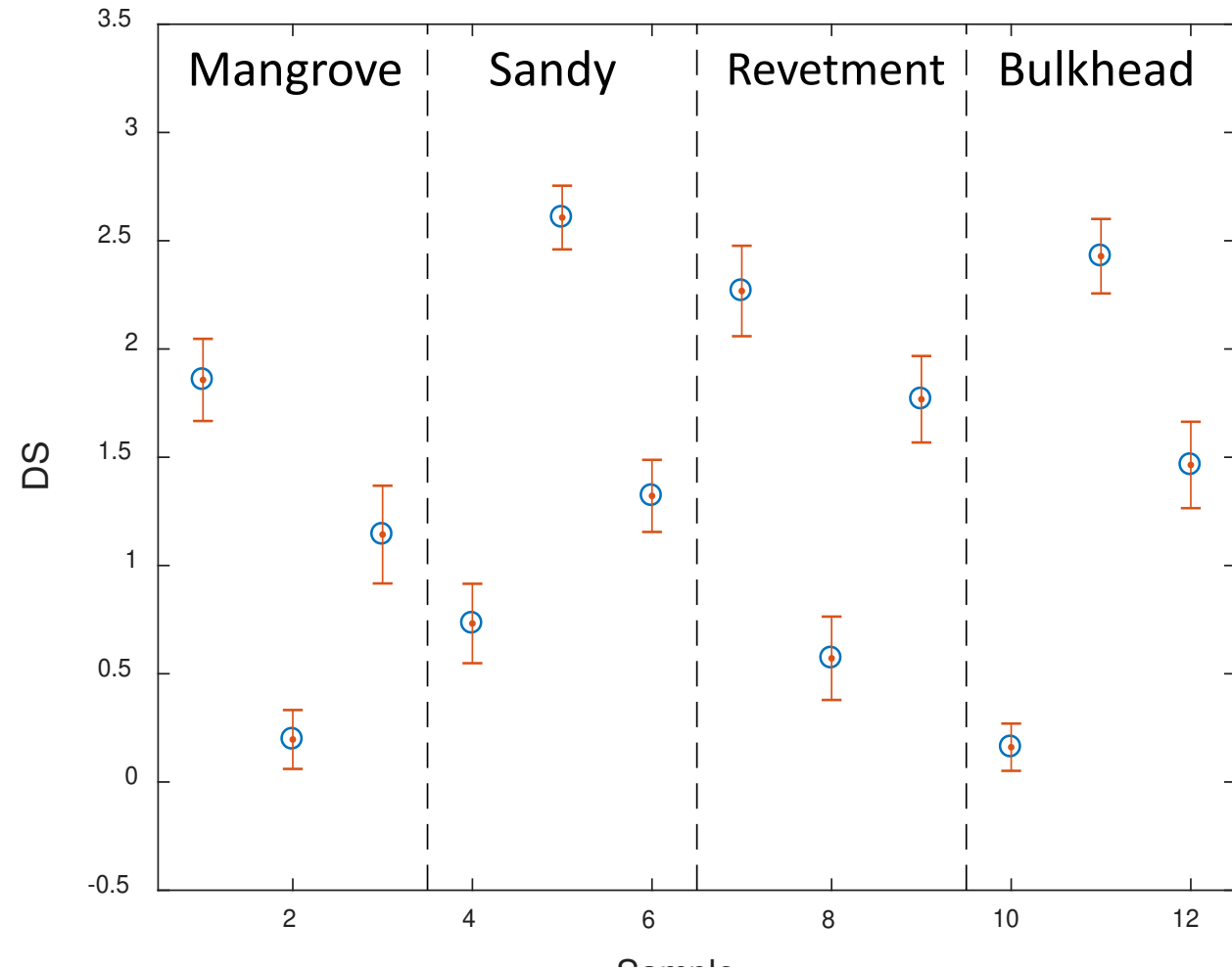


# Standardized Shoreline Damage Assessments



# Standardized Shoreline Damage Assessments

- 56 surveyors, 12 shorelines
- 95 % Confidence Intervals > 0.5 DS
- Larger variation for intermediate damage states





# Component-Based Structural Damage Assessments

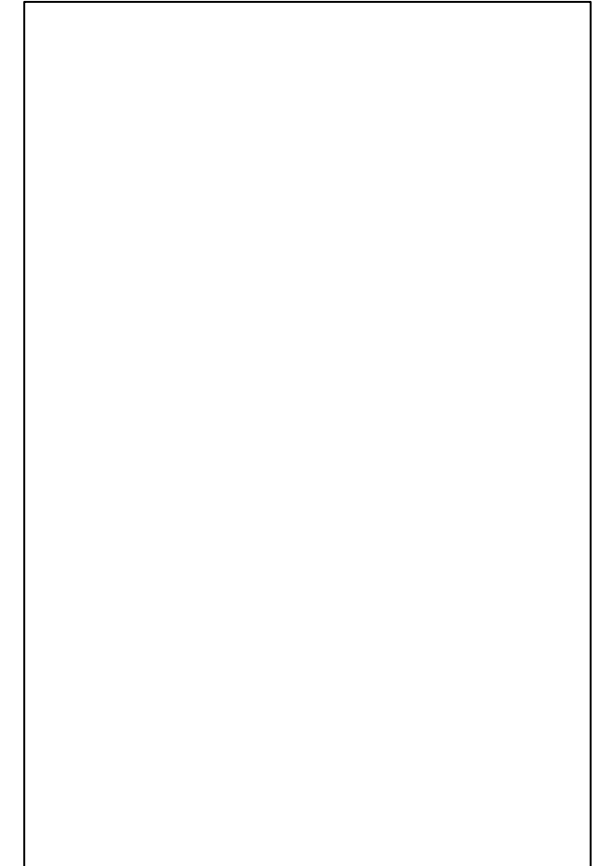
Component	0	1	2	3	4
Roof	<ul style="list-style-type: none"> <li>• No visible damage</li> </ul>	<ul style="list-style-type: none"> <li>• Few shingles missing (&lt;15% of roof area)</li> <li>• Minor damage to gutters</li> </ul>	<ul style="list-style-type: none"> <li>• Significant amount of shingles missing 15-30% of roof area)</li> <li>• Minor damage to frame</li> <li>• Roof interior is not exposed</li> </ul>	<ul style="list-style-type: none"> <li>• Holes in roof due to debris or wind- sheathing is exposed but not house interior</li> </ul>	<ul style="list-style-type: none"> <li>• Large parts of roof are missing or collapsed; structural damage</li> </ul>
Walls	<ul style="list-style-type: none"> <li>• No visible damage</li> </ul>	<ul style="list-style-type: none"> <li>• Minor cladding removal (&lt;10% of 1 wall)</li> <li>• Small scratches/ aesthetic damage</li> </ul>	<ul style="list-style-type: none"> <li>• Cladding removed from &gt;25% of wall surfaces</li> <li>• Interior sheathing exposed on &lt;25% of house but insulation and house interiors are not</li> </ul>	<ul style="list-style-type: none"> <li>• Minor structural wall damage, including debris caused holes or repairable damage</li> </ul>	<ul style="list-style-type: none"> <li>• Walls have collapsed, bent or are out of plumb, structural damage</li> <li>• Large holes in walls</li> <li>• major structural damage</li> </ul>
Foundation	<ul style="list-style-type: none"> <li>• No visible damage</li> </ul>	<ul style="list-style-type: none"> <li>• Scour &lt;0.5 feet around foundation</li> <li>• Water marks around foundation</li> <li>• Structurally sound</li> </ul>	<ul style="list-style-type: none"> <li>• Scour 0.5-2' deep</li> <li>• Structurally sound foundation</li> <li>• Evidence of weathering/minor damage on piles</li> </ul>	<ul style="list-style-type: none"> <li>• One pile out of plumb, or damaged</li> <li>• Scour &gt;2' deep</li> <li>• Minor damage to foundation</li> </ul>	<ul style="list-style-type: none"> <li>• Major foundation damage</li> <li>• Differentially settlement</li> <li>• &gt;1 pile is damaged</li> <li>• House is missing</li> </ul>
Landscaping, Attachments and Detached Structures (If Waterfront, Shoreline Condition)	<ul style="list-style-type: none"> <li>• No visible damage</li> </ul>	<ul style="list-style-type: none"> <li>• &lt;2 Exterior structures damaged or removed</li> <li>• Damage to stair, porches, detached garage, or walkways, most structures remain in tact</li> <li>• Shoreline- aesthetic damage</li> </ul>	<ul style="list-style-type: none"> <li>• 2 or more exterior structures are gone or destroyed</li> <li>• Damage/ collapse of deck, shed</li> <li>• Landscaping damage- &gt;50% of trees, bushes uprooted</li> <li>• Shoreline- moderate damage</li> </ul>	<ul style="list-style-type: none"> <li>• Collapse of detached garage</li> <li>• Shoreline- complete damage</li> </ul>	
Openings: Windows, Doors, Attached Garages	<ul style="list-style-type: none"> <li>• No visible damage</li> </ul>	<ul style="list-style-type: none"> <li>• 1 window or door is broken (glass only)</li> <li>• Screens may be damaged or missing</li> </ul>	<ul style="list-style-type: none"> <li>• 2+ windows/doors broken or removed</li> <li>• Damage to frames of doors and windows</li> <li>• Attached garage door damaged or gone</li> </ul>		
Interior	<ul style="list-style-type: none"> <li>• No visible damage</li> </ul>	<ul style="list-style-type: none"> <li>• No flooding</li> <li>• Minimal/no evidence of rain intrusion- minor water damage in corners or around windows only</li> <li>• Minor water damage to interior furnishings</li> </ul>	<ul style="list-style-type: none"> <li>• Slight evidence of flooding</li> <li>• Water marks (0-1') above floor</li> <li>• Evidence of rain intrusion- dampness/ minor water damage on &lt;10% of wall area or ceiling</li> <li>• Water damage to interior furnishings</li> <li>• No mold</li> </ul>	<ul style="list-style-type: none"> <li>• Water marks (1'-4')</li> <li>• Rain/water damage to ceiling: wet spots, dripping, or sagging</li> <li>• Dampness on &gt;25% of wall areas and evidence of dripping or cracks on walls</li> <li>• Mold</li> </ul>	<ul style="list-style-type: none"> <li>• Water marks 4' or higher</li> <li>• Structural ceiling damage from rain- wet spots and sagging</li> <li>• Structural damage to interior walls</li> </ul>

# Component-based Structural Damage Assessments

Key West

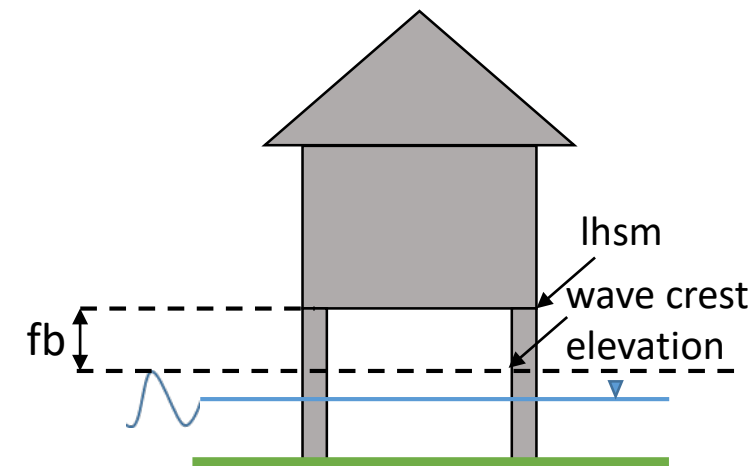
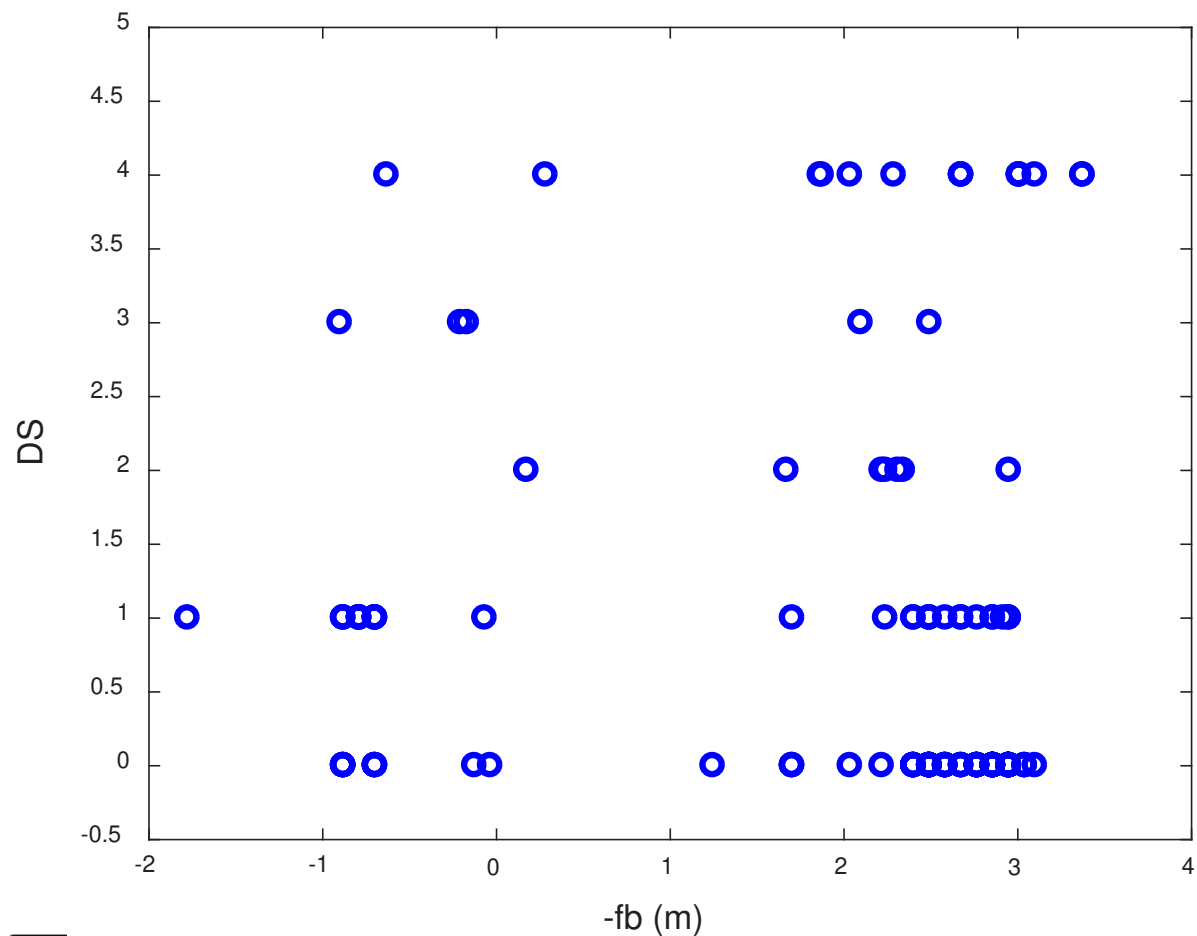
Big Pine Key

Damage  
State



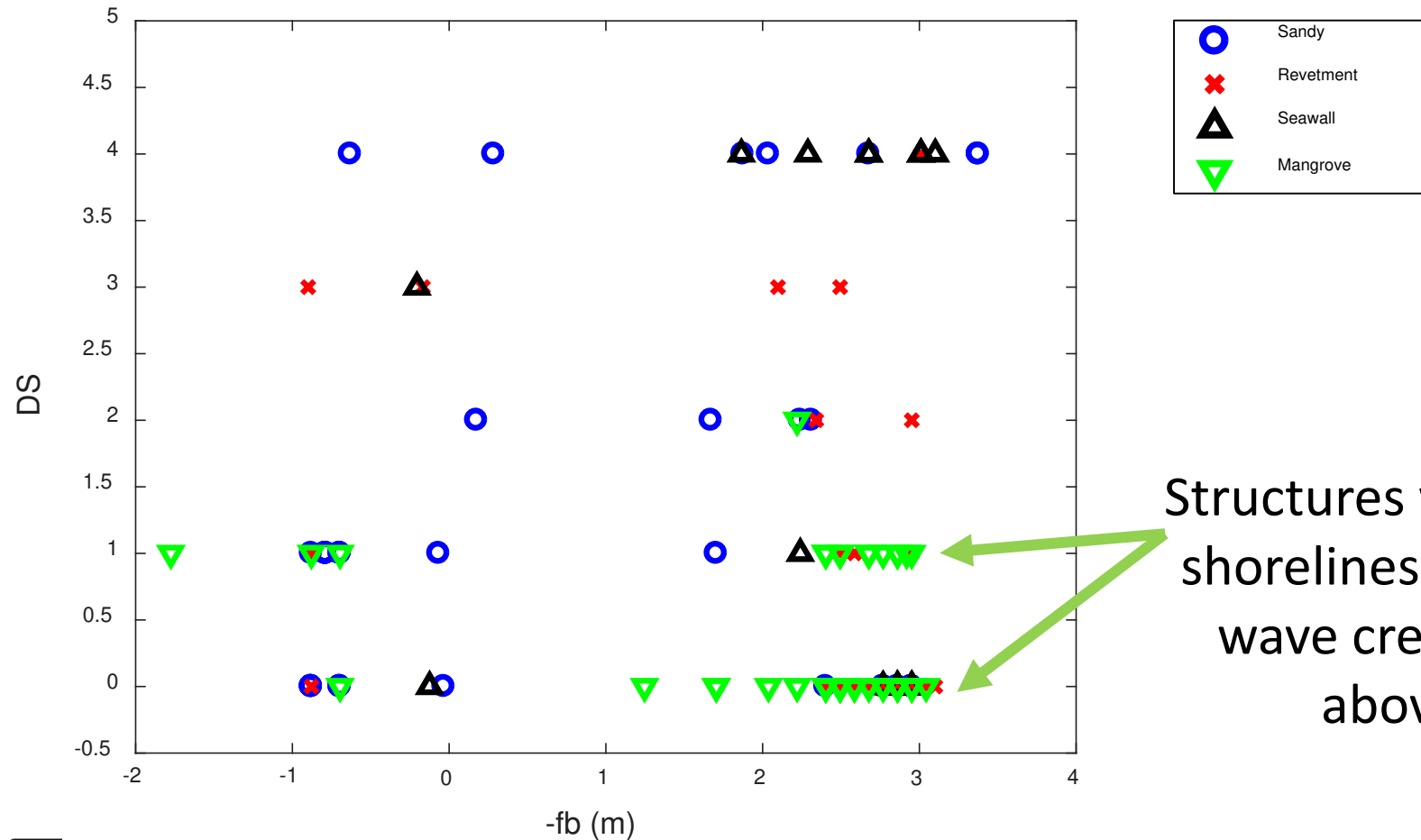


# Structural Fragility: Relate Hazard to Structural Damage (?)



*fb*=freeboard  
*DS*= damage state

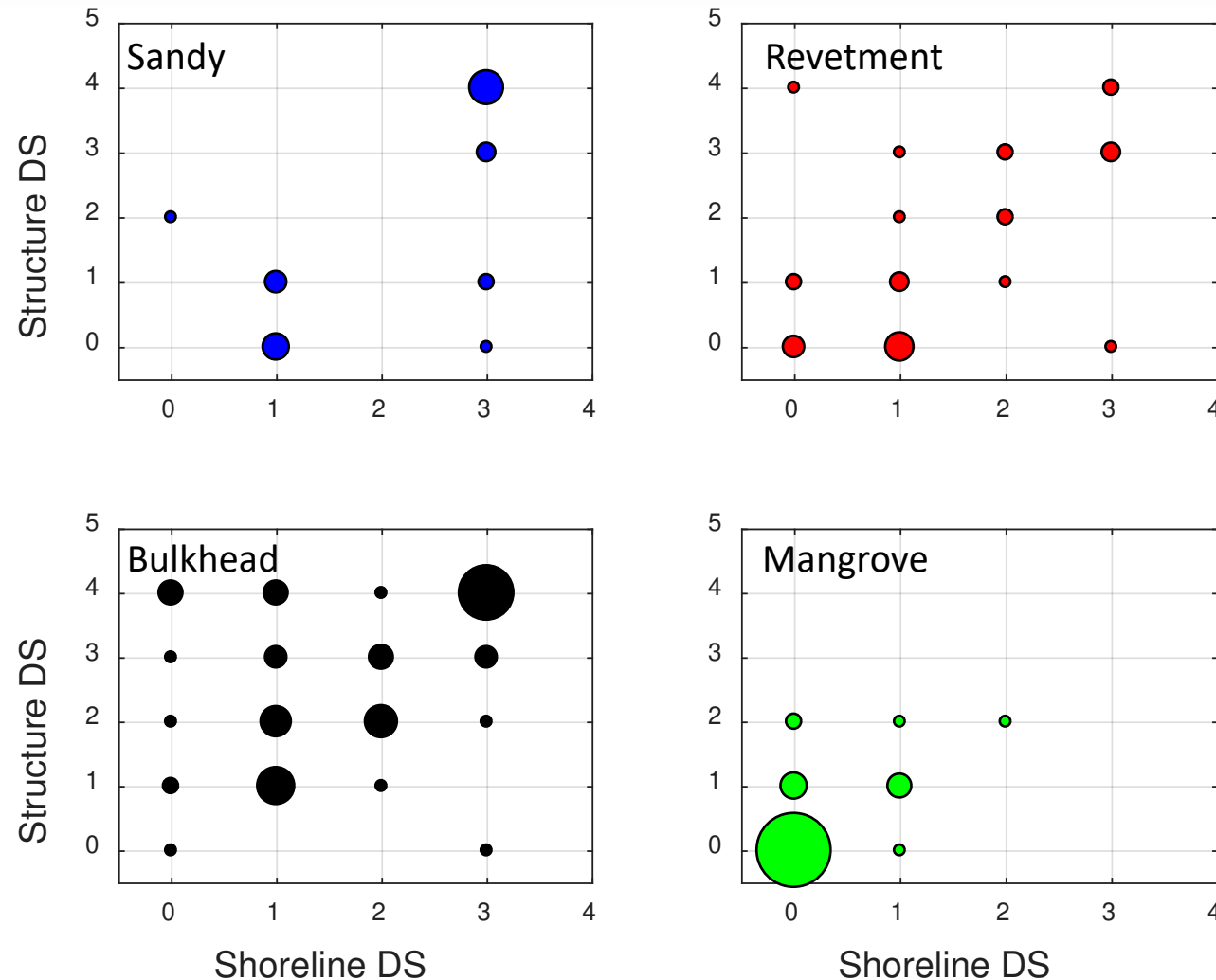
# Relate Hazard, Structural Damage, and Shoreline Type



Structures with mangrove shorelines: DS for higher wave crest elevations above LHSM



# Shoreline Damage Affects Structural Damage



# Structural and Shoreline Fragilities: Multinomial Regression

Multinomial Logistic Regression:

- Shoreline Damage, Structural Damage as ordinal response variables
- Shoreline type (mangrove vs. other) as a categorical predictor variable

$$Y_{i,k} \sim \prod_{i=0}^1 \frac{N!}{Y_{i,k}!} P(DS = DS_i | x_k)$$

Statistical Significance and AIC for Empirical Multinomial Fragility Models

Model	$p_{fb}$	$p_{\eta wave}$	$p_{Shoreline}$	AIC
Shoreline	---	0.0028	1.32 x 10 <sup>-23</sup>	161
Structure	0.041	---	4.89 x 10 <sup>-24</sup>	271

Log Odds/  
Relative risk

$$\frac{P(DS = 0)}{P(DS > 0)}$$

$$\frac{P(DS \leq 1)}{P(DS > 1)}$$

$$\frac{P(DS \leq 2)}{P(DS > 2)}$$

$$\frac{P(DS \leq 3)}{P(DS > 3)}$$

$$\frac{P(DS \leq 3)}{P(DS > 3)}$$

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$$\frac{P(DS \leq 3)}{P(DS > 3)}$$



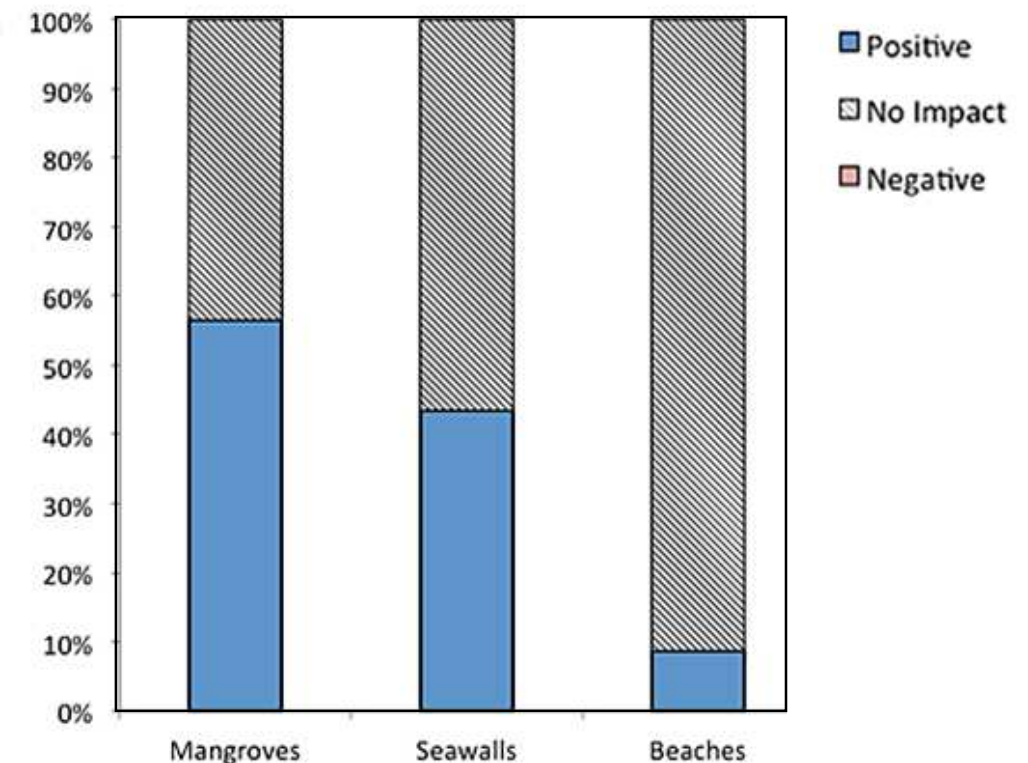
# Interconnectivities between Shoreline Type, Structural Damage, and Homeowner Perceptions

- Mixed mode interviews
- Perceived impact of mangroves, seawalls, and beaches, on social and ecological systems during Hurricane Irma

*“Mangroves are the only thing keeping the island from eroding”*

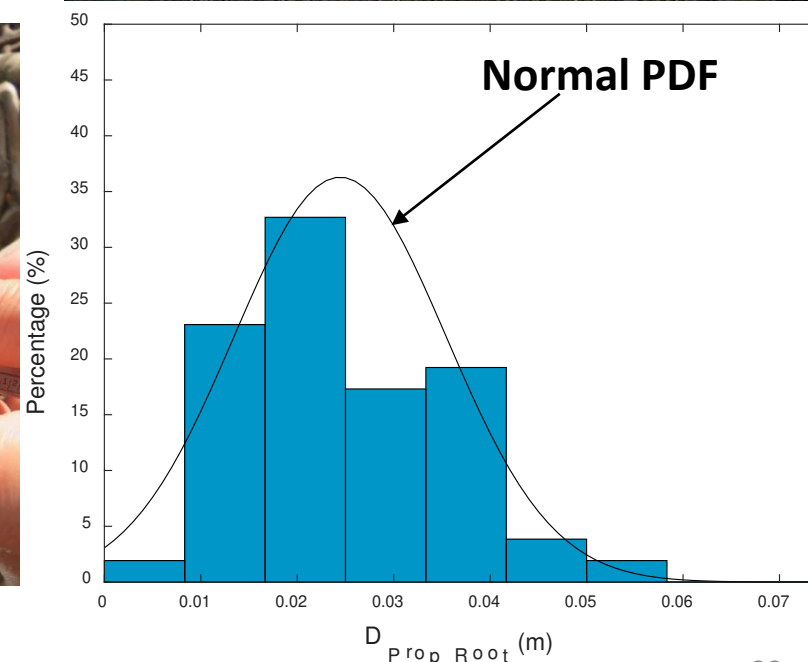
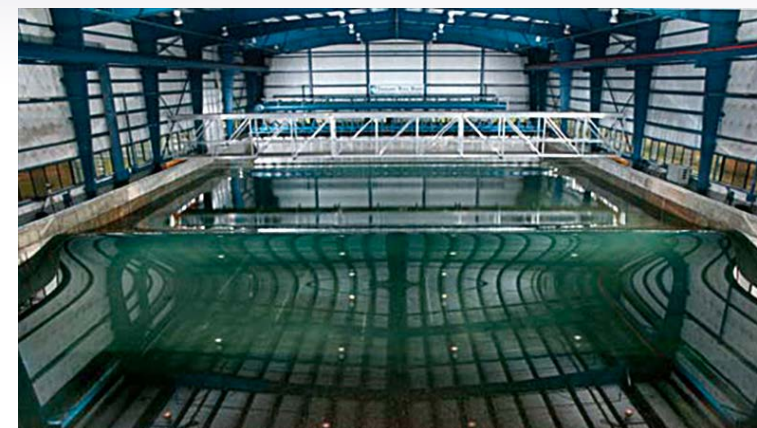
*“90% of beaches were swept away”*

*“Without mangroves, the impact of the storm would have been much worse”*



# Ongoing Work

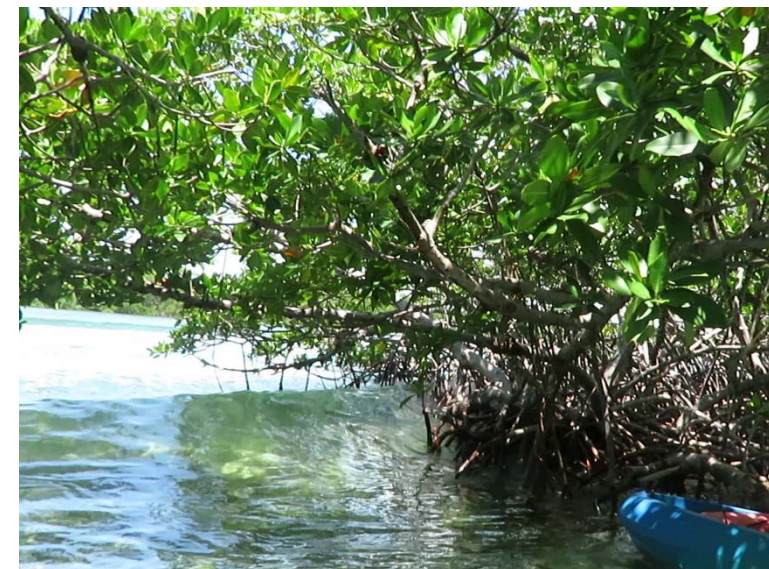
- **July, 2018:** Field study to characterize mangrove prop root density, average diameter, elastic modulus, canopy characteristics
- **Fall, 2018:** 1:16 scale laboratory experiments
  - Effects of roots, leaves, scaling
- **Spring, 2019:** Field experiments, Key West, FL





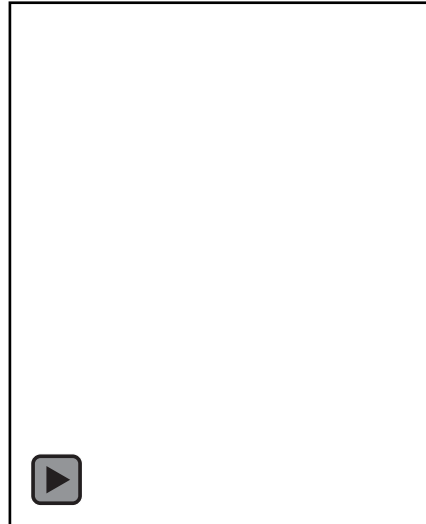
# Conclusions

- Case study of damage to shorelines, structures after Hurricane Irma
- Ongoing longitudinal investigation to identify recovery trends, repair decisions
- **Natural and nature-based features** may mitigate overland flow and resulting inland damage during storm events **in coordination with engineered structures**
  - Need quantitative measurements!





# Thank you for your kind attention!



Northeastern





