

Beyond NDVI: A Multi-index Remote Sensing Analysis of Wetland Marsh Recovery Following the Mississippi River Gulf Outlet Closure

Supplementary Material

S1. Lloret et al [1] Disturbance Framework

The STL derived Q3 annual values were then fed directly into the Lloret et al. [1] disturbance framework, which quantified community level response to each storm event using four dimensionless ratio metrics. The same framework has similarly been applied in salt marsh and coastal wetland contexts by Castagno et al. [2]. For each storm event, community mean Q3 index values were extracted for three temporal windows namely;

Pre = community mean Q3 of (disturbance_q3_year) – 1

Dist = community mean Q3 of disturbance_q3_year

Post = community mean Q3 of (disturbance_q3_year) + 1

Where (disturbance_q3-year) is the Q3 year in which the storm disturbance signal first manifested in vegetation. For storms making landfall in Q4 (Oct-Dec), the growing season peak had already passed so (disturbance_q3_year) was set to the following calendar year's Q3. Four metrics were then derived exactly as defined in [1]

Resistance $R_t = (\text{dist}) / (\text{pre})$ ($R_t < 1.0$, disturbance year loss)

Recovery $R_c = (\text{post}) / (\text{dist})$ ($R_c > 1.0$, recovery above dist level)

Resilience $R_s = (\text{post}) / (\text{pre})$ ($R_s \geq 1.0$, full resilience, post at or above pre)

Relative Resilience $RRS = [(\text{post}) - (\text{dist})] / (\text{pre})$ ($RRS > 0$, net recovery gain)

Storm events were identified systematically from the HURDAT2 Atlantic Basin hurricane tracks (1984-2024) [3,4]. All storms passing within 300km of Shell Beach at Category 1 or greater intensity (≥ 64 kt) or within 100 km at tropical storm strength (≥ 34 kt) (short named 300/100km) were accounted for under the distance threshold for storms that likely had an impact on the study area. The thresholds were chosen based on documented surge reach distances for Gulf of America systems, and these types of storms could drive 0.5m to 1.0m surge at Shell Beach [5]. A total of 22 storm events were identified and where multiple storms affected the site within the same Q3 year, they were grouped together. The Lloret et al. [1] disturbance framework was conducted using NDVI and NDII as complementary indices. NDVI quantifies photosynthetic capacity through chlorophyll absorption, while NDII assesses canopy water content via shortwave infrared reflectance [6,7]. The results were shown in Table S1 and Figure S1 below

Lloret Resistance (Rt) vs Resilience (Rs) by Community
Shell Beach 1984-2025 | Colour = community; marker = storm | Error bars = ± 1 SE

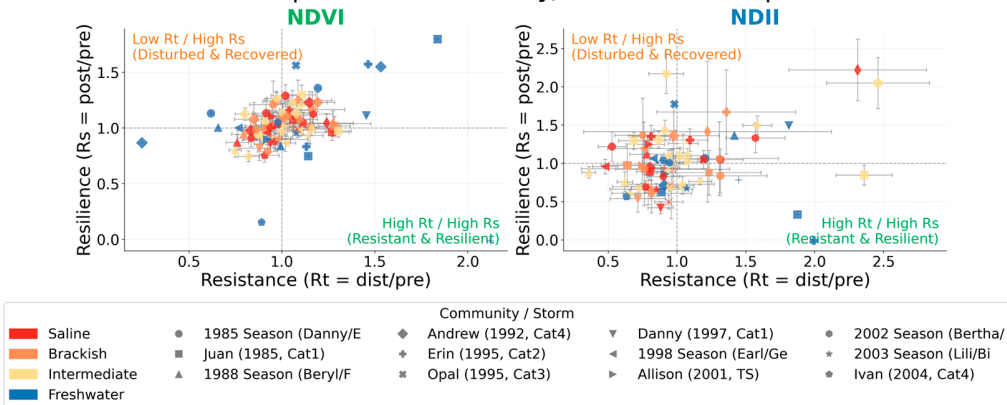


Figure S1. Lloret resistance-resilience scatter matrix

Table S1. Lloret disturbance framework analysis

Storm Event	Year	NDVI Rt	NDVI Rs	NDII Rt	NDII Rs	KNDVI Rt	KNDVI Rs
Danny/Elena	1985	0.904	1.072	1.218	0.918	0.997	1.075
Juan (Cat1)	1985	1.252	1.317	0.753	0.949	1.093	1.354
Beryl/Florence	1988	0.932	0.953	0.901	0.986	0.821	0.948
Andrew (Cat4)	1992	0.682	1.012	0.887	1.084	0.722	1.172
Erin (Cat2)	1995	1.172	1.297	1.345	1.492	1.176	1.456
Opal (Cat3)	1995	1.109	1.150	1.088	1.098	1.237	0.979
Danny (Cat1)	1997	1.041	0.926	1.033	0.781	0.792	0.730
Earl/Georges	1998	0.909	0.926	0.744	1.028	0.924	0.936
Allison (TS)	2001	0.953	1.009	0.885	1.026	0.928	1.097
Bertha/Hanna/Isidore	2002	1.060	1.099	1.190	1.126	1.185	1.234
Lili/Bill	2002	1.041	0.918	0.975	0.690	1.060	0.801
Ivan (Cat4)	2004	0.885	0.613	0.718	0.618	0.772	0.603
Cindy/Dennis/Katrina	2005	0.869	0.986	0.866	1.167	0.790	0.992
Gustav (Cat2)	2008	1.247	0.680	1.091	0.979	0.952	0.839
Ida (Cat1)	2009	1.059	1.031	0.935	0.811	1.134	1.054
Lee (TS)	2011	0.974	1.191	0.770	1.082	0.935	1.399
Isaac (Cat1)	2012	1.225	1.026	1.536	1.580	1.513	1.065
Nate (Cat1)	2017	1.037	1.290	N/A	N/A	1.081	1.652
Barry (Cat1)	2019	1.249	0.926	2.117	0.591	1.555	0.878
Cristobal/Sally	2020	0.739	0.906	N/A	N/A	0.558	0.853
Zeta/Claudette/Ida	2020	1.236	1.288	N/A	N/A	1.586	1.681
Francine (Cat2)	2024	1.024	0.981	1.403	0.672	1.058	0.973

S2. Pre-Storm Early Warning Analysis

For each of the 22 storms identified in section 3.5, the site mean STL residual z-score in Q3 of the year immediately before landfall was extracted as the pre-storm anomaly indicator. Because z-scores were computed relative to the full 1984-2025 deseasonalized baseline, a negative z-score in the pre-storm year

indicated that vegetation was already suppressed relative to 42-year historical norms. This condition was associated with elevated storm sensitivity in coastal marsh systems [8,9]. Two thresholds were applied and reported separately in Table S2

Primary threshold: $z < -1.0$, one standard deviation below the deseasonalized long-term mean. A departure of -1.0 SD corresponds to approximately the lowest 16th percentile of the historical distribution and is the standard threshold in satellite vegetation monitoring [10]. In drought early warning frameworks, -1.0 SD defines the boundary between near-normal and mild drought vegetation anomaly classes [11,12]. Its selection here was therefore consistent with the operation literature and represented a conservative criterion, only pre-storm suppressions large enough to indicate meaningful stresses were flagged.

Secondary threshold: $z < -0.5$, a half standard deviation below the mean. A departure of 0.5 SD corresponds to the lower 31st percentile of a normal distribution and identifies “below normal” conditions that fall short of the one sigma anomaly criterion. Half sigma thresholds are used as “watch” or “advisory” levels in drought monitoring systems to capture early-stage ecosystem stress before it escalates to the full anomaly thresholds [13,14]. Including this secondary criterion allowed identification of events where pre-storm vegetation were moderately but not severely suppressed, which is ecologically relevant in a coastal marsh context where even pre-storm moisture stress can compound salinity-driven vulnerability [8].

However, this analysis was exploratory because storm impacts on vegetation dynamics depend on multiple interacting factors such as storm track, surge height, antecedent water level, salinity, vegetation community composition and winds, that cannot be reduced to a single pre-storm scalar. Our framework characterised pre-storm baseline rather than predicting storm impact severity.

For most pre-MRGO storms (1984-1998), site mean z-scores were near zero or slightly negative, consistent with the site still under active MRGO-driven degradation during that period. The low count of primary threshold warning signals (2 of 22 events) in this 42-year context confirms that the 1984-2025 deseasonalised baseline is a substantially more demanding reference than shorter periods baseline where any deviation from a 5-year normal period would constitute a warning signal.

Table S2. STL Z-score early warning metrics

Storm Event	Year	NDVI z	NDII z	KNDVI z	Warning $z < -1.0$	Warning $z < -0.5$
Danny/Elena	1985	-0.15	-0.03	-0.12	No	No
Juan (Cat1)	1985	-0.38	+0.44	-0.36	No	No
Beryl/Florence	1988	+0.30	+0.17	+0.59	No	No
Andrew (Cat4)	1992	+0.25	+0.36	+0.29	No	No
Erin (Cat2)	1995	-0.43	-0.52	-0.48	No	yes
Opal (Cat3)	1995	-0.02	+0.35	+0.05	No	No
Danny (Cat1)	1997	+1.10	+0.71	+1.55	No	No
Earl/Georges	1998	+0.14	-0.07	+0.15	No	No
Allison (TS)	2001	-0.06	-0.05	-0.12	No	No
Bertha/Hanna/Isidore	2002	-1.06	-0.66	-1.02	yes	yes
Lili/Bill	2002	+0.14	+0.17	+0.24	No	No
Ivan (Cat4)	2004	+0.83	+0.44	+1.16	No	No
Cindy/Dennis/Katrina	2005	-0.11	-0.45	-0.09	No	No
Gustav (Cat2)	2008	-0.01	-0.09	-0.00	No	No
Ida (Cat1)	2009	+0.14	+0.37	-0.04	No	No

Lee (TS)	2011	+0.13	-0.02	+0.22	No	no
Isaac (Cat1)	2012	-0.17	-0.53	-0.22	No	yes
Nate (Cat1)	2017	-0.90	-1.14	-0.99	yes	yes
Barry (Cat1)	2019	-0.57	-0.12	-0.68	No	yes
Cristobal/Sally	2020	+2.02	+1.98	+1.95	No	no
Zeta/Claudette/Ida	2020	-0.48	-0.19	-0.55	No	yes
Francine (Cat2)	2024	-0.55	-0.88	-0.35	no	yes

S3. Full Pairwise Sen Slope Analysis

The weak NDII-NDVI Pearson correlation ($r = 0.590$) in section 4.4 predicted that station-level trend magnitudes should diverge between these indices. Implying that lots with rapid canopy moisture loss need not show equally rapid structural biomass loss. The pairwise Sen slope scatter matrix in Figure S below visualises trend agreement across all six index combinations at station level. NDVI-kNDVI slopes align tightly with a high r , confirming their structural redundancy. Most station level Sen slopes were negative for NDVI, NDII and kNDVI reflecting the dominant declining trend. NDVI-NDRE slopes showed moderate agreement with NDRE slope spanning positive and negative values over the shorter 2015-2025 record. NDII-NDVI, NDII-kNDVI and NDII-NDRE scatter plots showed additional scatter relative to the NDVI-kNDVI pair. A subset of stations showed more negative NDII slopes than their NDVI slopes, indicating that canopy moisture decline was proceeding faster than structural biomass decline at those plots. This NDII-NDVI slope divergence is ecologically consistent with plots experiencing physiological water stress reflected in NDII at a greater rate than structural biomass changes as reflected in NDVI and possibly due to residual salinity effects or altered inundation regimes in marginal community zones [15].

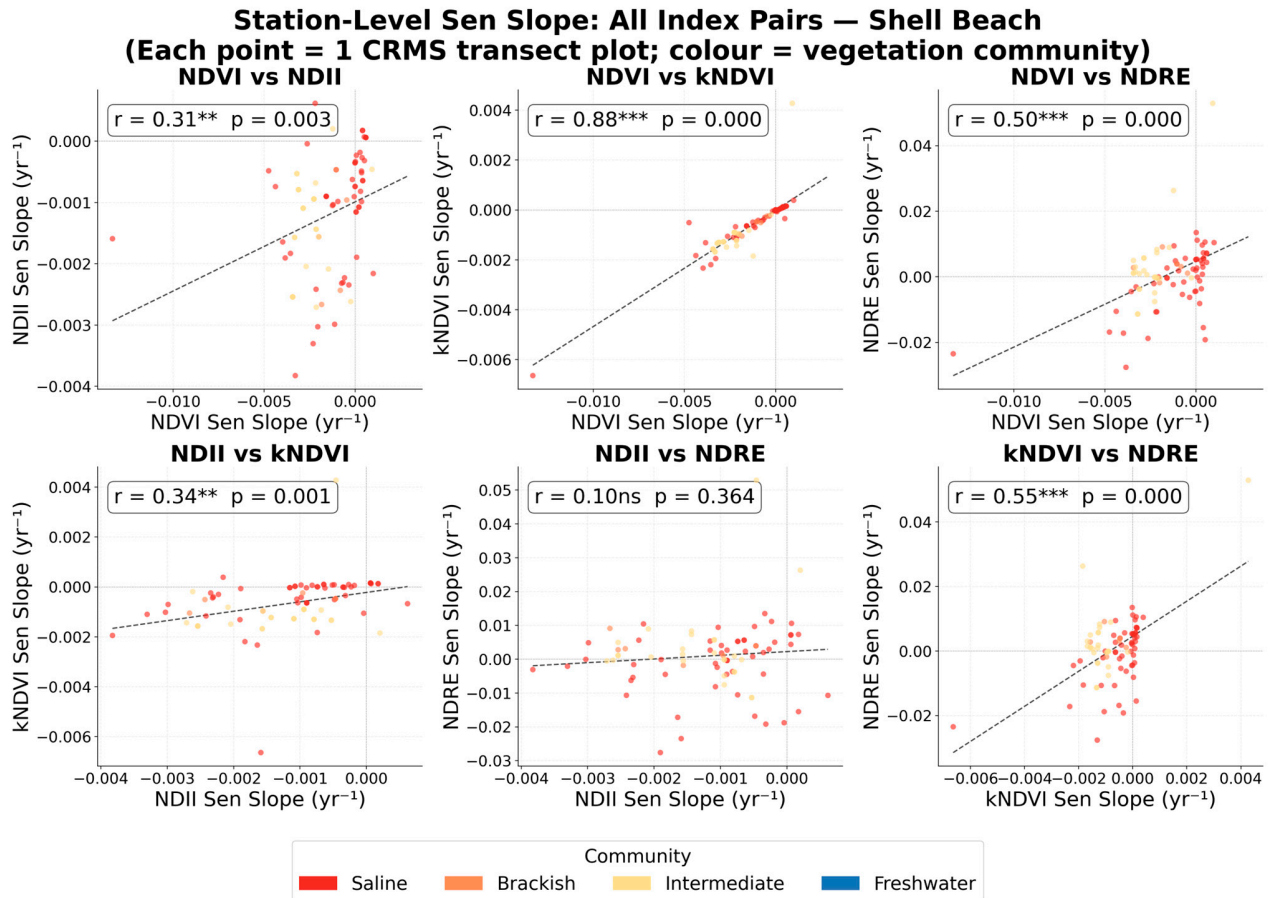


Figure S2. Station level Sen slope analysis

References

1. Lloret, F.; Keeling, E.G.; Sala, A. Components of Tree Resilience: Effects of Successive Low-growth Episodes in Old Ponderosa Pine Forests. *Oikos* 2011, doi:10.1111/j.1600-0706.2011.19372.x.
2. Castagno, K.A.; Tomiczek, T.; Shepard, C.C.; Beck, M.W.; Bowden, A.A.; O'Donnell, K.; Scyphers, S.B. Resistance, Resilience, and Recovery of Salt Marshes in the Florida Panhandle Following Hurricane Michael. *Sci. Rep.* 2021, 11, 20381, doi:10.1038/s41598-021-99779-8.
3. Landsea, C.W.; Franklin, J.L. Atlantic Hurricane Database Uncertainty and Presentation of a New Database Format. 2013, doi:10.1175/MWR-D-12-00254.1.
4. Levinson, D; Knapp, K; Kruk, M; Diamond, H; James, K The International Best Track Archive for Climate Stewardship (IBTrACS) Project: Overview of Methods and Indian Ocean Statistics | Springer Nature Link Available online: https://link.springer.com/chapter/10.1007/978-90-481-3109-9_26 (accessed on 14 May 2026).
5. Needham, H.F.; Keim, B.D. A Storm Surge Database for the US Gulf Coast. *Int. J. Climatol.* 2012, 32, 2108–2123, doi:10.1002/joc.2425.
6. Sriwongsitanon, N.; Gao, H.; Savenije, H.; Maekan, E.; Saengsawang, S.; Thianpopirug, S. The Normalized Difference Infrared Index (NDII) as a Proxy for Soil Moisture Storage in Hydrological Modelling. *Hydrol. Earth Syst. Sci. Discuss.* 2015, 12, 8419–8457, doi:10.5194/hessd-12-8419-2015.

7. Huang, S.; Tang, L.; Hupy, J.P.; Wang, Y.; Shao, G. A Commentary Review on the Use of Normalized Difference Vegetation Index (NDVI) in the Era of Popular Remote Sensing. *J. For. Res.* 2021, 32, 1–6, doi:10.1007/s11676-020-01155-1.
8. Pennings, S; Glazner, R; Hughes, Z; Kominoski, J; Armitage, A Effects of Mangrove Cover on Coastal Erosion during a Hurricane in Texas, USA - Pennings - 2021 - Ecology - Wiley Online Library Available online: <https://esajournals.onlinelibrary.wiley.com/doi/full/10.1002/ecy.3309> (accessed on 14 May 2026).
9. Steyer, G.D. Coastwide Reference Monitoring System (CRMS); U.S. Geological Survey, 2010;
10. Anyamba, A.; Tucker, C.J. Analysis of Sahelian Vegetation Dynamics Using NOAA-AVHRR NDVI Data from 1981–2003. *J. Arid Environ.* 2005, 63, 596–614, doi:10.1016/j.jaridenv.2005.03.007.
11. Sheffield, J.; Wood, E.F. Projected Changes in Drought Occurrence under Future Global Warming from Multi-Model, Multi-Scenario, IPCC AR4 Simulations. *Clim. Dyn.* 2008, 31, 79–105, doi:10.1007/s00382-007-0340-z.
12. WMO Concepts, Progress and Future Challenges.; 2006.
13. Anderson, Liana; Malhi, Yadvinder; Aragao, Luiz; Ladle, Richard; Barbier, Nicholas; Philips Oliver Remote Sensing Detection of Droughts in Amazonian Forest Canopies - Anderson - 2010 - New Phytologist - Wiley Online Library Available online: <https://nph.onlinelibrary.wiley.com/doi/full/10.1111/j.1469-8137.2010.03355.x> (accessed on 14 May 2026).
14. Svoboda, M.; LeCompte, D.; Hayes, M.; Heim, R.; Gleason, K.; Angel, J.; Rippey, B.; Tinker, R.; Palecki, M.; Stooksbury, D.; et al. THE DROUGHT MONITOR. 2002, doi:10.1175/1520-0477-83.8.1181.
15. Wilson, N.R.; Norman, L.M. Analysis of Vegetation Recovery Surrounding a Restored Wetland Using the Normalized Difference Infrared Index (NDII) and Normalized Difference Vegetation Index (NDVI). *Int. J. Remote Sens.* 2018, 39, 3243–3274, doi:10.1080/01431161.2018.1437297.