Modeling the Impacts of Sea Level Rise and Climate Change on Coastal Forests and Hydrology

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REVIEW ARTICLE
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nature climate change

Corrected: Author Correction

Sea-level driven land conversion and the formation of ghost forests

Matthew L. Kirwan[1*] and Keryn B. Gedan[2]

Ghost forests created by the submergence of low-lying land are one of the most striking indicators of climate change along the Atlantic coast of North America. Although dead trees at the margin of estuaries were described as early as 1910, recent research has led to new recognition that the submergence of terrestrial land is geographically widespread, ecologically and economically important, and globally relevant to the survival of coastal wetlands in the face of rapid sea level rise. This emerging understanding has in turn generated widespread interest in the physical and ecological mechanisms influencing the extent and pace of upland to wetland conversion. Choices between defending the coast from sea level rise and facilitating ecosystem transgression will play a fundamental role in determining the fate and function of low-lying coastal land.

Introduction

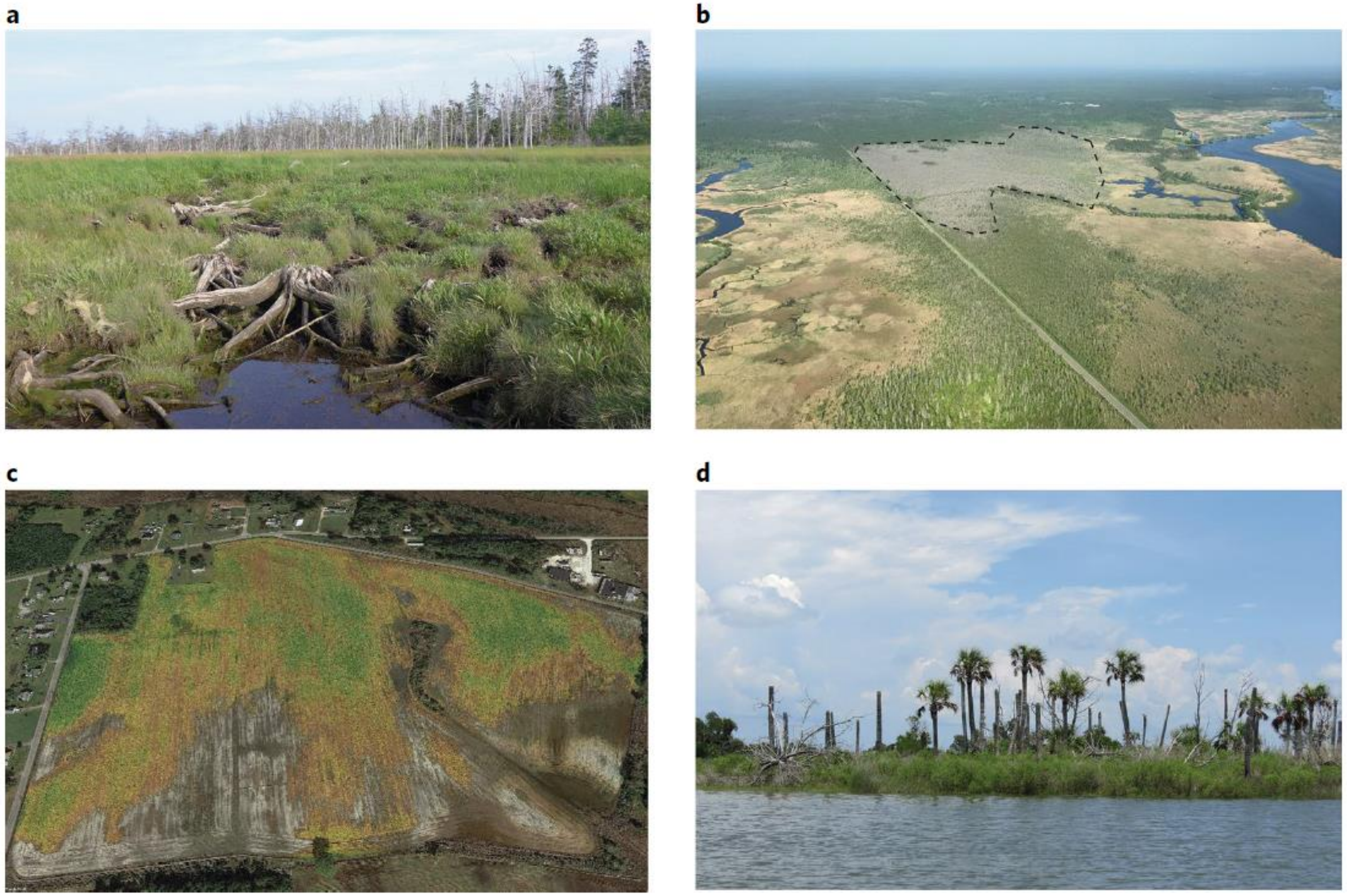

Fig. 1 | Geographic distribution of sea-level driven land conversion in North America. a, Red spruce ghost forest and buried stumps, New Brunswick, Canada. **b**, Atlantic white cedar ghost forest in New Jersey (indicated by dashed line). **c**, Salt damaged agricultural field in Virginia, where white and grey areas indicate bare ground, and yellow-red colours represent stressed crops. **d**, Palm tree ghost forest in Florida. Credit: David Johnson (**a**), Kenneth W. Able (**b**), USDA Farm Service Agency (**c**) and Amy Langston, Virginia Institute of Marine Science (**d**)

Kirwan and Gedan, Nature Geoscience, 2019

Introduction

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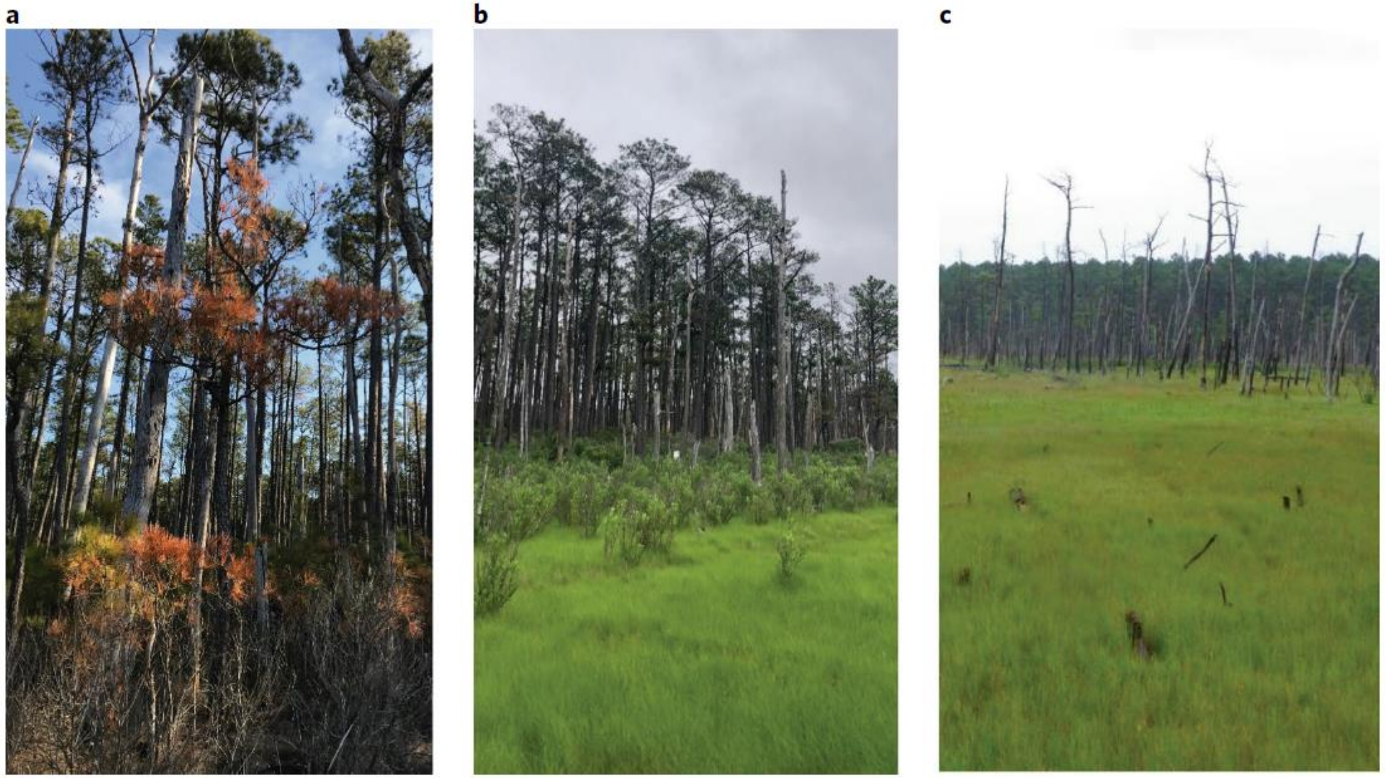
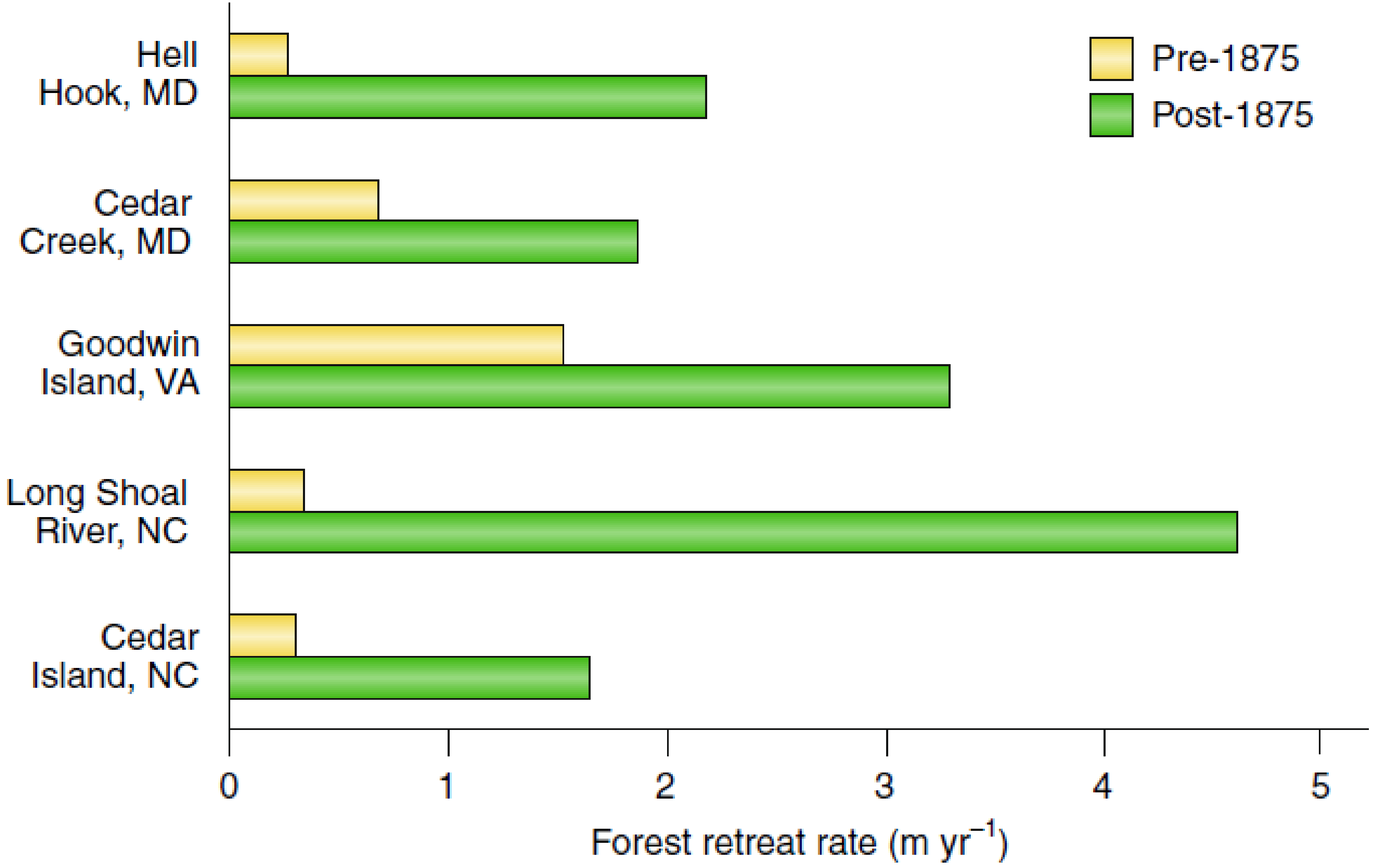


Fig. 3 | Stages of ghost forest creation. a–c, Photos show forest-to-marsh conversion in the Chesapeake Bay region (MD, USA) characterized by (**a**) death of tree saplings, (**b**) opening of canopy and invasion of *Phragmites* and shrubs, and (**c**) adult tree death and conversion to marsh, indicated by stumps in foreground and ghost forest in background. Image in **c** courtesy of Lennert Schepers, UAntwerpen.

Kirwan and Gedan, Nature Geoscience, 2019



Kirwan and Gedan, Nature Geoscience, 2019

Introduction

- Study the coastal forest variations by analyzing satellite datasets coupled with hydrological models

- Results can be used in assessment and resource management decisions

01 Introduction

LandSat 7

Launch Date: April 15, 1999

Sensors: Enhanced Thematic Mapper Plus (ETM+)

Altitude: 705 km

Orbit: polar, sun-synchronous

Equatorial Crossing Time: nominally 10 AM
(± 15 min.) local time (descending node)

Repeat Coverage: 16 days

Swath: 183km

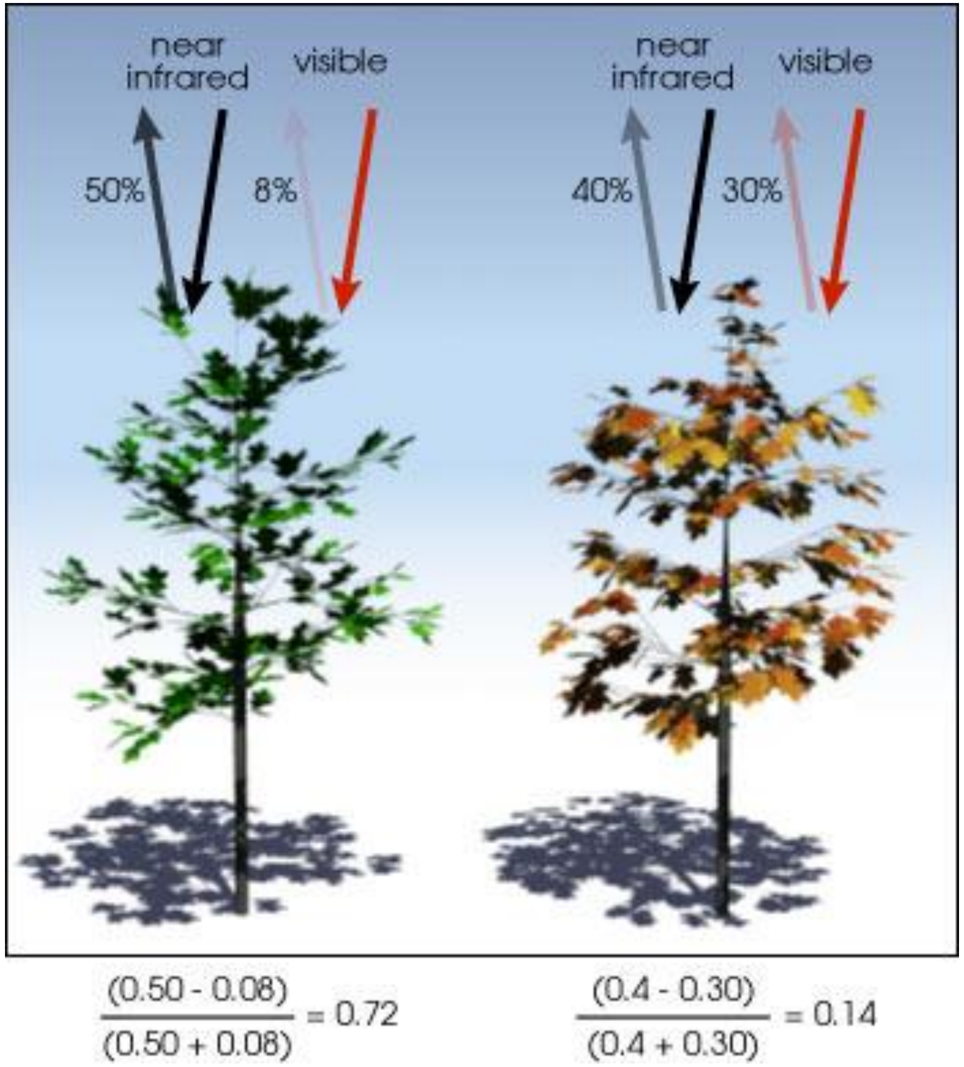
Source: NASA

01 Introduction

LandSat 7 NDVI Data

$$NDVI = \frac{NIR - R}{NIR + R}$$

where NIR is the reflectance in the near-infrared band and R is the reflectance in the red band



Source: Rouse, et al, 1974 & NASA

01 Introduction

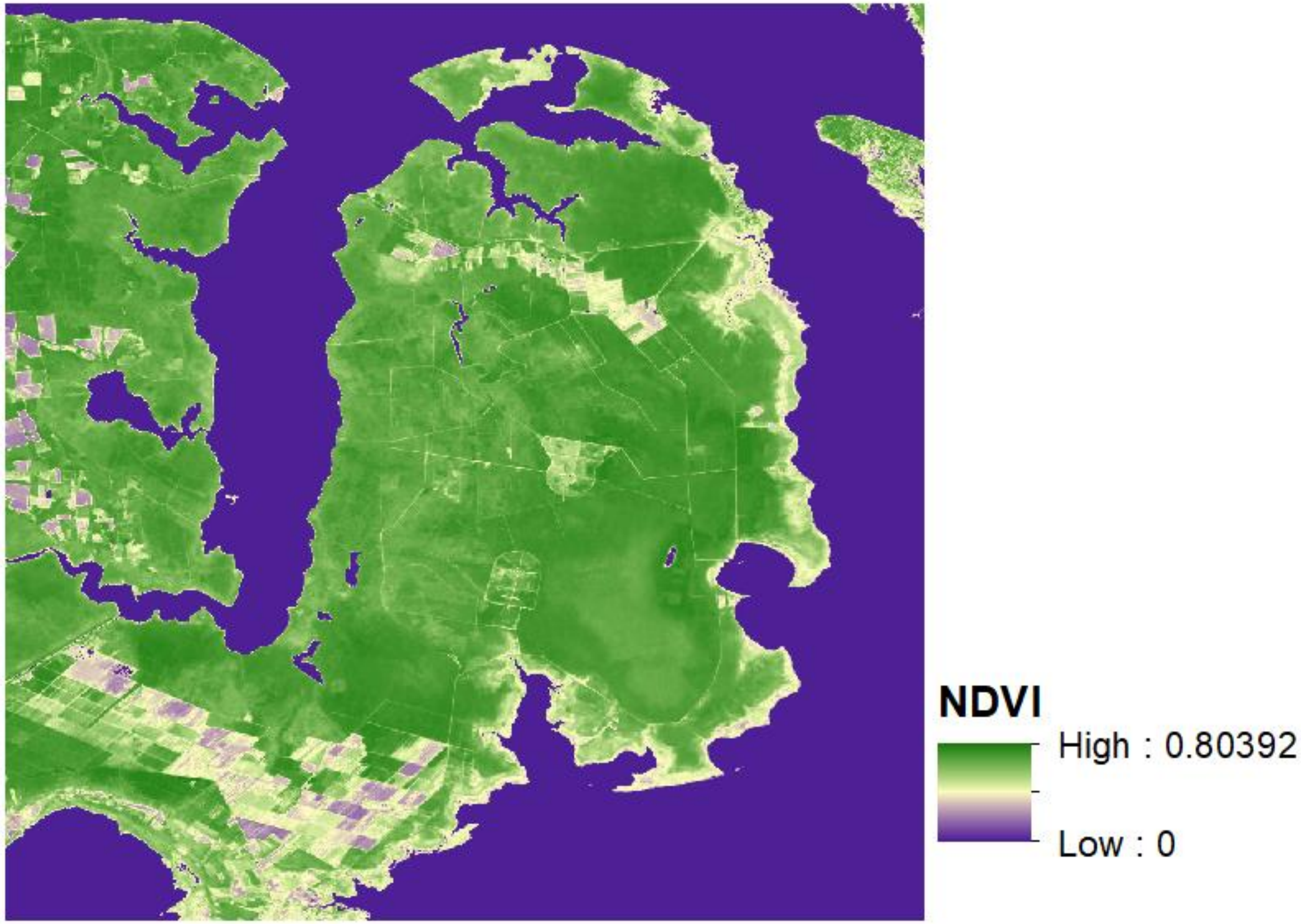
LandSat 7 NDVI Data

Duration: 1999-07-21 to 2014-12-21

Time Interval: 16 days

Spatial Range: NC coastal wetland

Spatial Resolution: 30m

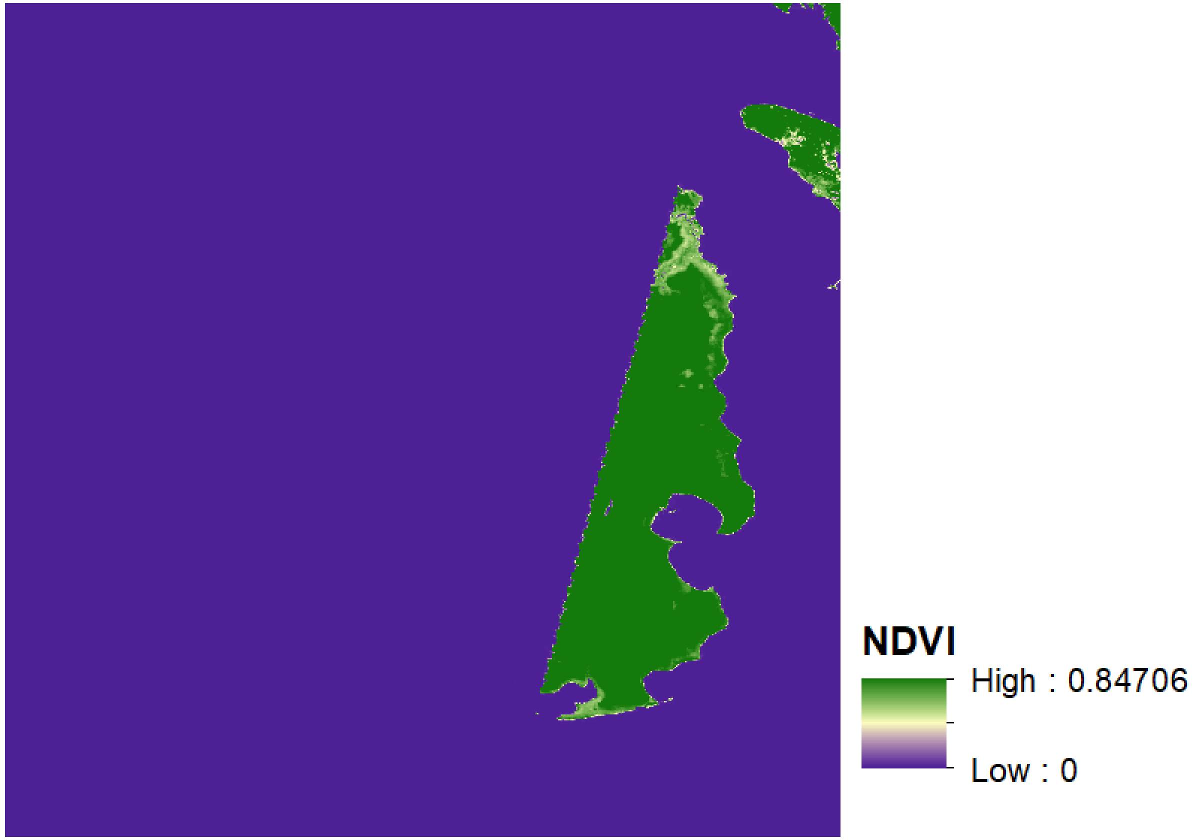


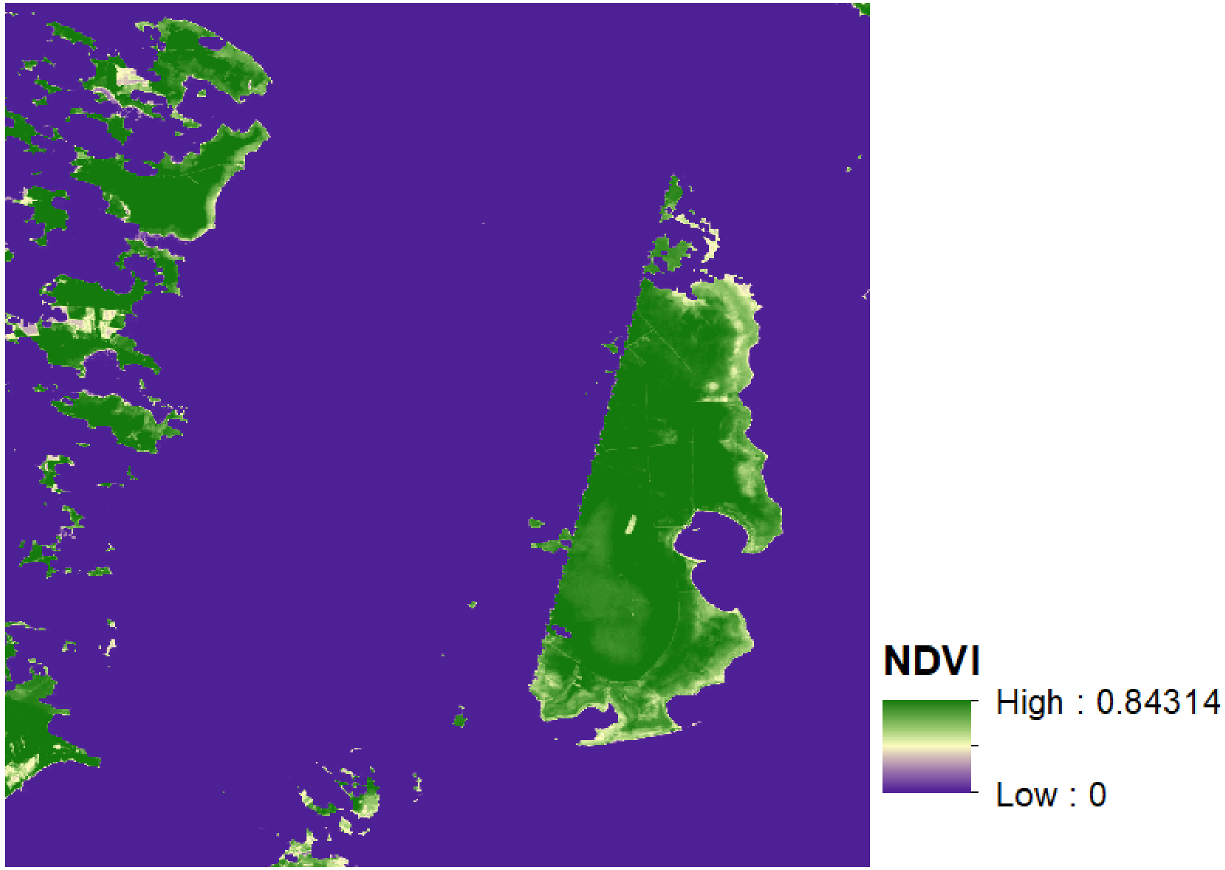
Oct 1999

Source: NASA

02 Issues

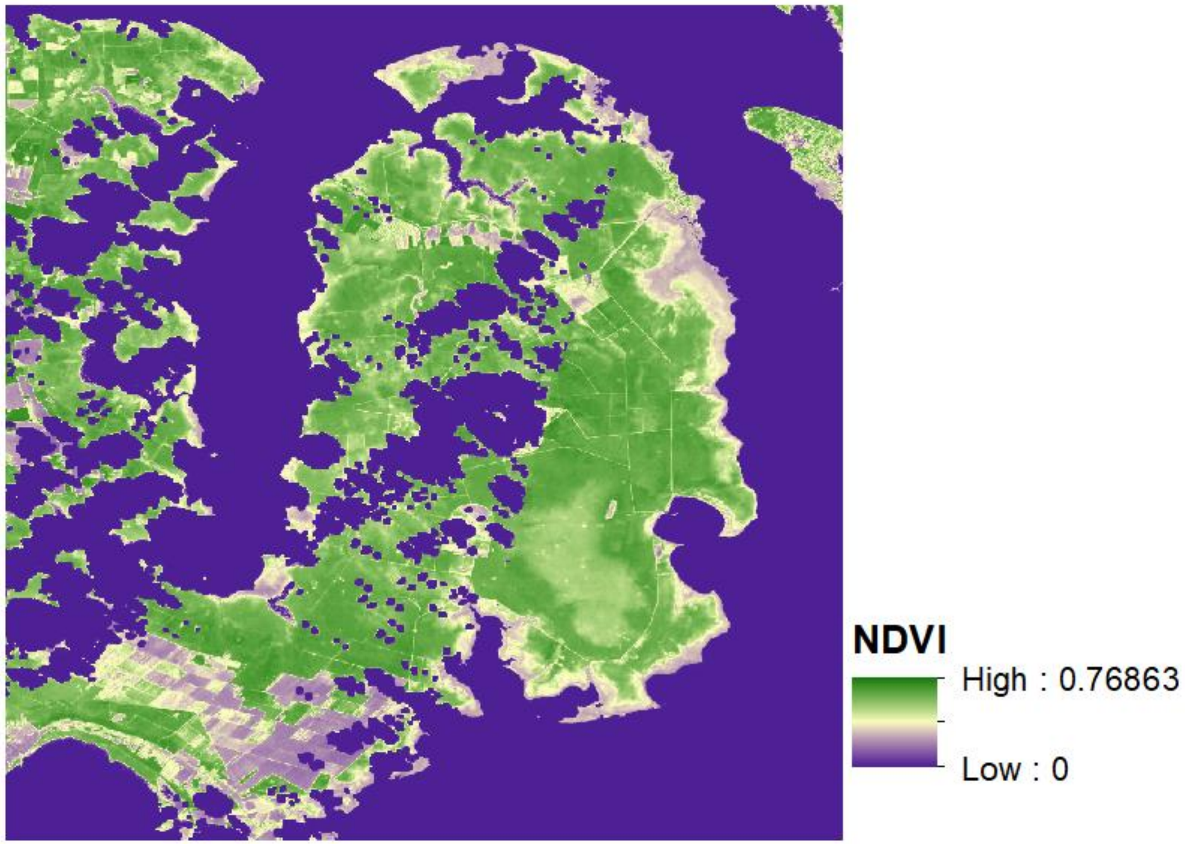
Missing Data

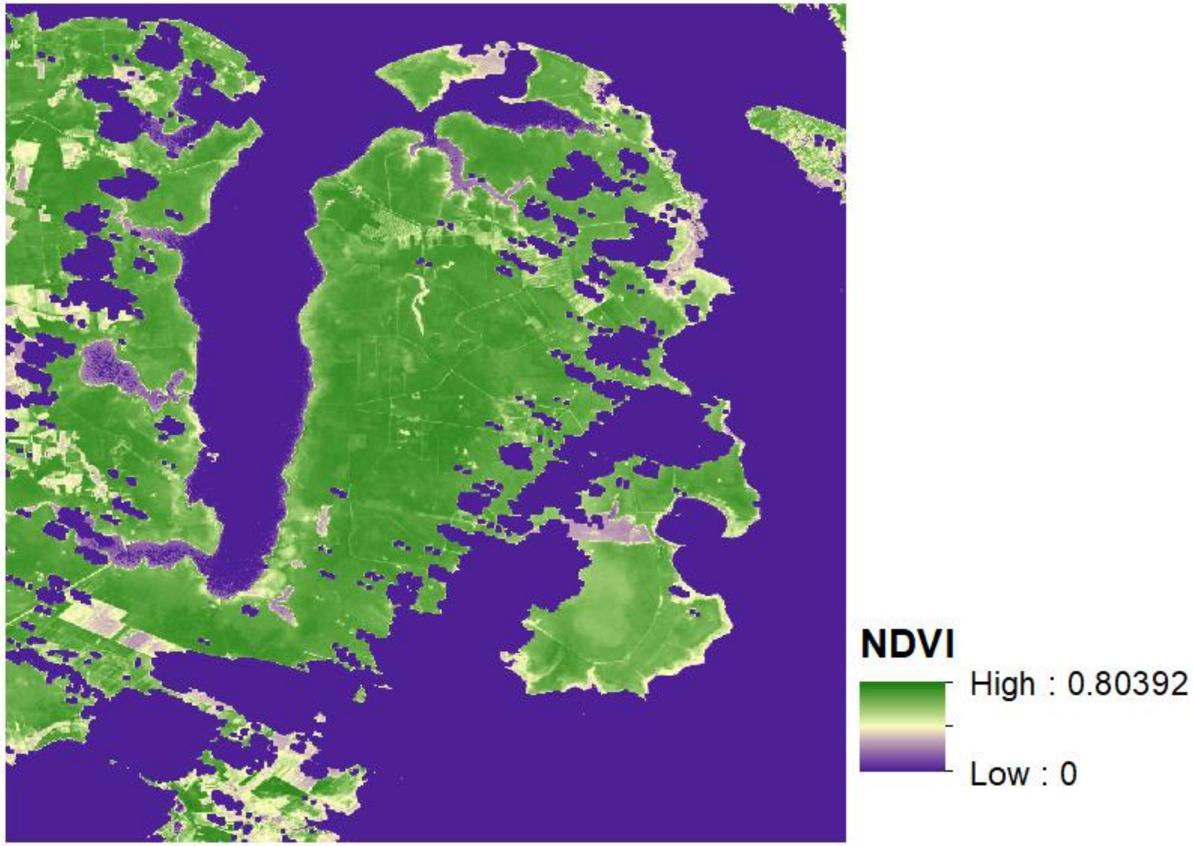




02 Issues

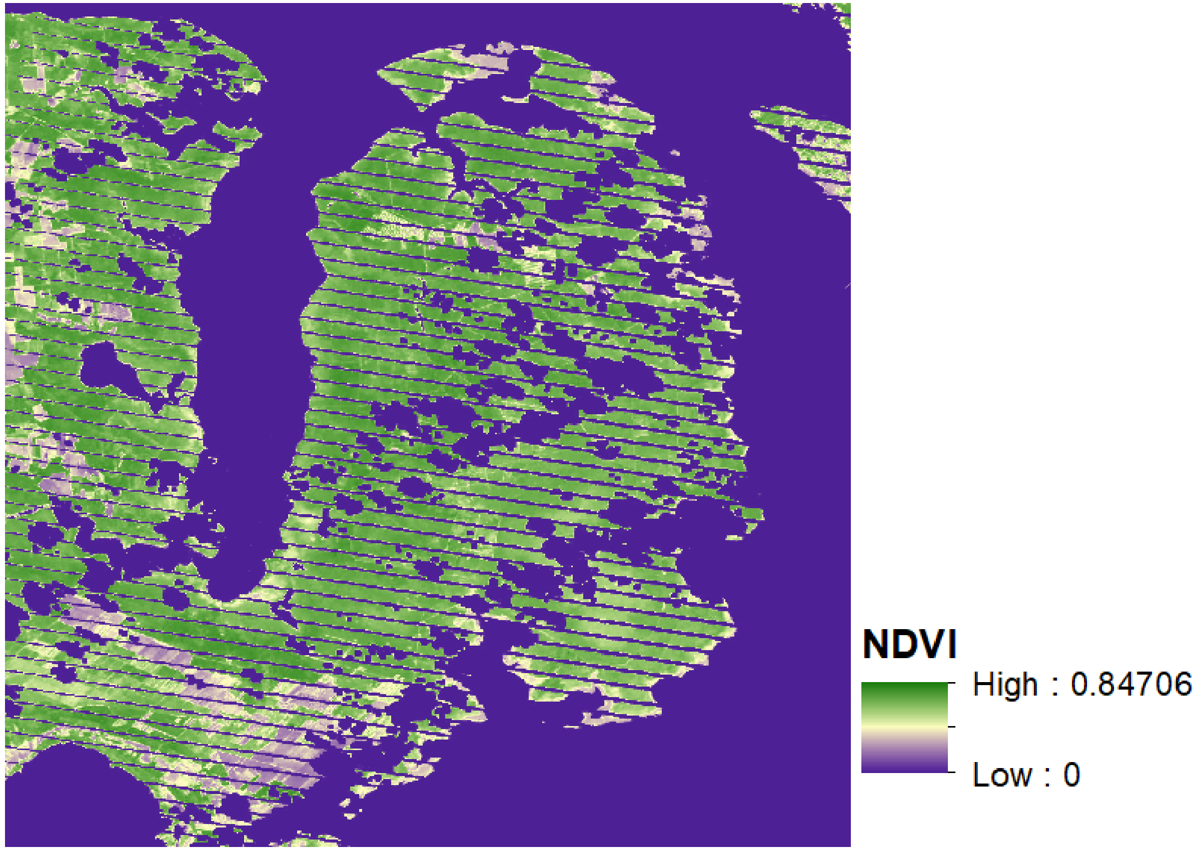
Cloud

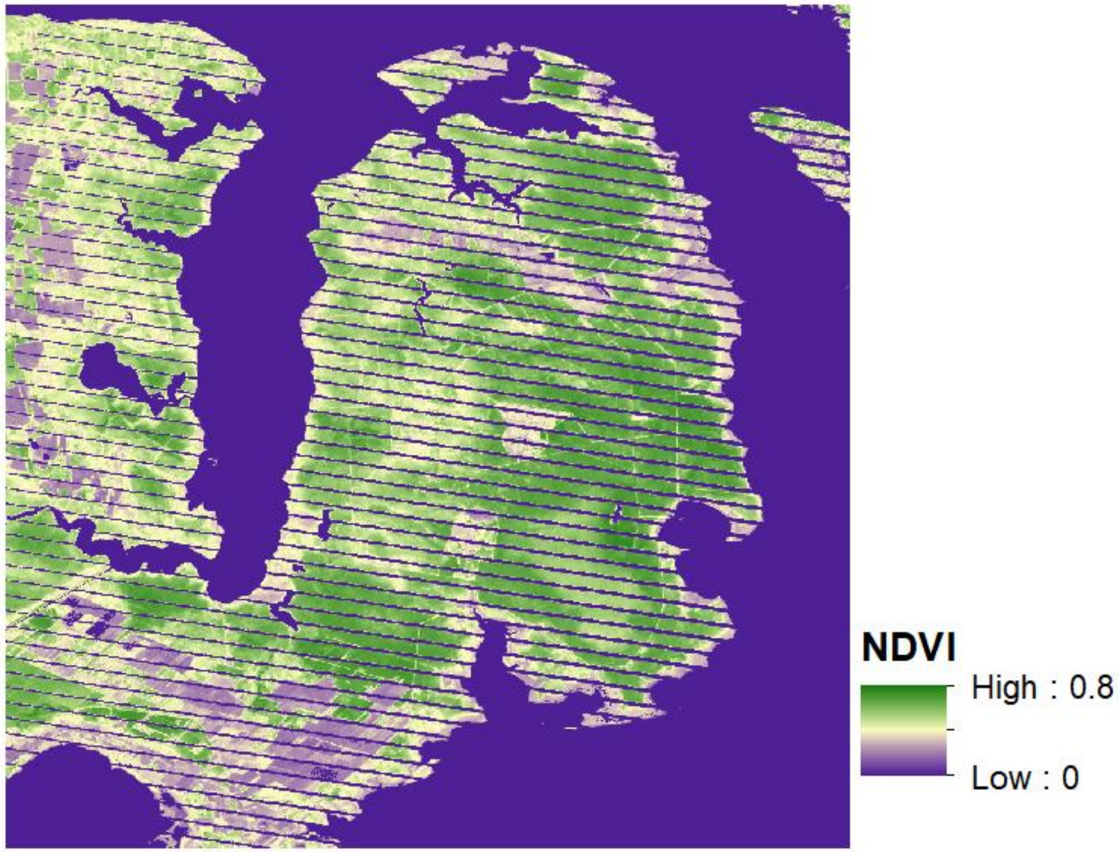




02 Issues

Discontinuous



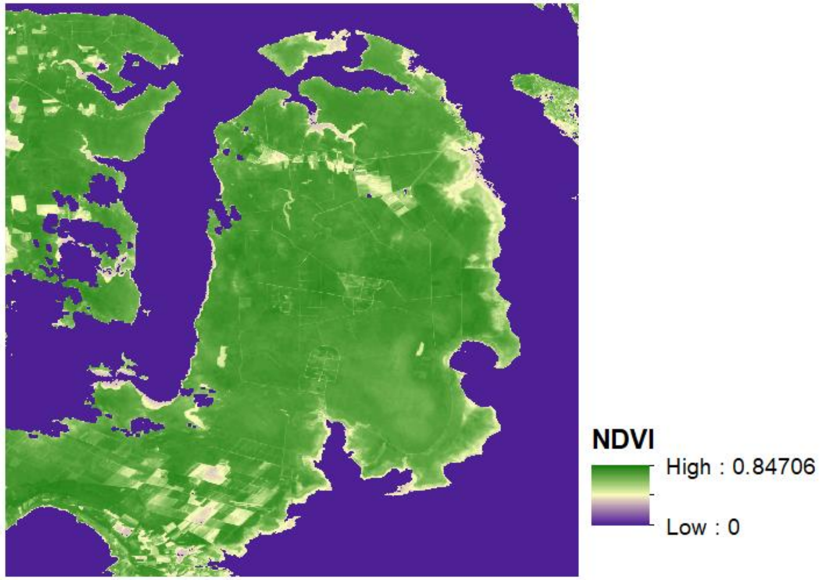


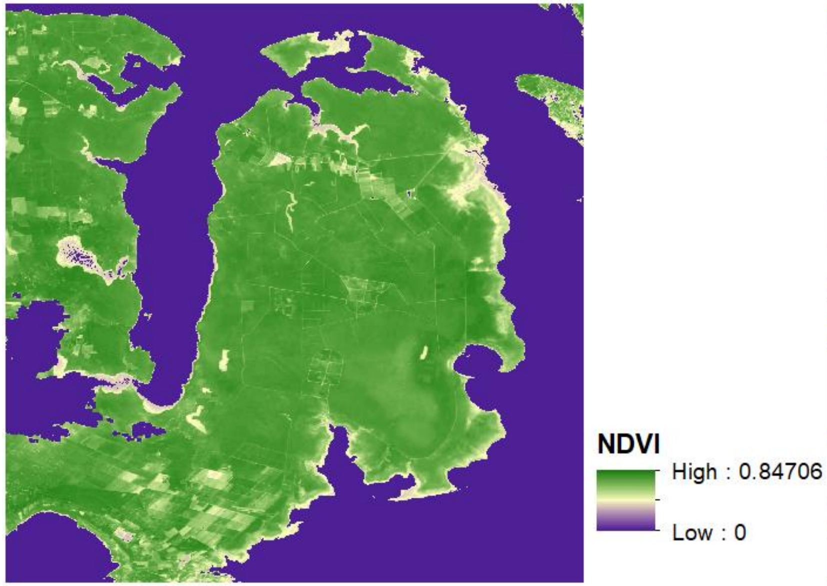
03 Solutions

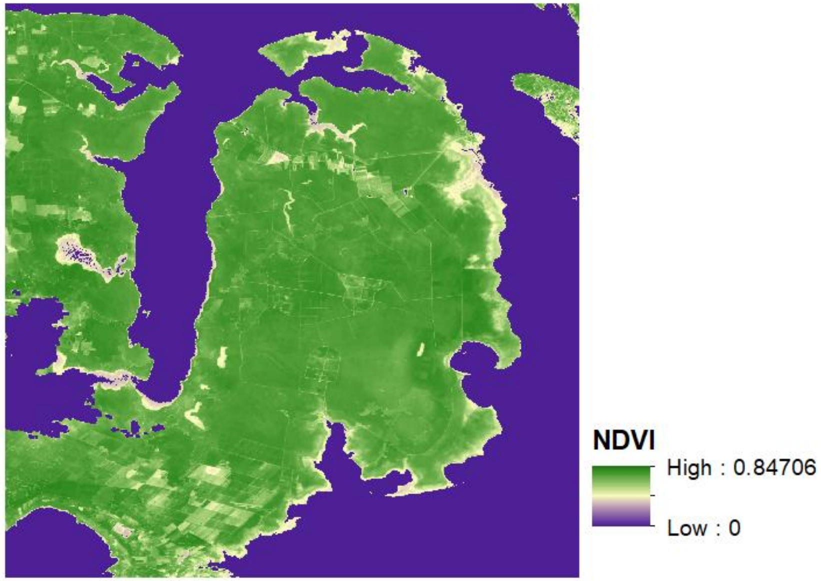
Monthly Mean

Two-month Mean

Three-month Mean







1999-07

1999-07 to 1999-08

1999-07 to 1999-09

Sentinel Data

All data have been downloaded and analysis is going on

01 Introduction of Sentinel Data

Sentinel 2

Sensors: Multispectral Instrument (MSI)

Repeat Coverage: 5 days

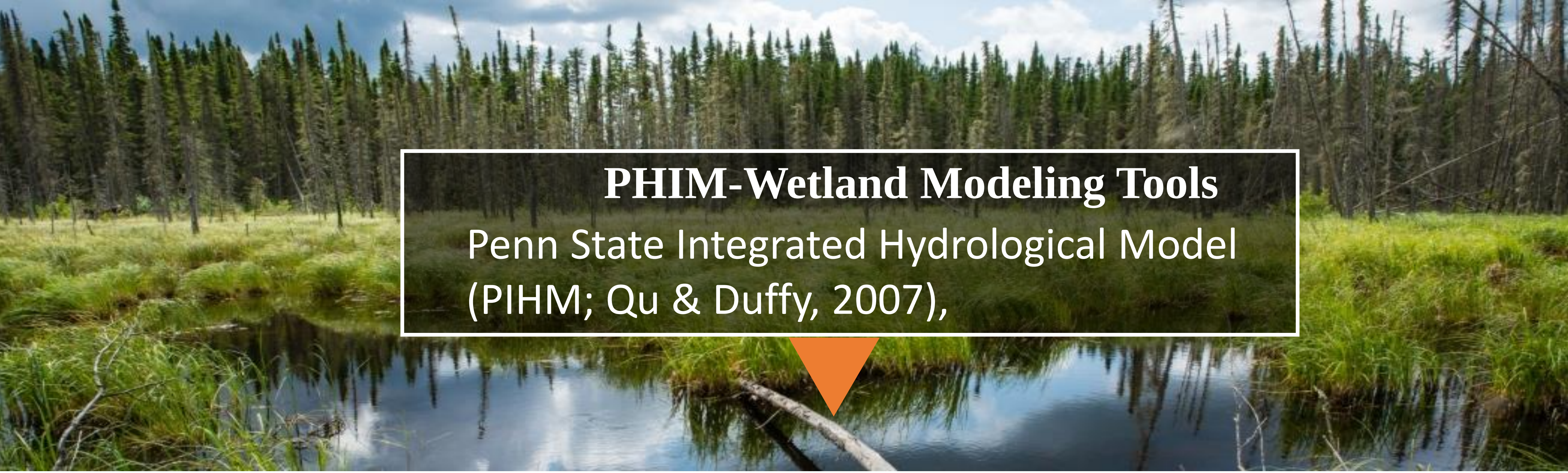
Each single satellite revisit time is 10 days.

Two satellites (Sentinel 2A and 2B)

Swath: 290 km

Coverage limits: 56° S to 84° N

Source: ESA



PHIM-Wetland Modeling Tools

Penn State Integrated Hydrological Model (PIHM; Qu & Duffy, 2007),

The process-based model have been successfully applied to the Alligator River and the SE US to

- **Understand coastal wetland hydrology at a regional scale**
- **Understand the hydrologic resilience of coastal wetland due to climate variability & sea level rise**

Modeling Tools of Coastal Wetland Hydrology

(Zhang et al. 2018 Hydrological Processes)

RESEARCH ARTICLE

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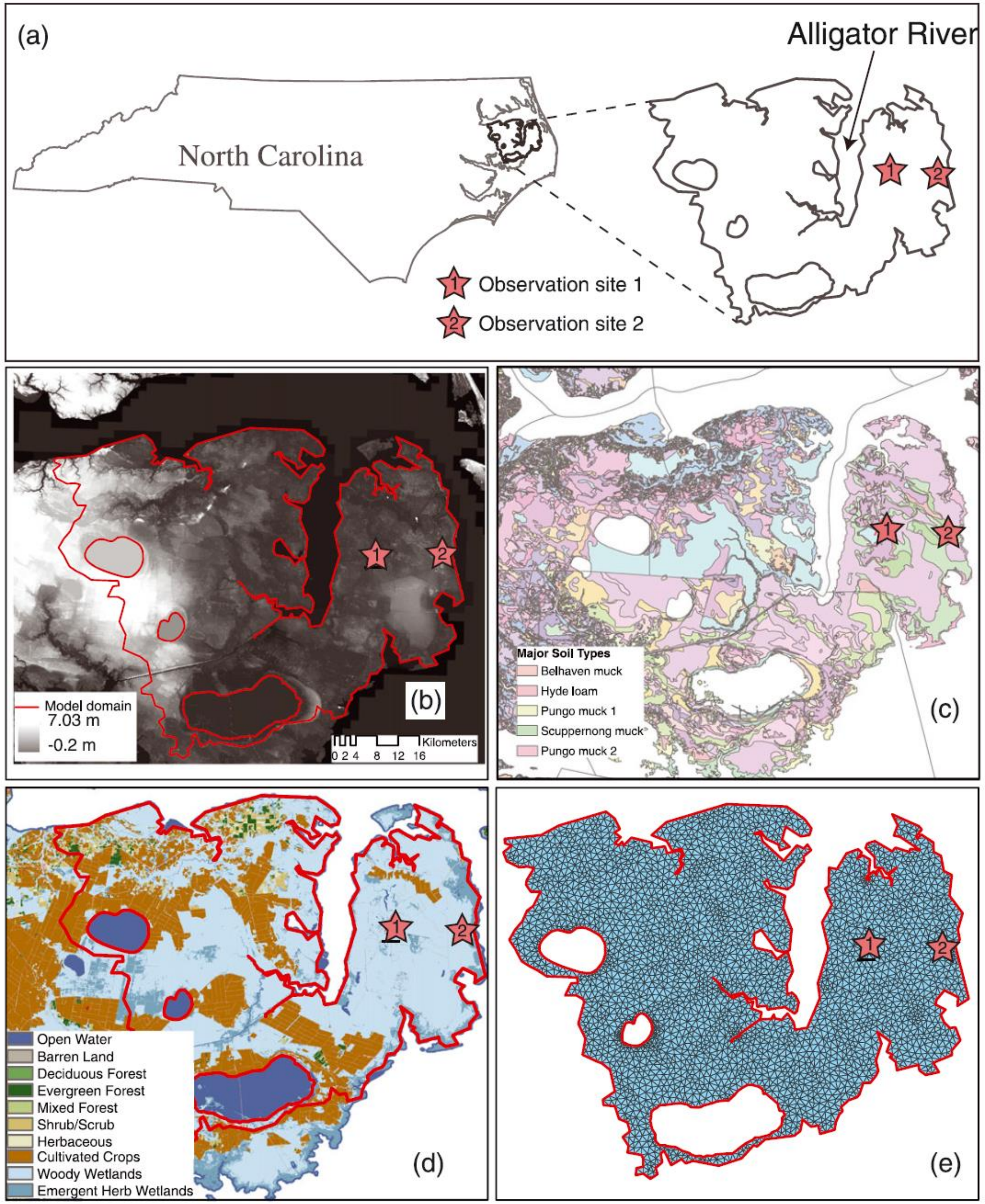
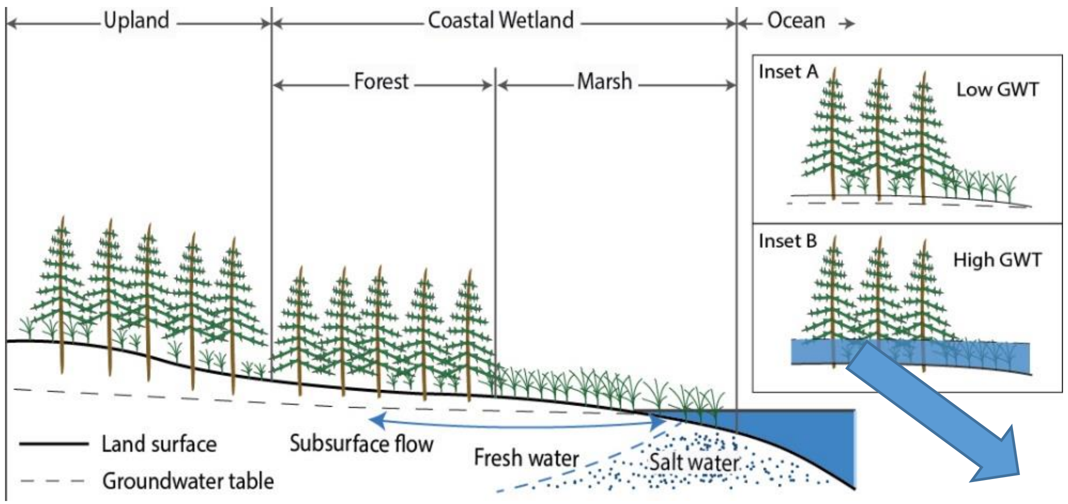
Understanding coastal wetland hydrology with a new regional-scale, process-based hydrological model

Yu Zhang[1] | Wenhong Li[1] | Ge Sun[2] | Guofang Miao[3] | Asko Noormets[4] | Ryan Emanuel[3] | John S. King[3]

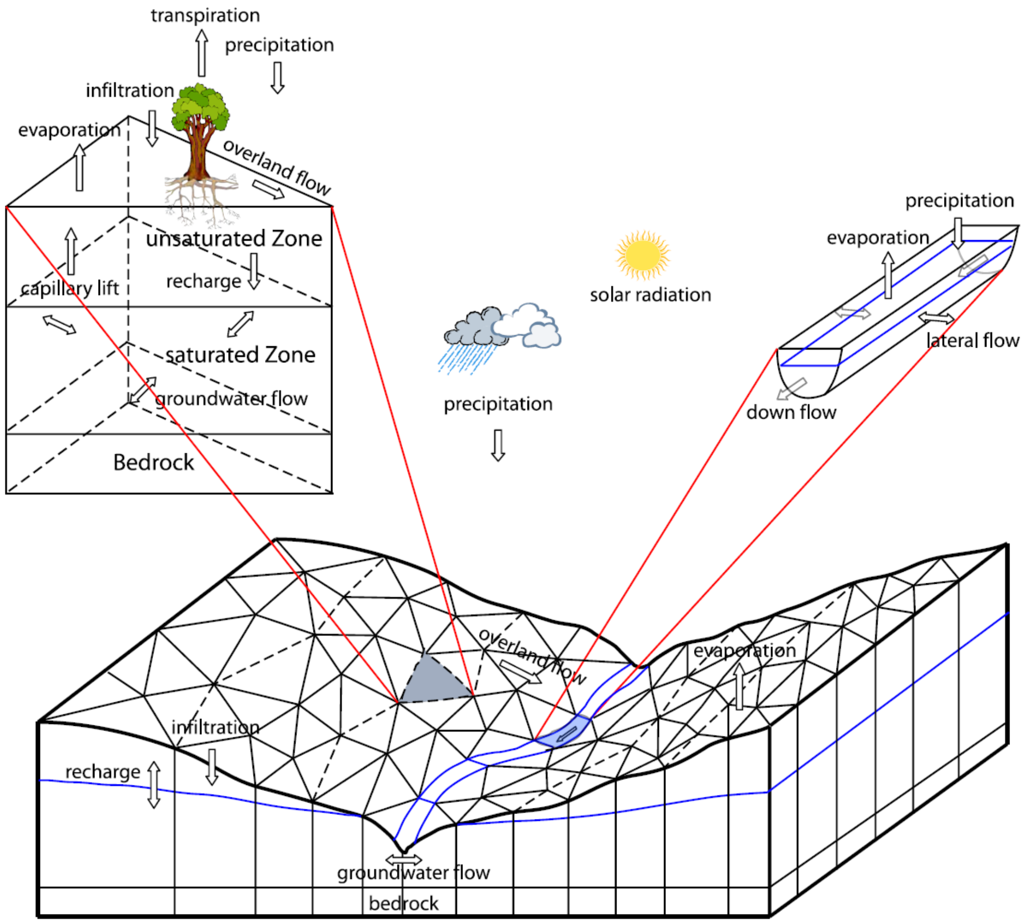


(Zhang et al. 2018, Hydrological Processes)

Understand Coastal Wetland Hydrology

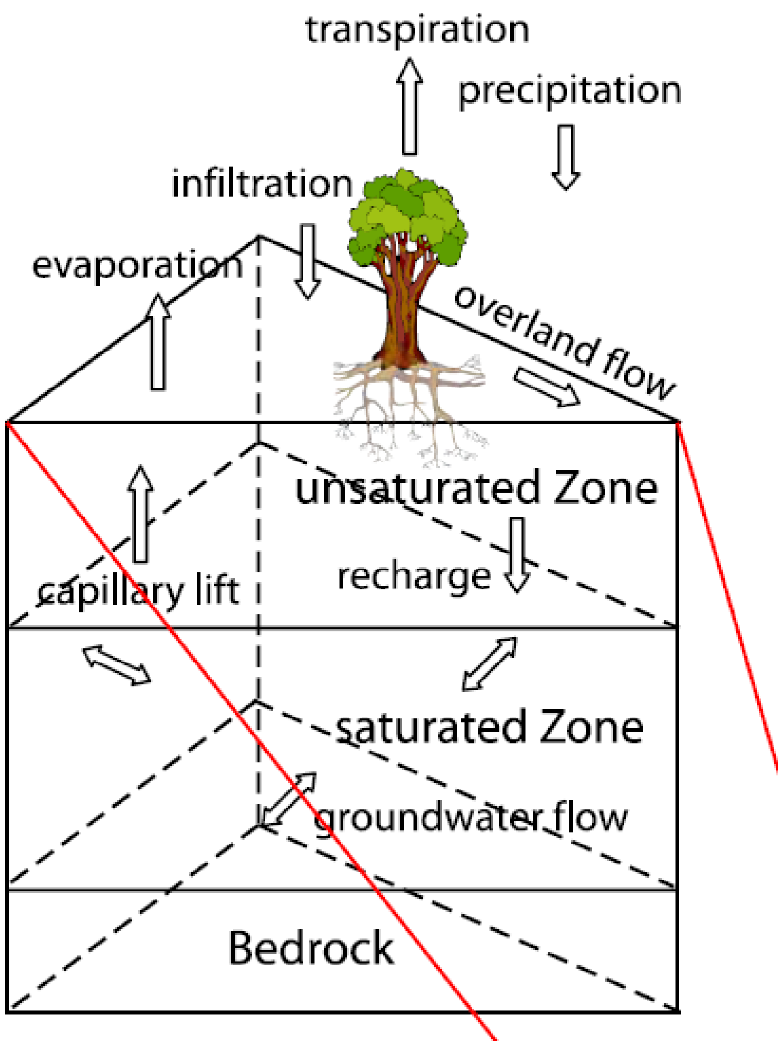


PIHM-Wetland



- A regional scale, spatial distributed, physically based, hydrologic model
- Using semi-discrete finite volume method and TINs (Triangular Irregular Network)

PHIHM-Wetland



PIHM-Wetland

$$
\begin{cases}
\frac{d\psi_{canopy}}{dt} = vFrac * (1 - sFrac) * P - E_c \\
\frac{d\psi_{snow}}{dt} = sFrac * P - SM \\
\frac{\partial\psi_{surf}}{\partial t} = TF - \nabla q_{sw} - I - E_s \\
\frac{d\psi_{unsat}}{dt} = I - R - E_g - E_{gt} \\
\frac{\partial\psi_{sat}}{\partial t} = \nabla q_{gw} + R - E_{sat} - E_{tsat} \\
\frac{\partial\psi_{salt}}{\partial t} = \nabla q_{salt}
\end{cases}
$$

Boundary Conditions

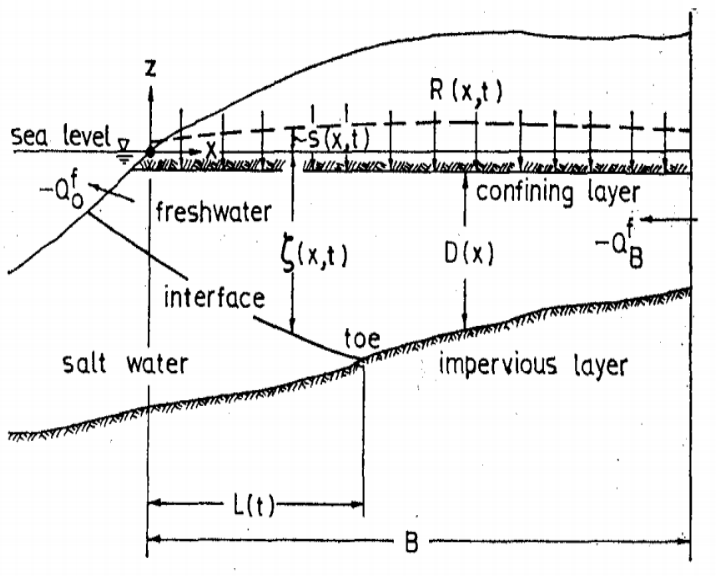
1) Tide and Sea level rise

The hydrological processes are subject to change due to the coastal processes, like tides and sea level rise.

$$q_{sw}(x) = \frac{[\psi_{surf}(x)]^{\frac{5}{3}}(\psi_{surf}(x)+z-h_{sea})/L}{n_s*(S)^{\frac{1}{2}}} \qquad \forall x \in \partial\Omega \qquad \text{model domain } \Omega \subset \mathbb{R}^n$$

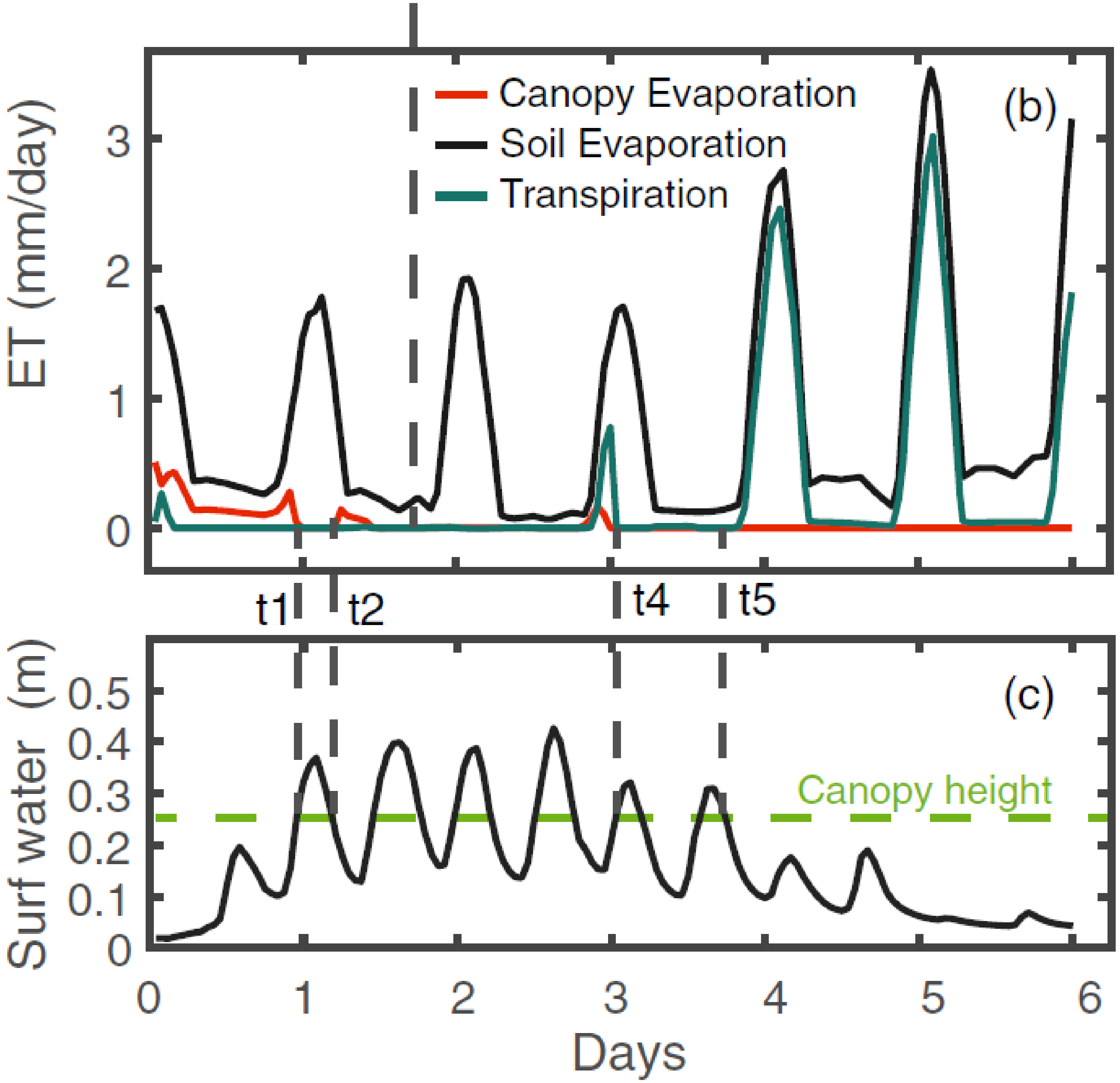
2) Saltwater intrusion

We assume that 1) the fresh and salt water are immiscible by ignoring the dispersion between the interface, and 2) the flow is Dupuit flow where the hydraulic head along a vertical direction is constant.



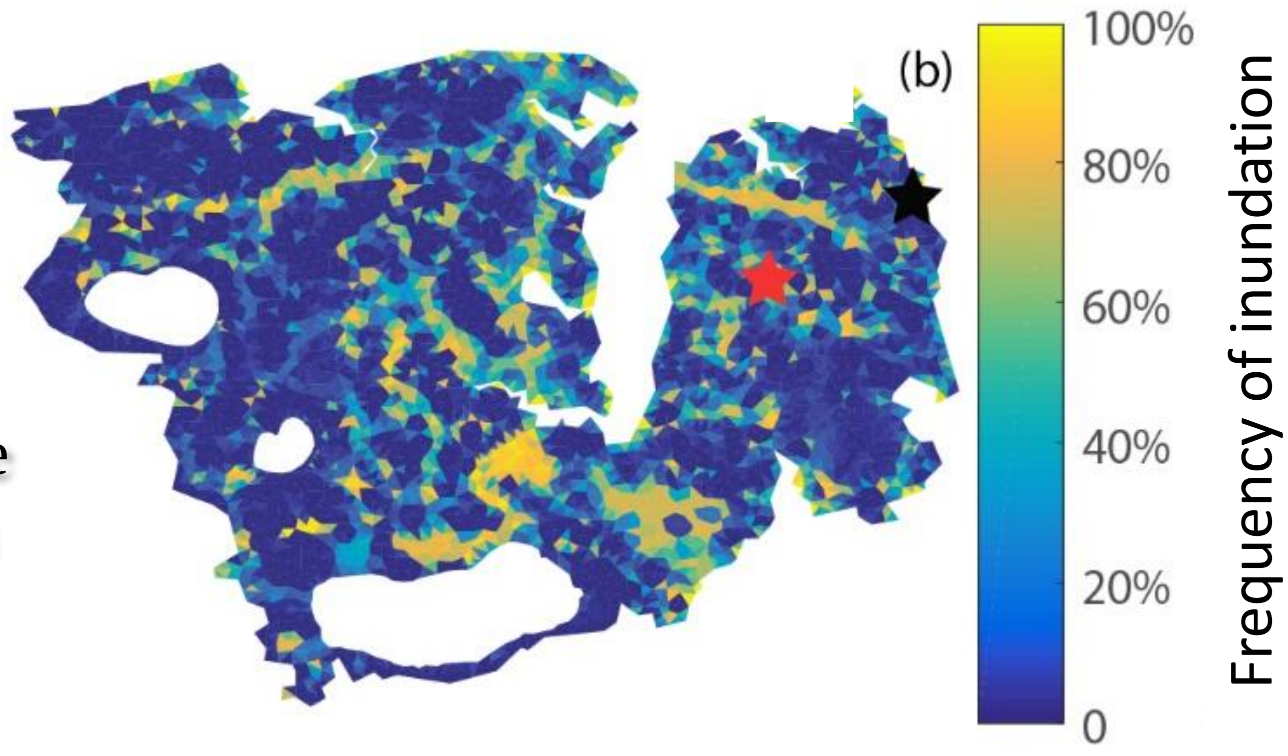
$$q_{gw}(x) = -K\frac{\partial(\psi_{sat}(x)+\psi_{salt}(x)+z_b)}{\partial x} \qquad \forall x \in \partial\Omega$$

$$q_{salt}(x) = -K\frac{\partial[\frac{\sigma_f\psi_{sat}(x)}{\sigma_s}+\psi_{salt}(x)]}{\partial x} \qquad \forall x \in \partial\Omega$$



(Zhang et al. 2018 Hydrological Processes)

Regional scale distribution of inundation



Consistent with the spatial distribution of inundation

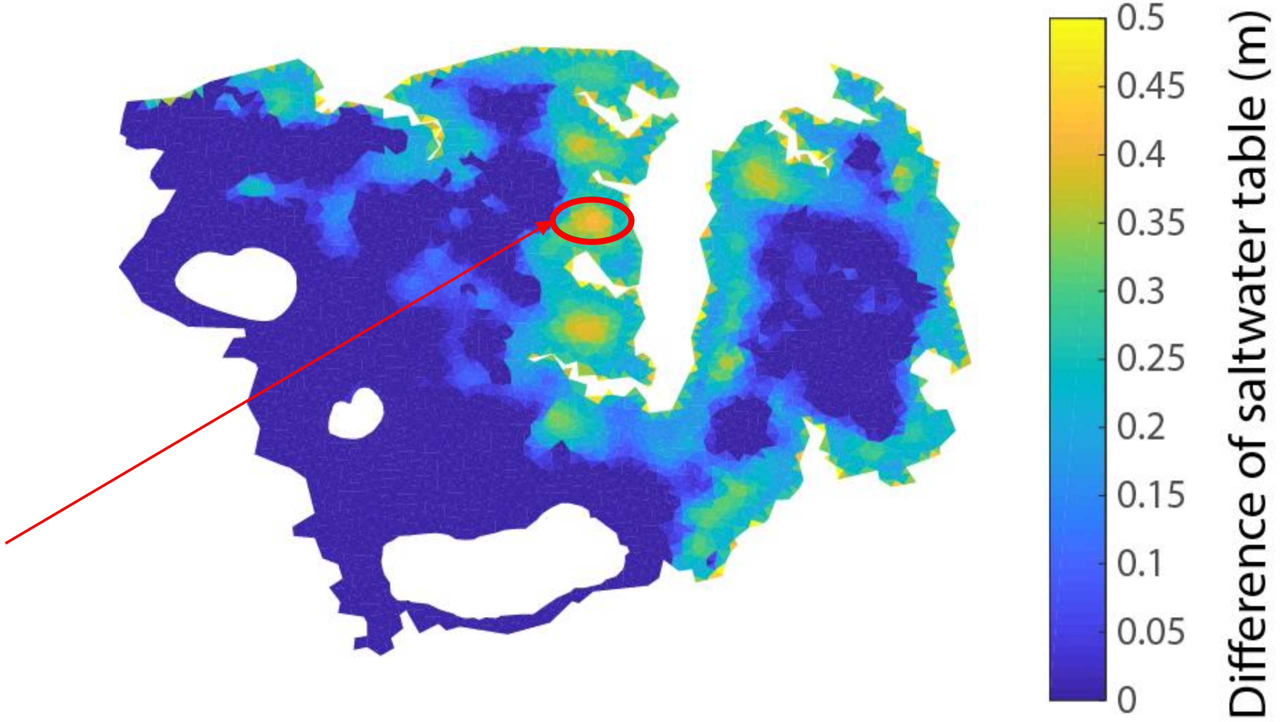
- From 2007 to 2016, frequency ranging from 5% (rarely occur) to 100% (always occur) each year.
- Two-thirds of these occurrences had a frequency higher than 50%.

(Zhang et al. 2018 Hydrological Processes)

Hydrologic resilience to sea level rise

Difference of saltwater table under extremely dry and wet periods

- Area with highest difference is 400 m from the coastlines
- Least resilient region to water availability



(Zhang et al. 2018 Hydrological Processes)

Summary

- Remote sensing technology used to study Ghost Forests: Challenges
- Hydrological model (PHIM-wetland) model: Validation
- Integrated assessment of SLR and climate variability (including hurricane activities) over the SE US
- Coupling projections of SLR and climate variability