Supporting Information for

# Detecting coastal wetland degradation by combining remote sensing and hydrologic modeling

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## S1 Sea levels at the local Oregon Inlet Marina, NC during the period of 1995-2019

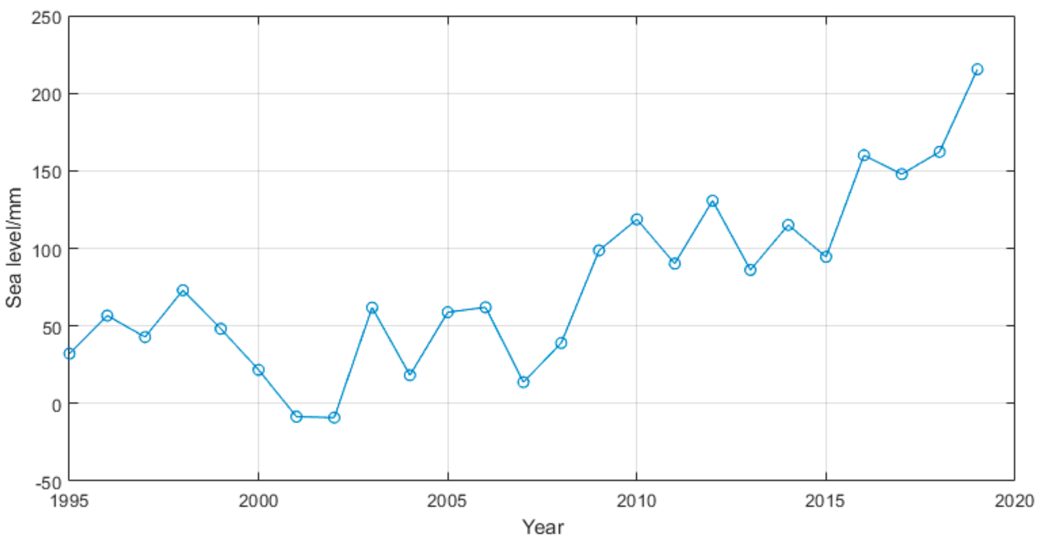


**Figure S1** Annual average sea levels observed at the local station Oregon Inlet Marina, NC from 1995 to 2019.

## S2 Detail information of Landsat data used in the study

All available atmospherically corrected Tier 1 Surface Reflectance product during 1995-2019 from Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI) were downloaded for WRS-2 Path 13 and Row 35, Path 13 and Row 36, and Path 14 and Row 35 from the US Geological Survey (USGS) (https://earthexplorer.usgs.gov/). A total of 962 Landsat images were obtained and analyzed in the study, of which 255 images were from Landsat 5 TM (January 23, 1995 - November 3, 2011), 534 images were from Landsat 7 ETM+ (July 5, 1999 - January 22, 2015), and 172 images were from Landsat 8 OLI (April 14, 2013 - December 27, 2019).

## S3 The advantages of seasonal scale NDVI analysis over annual scale NDVI analysis in determining the time of wetland degradation

In this study, we analyzed seasonal scale NDVI time series to identify when and where coastal wetland degradation happened. The time of degradation was determined as the year corresponding to the first growing season (summer when NDVI usually reaches its maximum value in a year) since the value of NDVI continuously falling below the lower threshold of the relatively higher structure-complex wetland type.

Although annual scale NDVI time series analysis can also determine the year when wetland degraded, results from seasonal scale NDVI time series analysis were more accurate. For example, Figure S2 exhibits the NDVI time series of the same pixel with Type 6 wetland degradation (i.e., emergent herbaceous wetlands degraded to non-vegetated areas) on the seasonal (Fig. S2a) and annual scales (Fig. S2b). Here, seasonal maximum NDVI values (the maximum value of all available NDVI values in the same season in a certain year) and annual maximum NDVI values (the maximum value of all available NDVI values in the same year) were used. Clearly, this selected pixel was an emergent herbaceous wetland ($0.1 \leq \text{NDVI} < 0.4$) at the beginning of the study period (1995 spring). Then, it degraded to non-vegetated areas ($-1.0 \leq \text{NDVI} < 0.1$) around 2014 and 2015. Figure S2a shows that its seasonal NDVI value declined to a value (0.02) below 0.1 in 2014 summer and continuously fluctuated below 0.1 until the end of the study period (2019 winter). Based on the criteria we mentioned in the paper, its wetland degradation time was 2014. However, Figure S2b indicates that it degraded in 2015, which is inconsistent with the result from the seasonal scale NDVI analysis and deviates from the reality. Therefore, although the wetland degradation time determined by the two methods are both accurate to the year, seasonal scale NDVI analysis outperforms annual scale NDVI analysis.

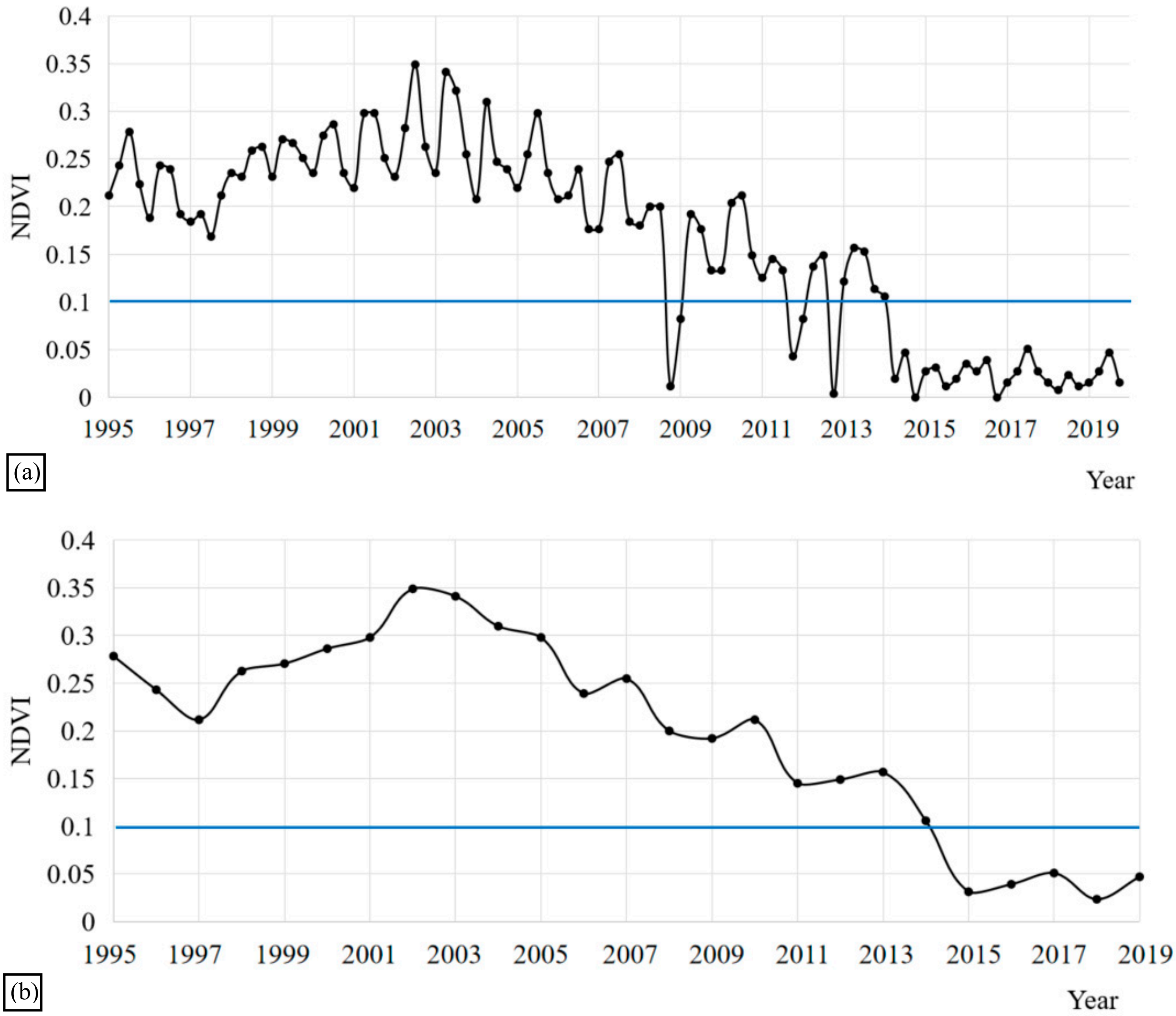


**Figure S2.** Time series of (a) seasonal maximum NDVI, (b) annual maximum NDVI of a randomly selected pixel with Type 6 wetland degradation within ARNWR. The year on the x-axis of (a) refers to the amercement of that year, i.e., the spring of each year.

## S4 Analysis of seasonal NDVI and water tables

### S4.1 Correlations between seasonal NDVI and water tables

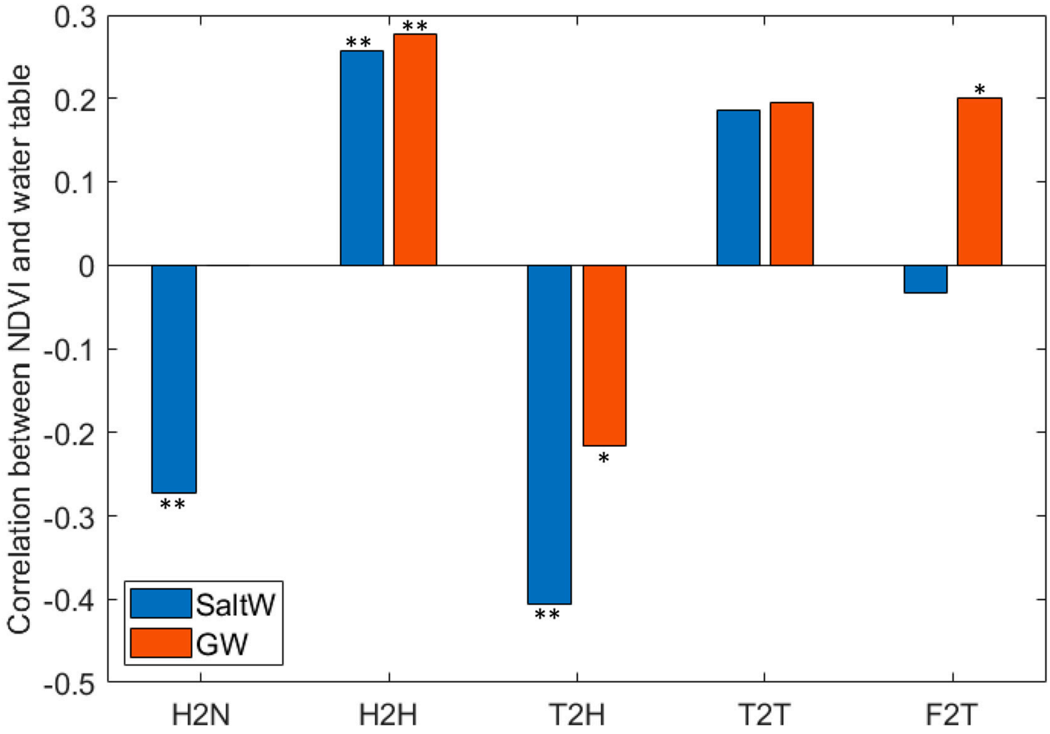


**Figure S3.** Correlations of grid-wise mean seasonal NDVI to the seasonal saltwater table (SWT) and groundwater table (GWT) for different types of wetland evolution. H2N: Emergent herbaceous wetlands degraded to non-vegetated areas (Type 6 degradation)[1]; H2H: Emergent herbaceous wetlands without degradation; T2H: Transitional forested wetlands degraded to emergent herbaceous wetlands (Type 5 degradation); T2T: Transitional forested wetlands without degradation; F2T: Forested wetlands degraded to transitional forested wetlands (Type 3 degradation). $p < 0.05$ is denoted with a single star (*); $p < 0.01$ is denoted with double stars (**).

Figure S3 suggests that seasonal NDVI was generally negatively correlated with seasonal groundwater tables (GWTs) and saltwater tables (SWTs) for all the grids with coastal wetland degradation (only except the relationship between the NDVI of Type 3 degradation and its seasonal mean GWTs) but positively correlated with seasonal GWTs and SWTs for the grids where coastal wetlands did not degrade, in agreement with the findings in Section 3.3.2. For the grids with Type 6 and Type 5 degradations, the correlations of seasonal NDVI with seasonal SWTs were also found stronger than those with GWTs. For Type 6 degradation (i.e., emergent herbaceous wetlands degraded to non-vegetated areas) and Type 5 degradation (i.e., transitional forested wetlands degraded to emergent herbaceous wetlands), the correlations between seasonal NDVI and seasonal mean SWTs are -0.27 and -0.41 (p values < 0.01), respectively.

### S4.2 Thresholds of water table depth to coastal wetland degradation

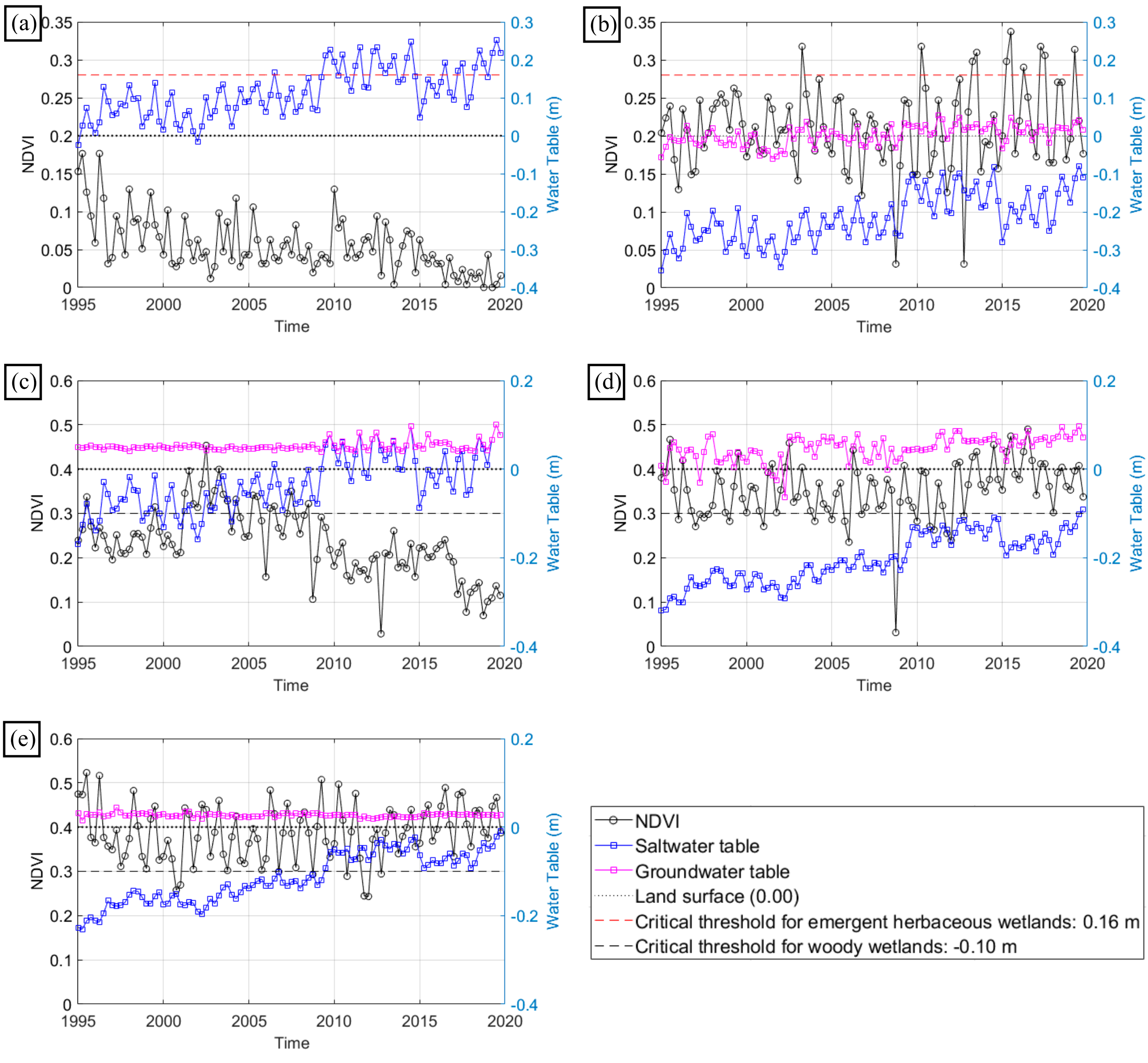


**Figure S4.** Evolutions of the grid-wise mean seasonal NDVI (left), seasonal GWTs (right, unit: m) and SWTs (right, unit: m) for (a) Type 6 degradation (emergent herbaceous wetlands degraded to non-vegetated areas)[2]; (b) Emergent herbaceous wetlands without degradation; (c) Type 5 degradation (transitional forested wetlands degraded to

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1 Due to that this triangular irregular grid was next to the sea (Fig.7a) and the simulated SWT was above the land surface, there was no distinction between saltwater and ground freshwater. Therefore, only the grid-wise mean seasonal NDVI time series with seasonal SWTs were presented.

emergent herbaceous wetlands); (d) Transitional forested wetlands without degradation; (e) Type 3 degradation (forested wetlands degraded to transitional forested wetlands). Red and black horizontal dash lines represent the critical thresholds for emergent herbaceous wetlands (0.16 meters) and woody wetlands (-0.10 meters), respectively.

Figure S4a shows the evolution of grid-wise mean seasonal NDVI and seasonal SWTs for the pixels with Type 6 degradation (i.e., emergent herbaceous wetlands degrading to non-vegetated areas). In 1995, the maximum seasonal NDVI value of the wetland was 0.18, suggesting that it was an emergent herbaceous wetland ( $0.1 \leq \text{NDVI} < 0.4$ ). From 1995 to 2009, although the maximum seasonal NDVI values of the wetland within a year were occasionally below 0.1 due to environmental stresses, the NDVI value reached back to higher than 0.1 in 2010. However, the NDVI values dropped below 0.1 in 2011 and never recovered by the end of the study period (2019 winter), indicating that the emergent herbaceous wetlands degraded to non-vegetated areas (Type 6 degradation) in 2011. Correspondingly, the seasonal SWT rose to 0.16 meters above the land surface and maintained a high level after 2011. We noticed that neither seasonal SWTs nor GWTs ever reached 0.16 meters above the land surface in emergent herbaceous wetlands (Fig. S4b). The results suggest that the seasonal water table level higher than 0.16 meters from the land surface might be a critical threshold for emergent herbaceous plants' survival. Similarly, in woody wetlands, we found that Type 3 and Type 5 degradations happened when seasonal SWTs reached above -0.10 meters (Figs. S3c and S3e), while in transitional forested wetlands without degradation, the seasonal SWT was always below -0.10 meters (Fig. S4d), implying that the seasonal SWT within 10 cm below the land surface is critical for woody vegetation. These findings are all consistent with the results in Section 3.3.3.

[2] Seasonal GWTs were not presented for the same reason in Fig. S4.