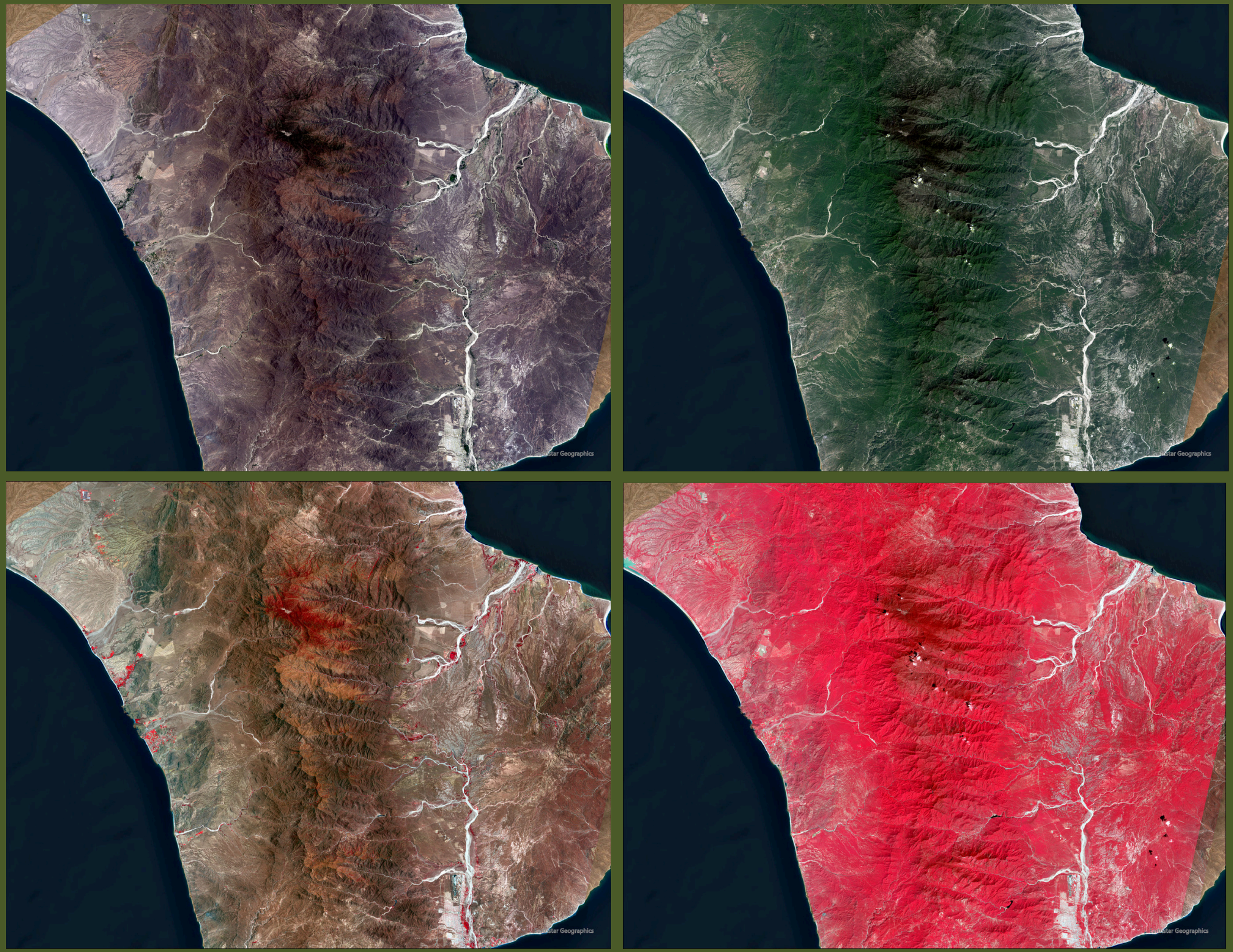
How a Desert Breathes
Analyzing Vegetation Response to Major Storms in Southern Baja California Sur



Southern BCS before (left) and after (right) Hurricane Oliver - true color top - color infrared bottom - maps by Liam Galleher

In Southern Baja California Sur, change is not dictated by 4 seasons, but **energized by opportunity**. Months of drought can be abruptly interrupted by a single tropical storm, harboring enough moisture to transform vast landscapes from completely desolate, to entirely green overnight. Despite this widespread and dramatic phenomenon, the magnitude and spatial pattens of post-storm bloom have never been systemically mapped for this region. With remote sensing, we can quantify how the desert “breathes,” discerning patterns for both ecological and social considerations. Post-storm bloom impacts erosion risk, grazing capacity, wildlife habitat, and the long-term health of both the dryland ecosystem and the people who inhabit it. This project relies on Landsat imagery to measure change in NDVI, highlighting vegetation response to four major storm events between 2017 and 2025. The patterns identified can help shape decisions for land managers, conservation groups, and regional planners to anticipate fire risk, protect watersheds, and plan for sustainable development.

Primary Objectives

1. **Quantify** vegetation change before and after major storms by using Landsat-based change in NDVI
2. **Compare** spatial patterns across major storms with differing tracks, rainfall, and seasonal contexts
3. **Assess** the ecological significance of post-storm bloom for erosion control, habitat quality, dryland resilience, and watershed function
4. **Translate** technical findings into an accessible narrative for land managers and community stakeholders

Context

A Personal Revelation

I have often visited family in El Cardonal, a rural town on the East Cape of Southern Baja. The landscape is characterized by its vibrant beaches and arid mountains. Standing in the town center, you are surrounded by sea on one side, and rock, wood, cacti, and dirt on the other. The only green on the landscape stems from the small leaves of an elephant tree intermingling with matte cacti and dusty shrub cover.

Visiting El Cardonal in October 2025, I thought I had booked a flight to the wrong location - my plane was descending on what looked like a lush, emerald jungle. The landscape had transformed from completely brown to overwhelmingly green, revealing plant life I previously thought was reserved for rainforests further south. I was told that a hurricane had just blown through the area, and this landscape-scale transformation was to be expected from such rainfall. I was struck with how drastic the landscape I knew and loved had changed; even in the harshest of conditions, life finds a way. I was inspired to learn more about this phenomenon and its impact on the natural and social ecosystem of BCS.

Santiago, BCS, before and after Hurricane Oliver- photos by Liam Galleher

A Phenology Driven by Extremes

Unlike Mediterranean climates or temperate forests, phenology in Baja is motivated by irregular, high-intensity pulses of rainfall. Tightly linked to tropical storms and hurricanes, these rare events generate a vigorous and short-lived burst of productivity critical for:

- **Stabilizing soils after drought - a critical component of erosion control**
- **Providing forage for livestock**
  - **The livestock in this region is completely free-range to take advantage of the sparse vegetation (and I mean absolutely free-range… even your backyard is up for grabs!**
- **Sustaining pollinator activity**
- **Catalyzing landscape recovery after years of moisture deficit**

El Cardonal, BCS, before and after Hurricane Oliver - photos by Liam Galleher

Guiding Questions & Analytical Focus

Hypothesis

On average, regions at higher risk of erosion will exhibit a disproportionately positive change in NDVI, as post-storm rainfall yields enough concentrated moisture to activate dormant seeds and spur rapid bloom. Though each storm will have a distinct spatial signature, consistent greening patterns will emerge despite climactic and temporal variability.

Guiding Questions

1. How much vegetative greening occurs after major storm events in Southern Baja California Sur?
2. Where is post-storm bloom most pronounced?
3. How do spatial patterns differ by storm intensity?
4. What do these greening patterns reveal about dryland ecosystem function and its relationship with spontaneous rainfall?

What We Aim to Learn

By the end of this project, we will determine if post-storm greening is:

- **Consistent** across years and storm intensities
- **Predictable** based on storm track
- **Ecologically meaningful** for wildlife habitat
- **Informative** for decision making surrounding regional planning and climate resilience

Non-Technical Problem Statement

Southern Baja can be brown for most of the year, then explode with vegetation after a single storm, but we don't have clear maps showing where this greening happens or how strongly different storms trigger it. This project uses satellite imagery to track how the landscape responds to major rainfall events, helping communities, planners, and land managers better understand ecological resilience and storm impacts.

Technical Problem Statement

Despite frequent tropical systems affecting Southern Baja California Sur, there is little quantified evidence describing the spatial magnitude of post-storm vegetation response. This project applies Landsat-based NDVI change detection and erosion-risk zonal statistics to assess how four storms (2017-2025) altered vegetation patterns, with the goal of revealing storm effectiveness across terrain types and producing a reproducible workflow for arid-land phenology analysis.

Analysis

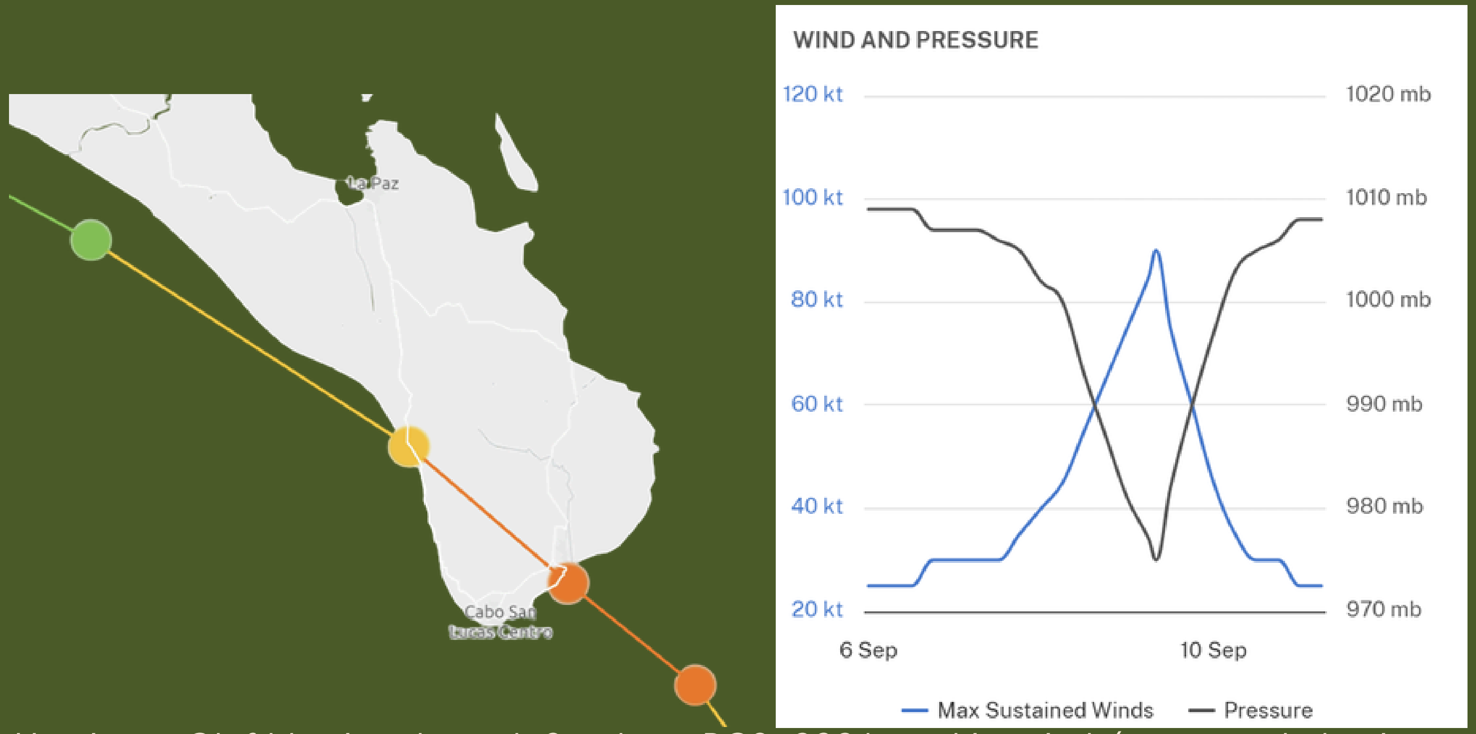
- Compare vegetation conditions before and after major storms using Landsat-based NDVI calculations.
- Analyze storm-specific change in NDVI to identify where greening intensifies, declines, or remains unchanged.
- Integrate erosion-risk layers to evaluate how post-storm bloom influences landscape stability.
- Use change in NDVI classifications and overlays to reveal clear patters in dryland phenology and ecological resilience that can be used for regional and conservation planning.

El Cardonal, BCS, after Hurricane Oliver - photo by Ross Wylde

Measurable Ecological Investments

Expected Deliverables

- Storm-by-storm NDVI and ΔNDVI maps that visualize vegetation response before and after major rainfall events.
- Comparative greening analyses that quantify how different storms affected ecosystem productivity across the region.
- Zonal statistics summarizing vegetation response by erosion risk class, revealing which landscapes are most responsive to rare precipitation pulses.
- Bar charts, maps, and summary tables that help planners and researchers understand spatial patterns of greening and vegetation recovery.
- A reproducible remote sensing workflow for desert phenology analysis applicable to future storms, drought years, or ecosystem monitoring initiatives.



Hurricane Olaf blowing through Southern BCS, 2021, and its wind / pressure behavior

Client Value & Practical Impact

Southern BCS, including communities such as Santiago, Los Barriles, El Cardonal, Todos Santos, and Cabo San Lucas, is experiencing rapid population growth and developmental pressure. Understanding how vegetation responds spatially to storm events directly supports:

- watershed protection and erosion forecasting
- rangeland and grazing management
- Regional planning for tourism
- hazard mitigation, especially flood-vegetation interactions and wildfire
- long-term conservation dryland ecosystems

These insights matter for planners, conservationists, emergency managers, and local residents navigating climate variability and intensifying storm seasons.

Storm seasons in Baja are becoming more erratic. Satellite imagery offers a unique, scalable way to track how the desert responds to these extremes. By treating storms as ecological "experiments," we can analyze how rainfall pulses shape vegetation patterns across space and time, creating a foundation for future monitoring, decision-making, and resilience planning.

Workflow Overview

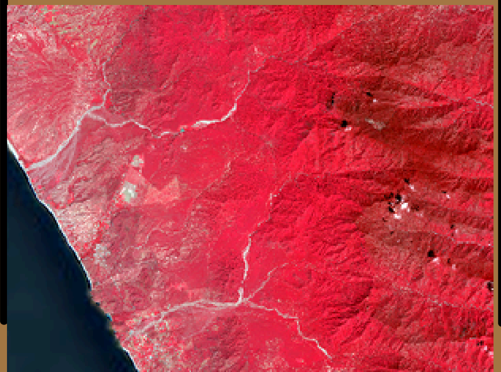
Evaluating the Outcomes of Major Storms in Southern Baja California Sur

DATA ACQUISITION

Dataset	Source	Geospatial Addition
Landsat 8 & 9 Surface Reflectan-ce	USGS EarthExpl-orer	Multispectral raster (Red + NIR)
Global Erosion Risk Map	Global Forest Watch	Classified raster (risk tiers)
Storm Track & Intensity Data	NOAA National Hurricane Center (NHC)	Polyline tracks + storm attributes
Rainfall & Precipitati on Totals	NASA IMERG / NOAA	Gridded precipitation raster

PRE-PROCESSING

- Download Landsat images for Hurricane Lidia (2017), Hurricane Lorena (2019), Hurricane Olaf (2021), and hurricane Oliver (2025 - noted as a 2nd hurricane Lorena from some sources)
- Using the raster calculator, convert all Landsat bands to surface reflectance.
- Using the 'composite bands' tool, build color infrared RGB composites for before and after every storm.
- Clip each raster to our Area of Interest, the southern Cape of BCS
- Ensure projection is consistent across all datasets
- Run the 'calculate statistics' tool on all rasters



NDVI COMPUTATION

- Compute NDVI for all pre and post storm rasters using the surface reflectance bands: NDVI = (NIR – Red) / (NIR + Red)
- By calculating NDVI, we can see the relative density and vigor of green vegetation before and after every hurricane
- Ensure all NDVI rasters fall between a range of -1 and 1 (confirm that reflectance scaling was successful)
- Apply stylistic and balanced color ramps to demonstrate vegetation growth
- Use NDVI maps to **visually** validate post-storm bloom, and to identify areas with patterns, unexpected noise, or errors.

STORM IMPACT ANALYSIS (ΔNDVI)

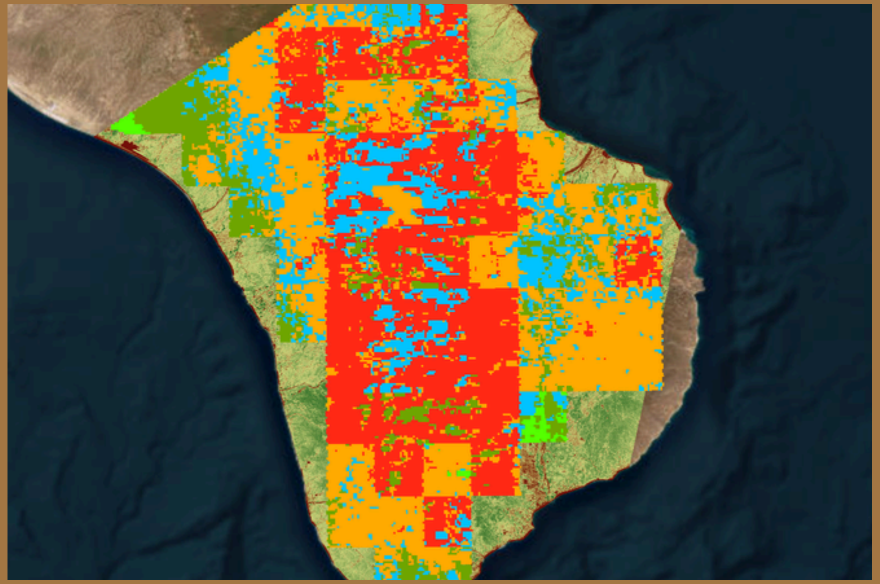
- Create ΔNDVI rasters by subtracting NDVI_before from NDVI_after to isolate storm-driven vegetation change independent of background conditions
- Symbolize the change in NDVI using a color scheme that emphasizes negative change in NDVI (loss of vegetation or surface exposure - red), neutral shift in NDVI (stable vegetation with little change before or after - yellow), and positive change in NDVI (rapid greening triggered by rainfall - green)
- Evaluate the spatial distribution of change in NDVI to identify hotspots of vegetation growth, vegetation loss, soil moisture retention, and consistently unaffected areas.
- Normalize symbology among all storms so values are comparable between storm years and intensities

LANDSCAPE ANALYSIS - EROSION

- Reclassify the Global Forest Watch erosion risk layer into three categories: low risk, medium risk, and high risk. This will support categorical analysis based on hurricane intensity.
- Use zonal statistics to summarize change in NDVI trends within each erosion class to produce metrics like mean, median, pixel count, and standard deviation to understand the relationship between post-storm bloom and erosion control
- Interpret the ecological and social considerations of any patterns identified to understand how post-storm bloom impacts the landscape and which areas benefit most from these events.

SYNTHESIZE VISUALZE REPRODUCE

- For each storm, design map panels showing NDVI , change in NDVI, and erosion to encourage visual comparison of storm impacts across time
- Develop bar charts illustrating change in NDVI zonal statistics to highlight consistent patterns, identifying the most vulnerable landscapes and how they fair in each storm
- Translate complex patterns into accessible narratives for nontechnical audiences
- Full PDF deliverable
- GIS project package
- Reproducible workflow documentation
- Dataset catalog
- Connect analytical insights to real-world, decision making contexts, such as watershed protection, livestock grazing, and regional planning.



Tools and Platforms

The software we rely on

ARCGIS PRO

- Best tool for raster-heavy operations (mosaicking, Extract by Mask, zonal stats, NDVI)
- High reliability with multi-temporal Landsat data
- Ideal for creating polished, client-facing cartography

PYTHON

- Enables automation for NDVI multi-raster analyses
- Ideal for reproducible scripts and batch processing
- Supports integration with field metrics, CSV summaries, and workflow scaling

LANDSAT

- Core spectral dataset for measuring vegetation response
- Provides Red + NIR bands necessary for NDVI
- Consistent 30 m resolution allows valid across-year comparisons

GLOBAL FOREST WATCH

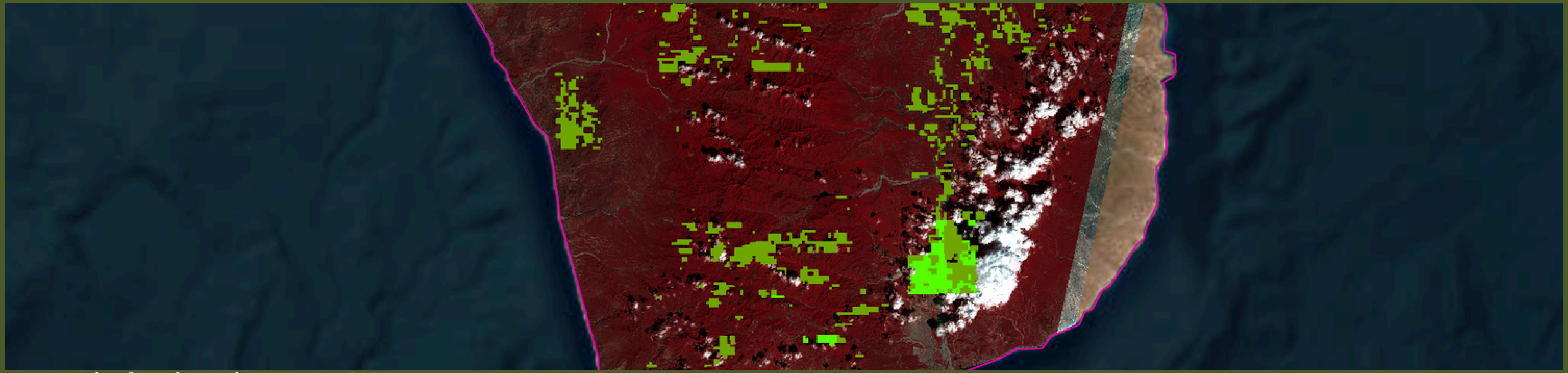
- Adds terrain vulnerability context
- Enables categorical zonal statistics for Low/Medium/High risk areas
- Supports interpretation of how landscape sensitivity shapes storm response

NOAA HURRICANE CENTER

- Storm track and timing data
- Essential for pairing Landsat scenes to pre- and post-event windows

NASA IMERG PRECIPITATION

- High-resolution gridded rainfall estimates
- Provides context for storm magnitude and spatial rainfall distribution



An example of overlaying layers in ArcGIS Pro

Constraints, Assumptions, and Ethical Considerations

CONSTRAINTS

- Landsat imagery is vulnerable to cloud contamination, especially in moist post-storm windows.
- ΔNDVI interpretation can be influenced by soil brightness, shadowing, and sparse vegetation typical of deserts.
- IMERG rainfall estimates may underrepresent localized rainfall extremes in mountainous terrain.
- Erosion risk classifications are coarse and may not capture fine-scale geomorphology.

CORE ASSUMPTIONS

- Landsat surface reflectance scaling was applied consistently across all scenes.
- NDVI change primarily reflects true vegetation response, not atmospheric or sensor artifacts.
- Erosion risk tiers represent meaningful differences in landscape susceptibility.
- Storm-driven greening occurs within a 2—6 week window, aligning with Landsat acquisition timing.

ETHICAL AND ANALYTICAL CONSIDERATIONS

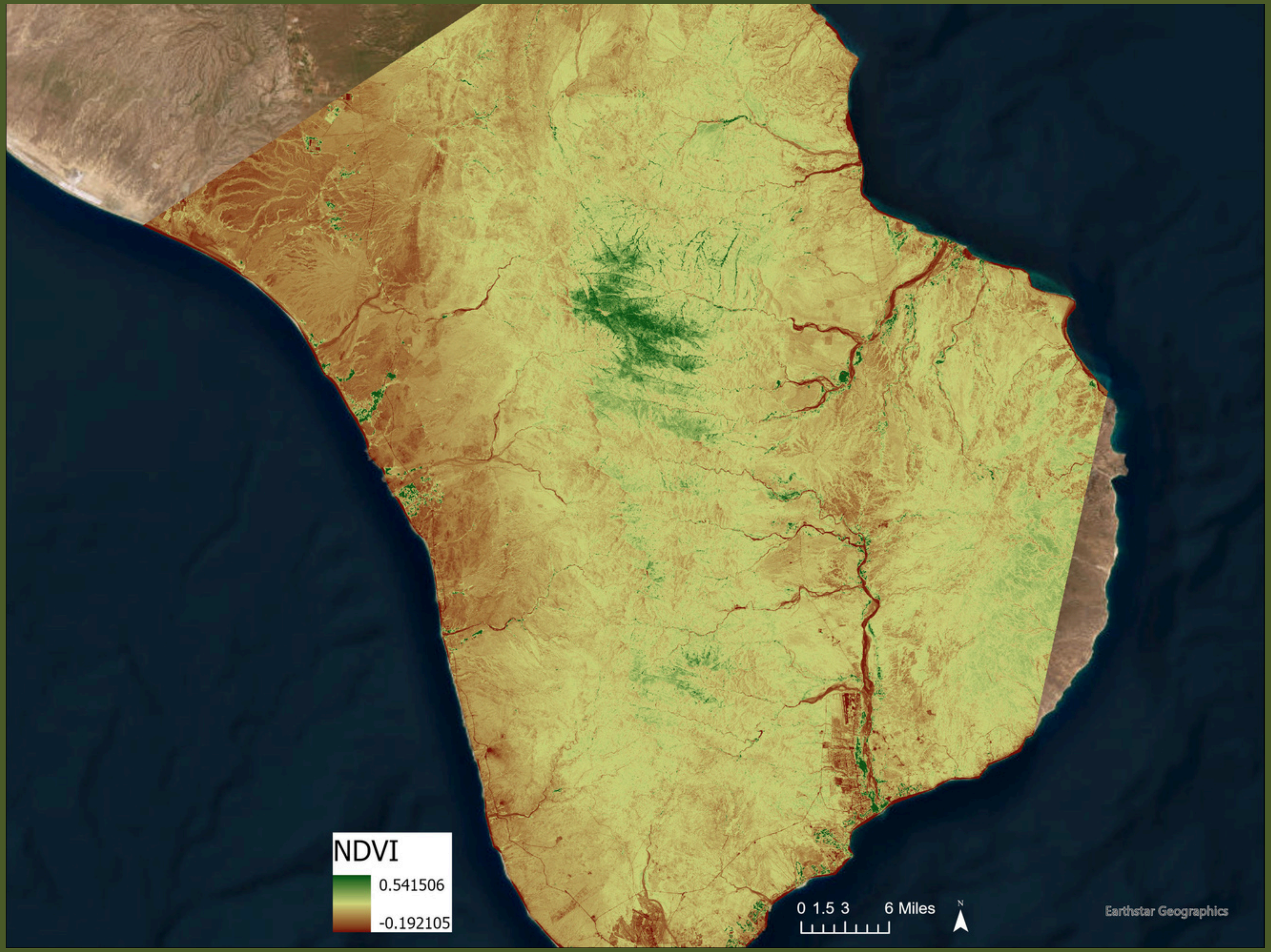
It is my responsibility as a geospatial investigator to:

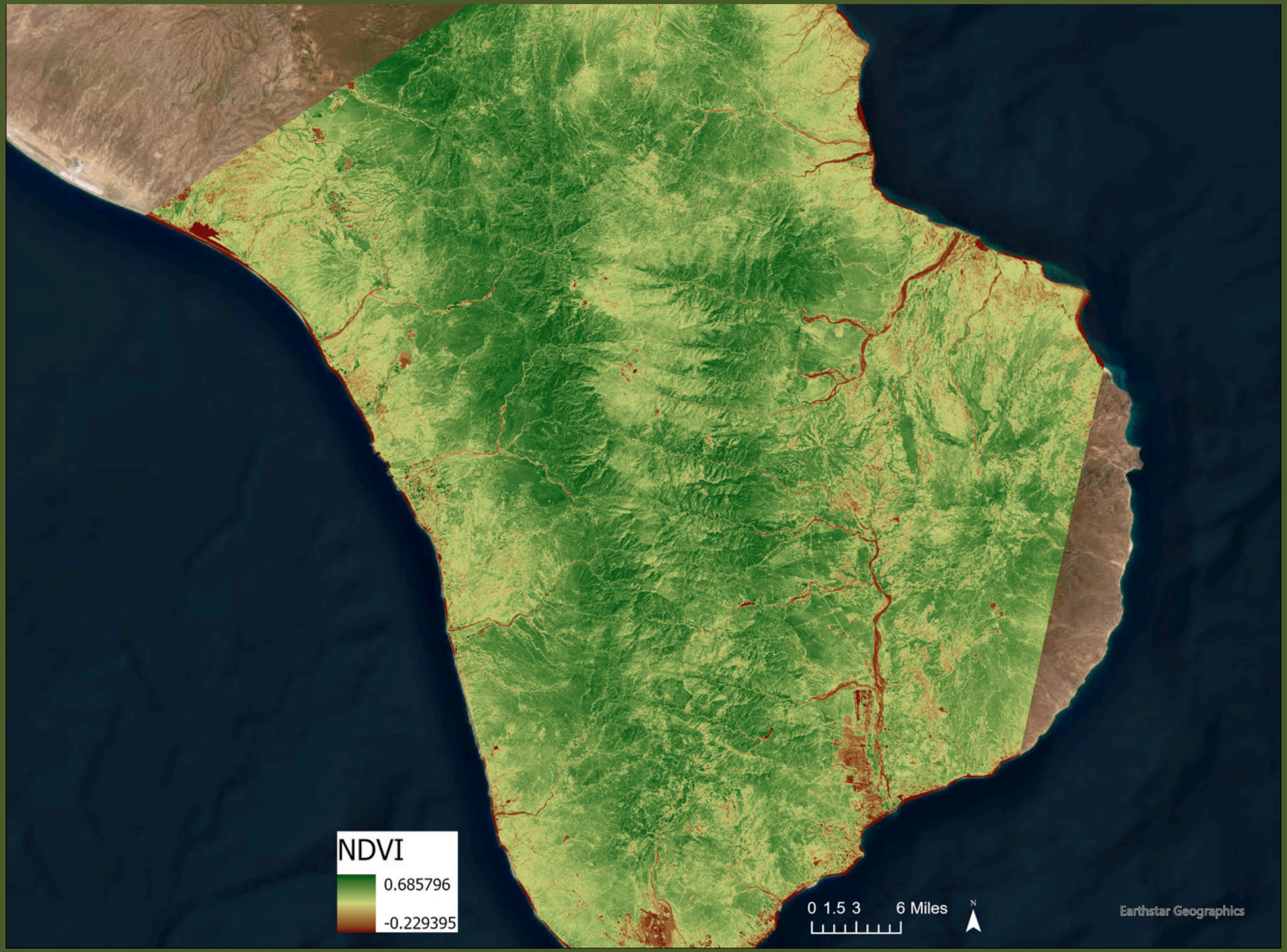
- Avoid overstating causality where only correlation is provable
- Be transparent about data gaps or inconsistencies
- Provide reproducible workflows for public accountability

Vegetation Response to Hurricane Oliver (2025): NDVI Analysis

Proof of Concept

The following workflow was applied to all 4 hurricanes, producing 8 images of pre and post-hurricane NDVI



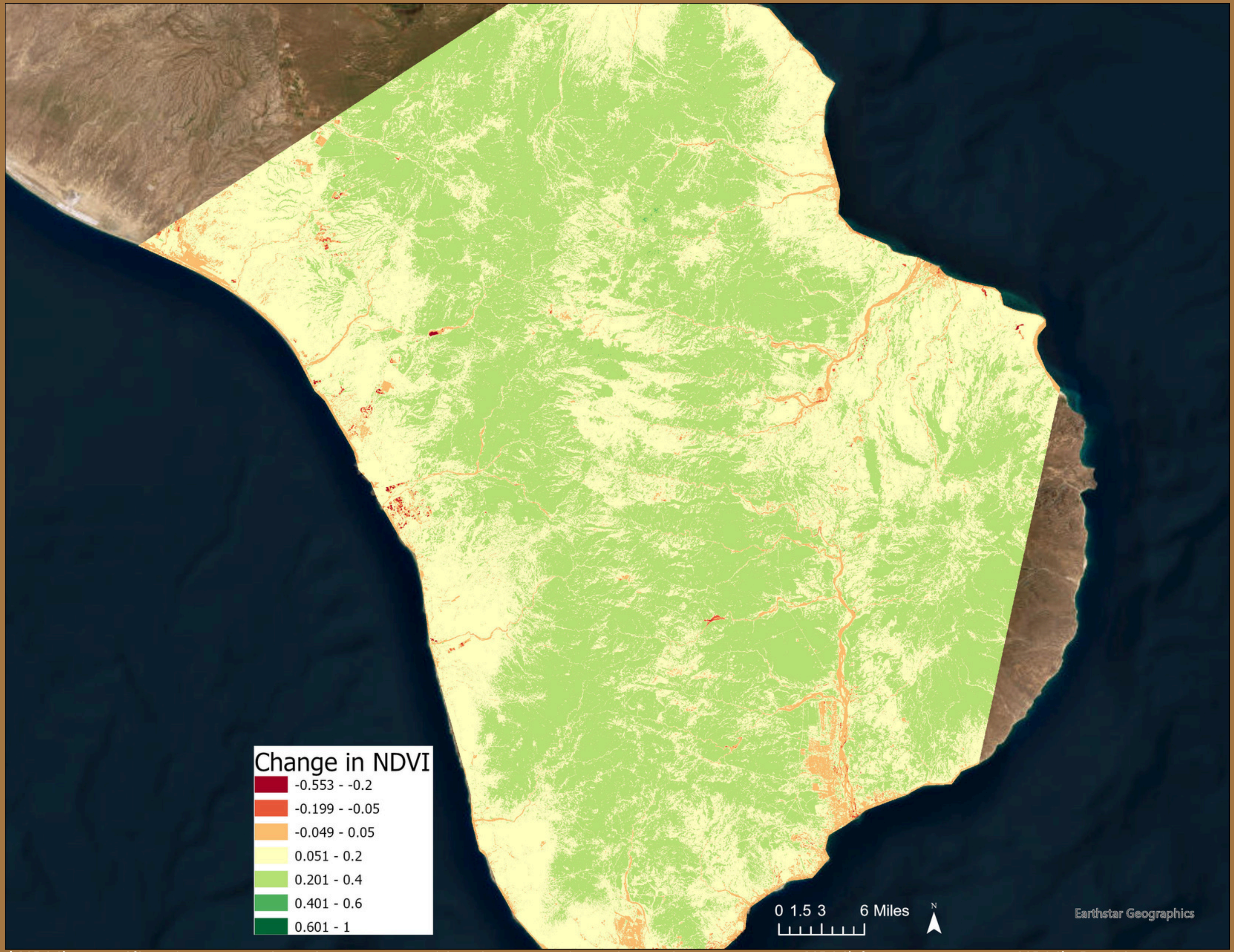


To illustrate how desert ecosystems respond to sudden rainfall, I processed Landsat 8/9 surface reflectance imagery captured immediately before and after each of the four selected rainfall events. After converting the Red and NIR bands to reflectance, I computed NDVI for each date to measure vegetation vigor, revealing characteristically low pre-storm values across Southern Baja California Sur under dry-season conditions. Following the storm, NDVI increased sharply across most of the landscape, capturing the rapid "green flash" typical of opportunistic desert phenology. The four storms included in this analysis, Lidia (2017), Lorena (2019), Olaf (2021), and Lorena/Oliver (2025), were chosen because each delivered substantial rainfall to the Southern BCS region, produced a visible ecological response in satellite imagery, and offered usable Landsat scenes both before and after recorded hurricanes. Together, they represent the most analytically robust and ecologically meaningful storm events from 2017-2025, offering an opportunity to study how desert vegetation responds across varying storm intensities, tracks, and seasonal contexts.

ΔNDVI After Hurricane Olaf (2021)

Proof of Concept

The following workflow was applied to all 4 hurricanes, producing 4 images of ΔNDVI



ΔNDVI quantifies the vegetation change caused by the storm by subtracting pre-storm NDVI from post-storm NDVI. Positive values (green) represent areas where vegetation surged after rainfall; negative values (red/orange) capture vegetation loss.

Discoveries from ΔNDVI

To measure vegetation change driven specifically by Hurricane Olaf, I used Landsat-based change detection. By subtracting the NDVI layer from before the storm from the NDVI layer captured immediately afterward, we get a raster that confirms suspected ecological trends. Because NDVI normalizes lighting and soil background effects, this approach cleanly isolates ecological change caused by rainfall, rather than differences in season, color tone, or image brightness. ΔNDVI is therefore a powerful way to quantify storm impacts in arid landscapes where greenness is normally minimal.

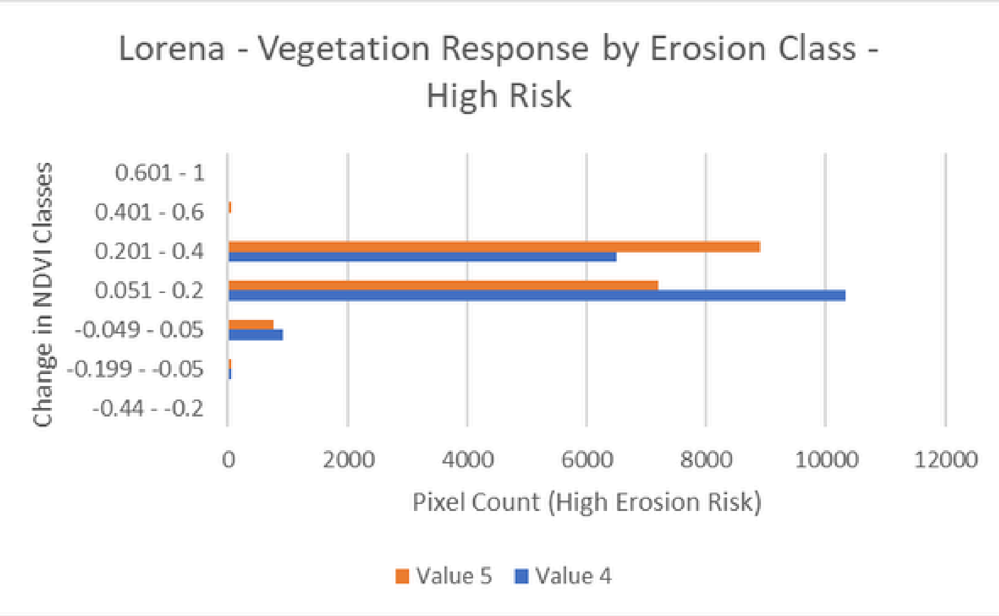
Hurricane Olaf produced a strong and spatially coherent greening response across Southern Baja California Sur. The brightest ΔNDVI values cluster around foothills, alluvial fans, and drainage corridors. These landforms naturally capture and retain stormwater. These areas typically remain dry throughout the year, but they are biologically adapted to respond explosively when moisture becomes available. In contrast, negative ΔNDVI values appear mostly in developed areas, riverbeds, or bare rock.

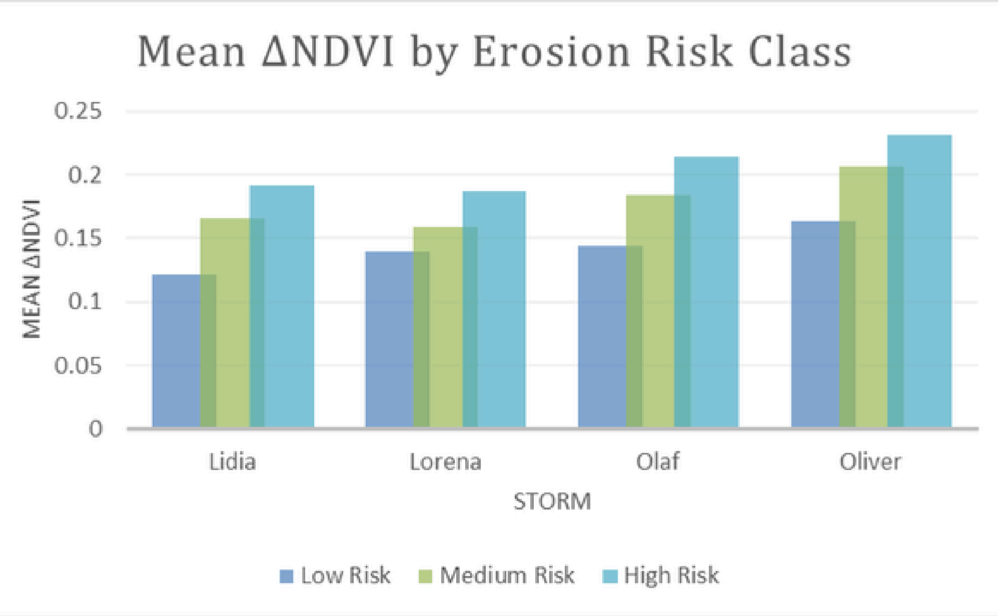
This type of analysis has practical value far beyond ecological curiosity. Land managers can use ΔNDVI to identify which landscapes are most responsive to rainfall and which remain degraded even after major storms, which is critical for public safety, restoration, erosion control, and watershed management. Urban planners and emergency management agencies can use the same insight to understand where post-storm vegetation may temporarily stabilize *or* destabilize soils. For conservation groups, ΔNDVI maps help reveal which habitats depend on rainfall pulses, supporting better strategies for monitoring long-term ecosystem health under climate change.

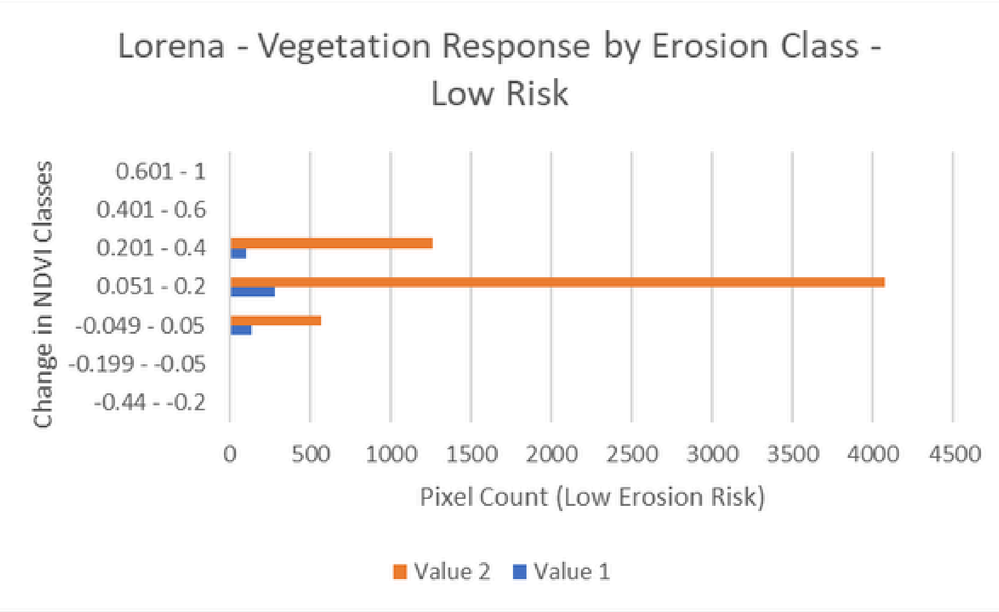
ΔNDVI Erosion Considerations
Proof of Concept

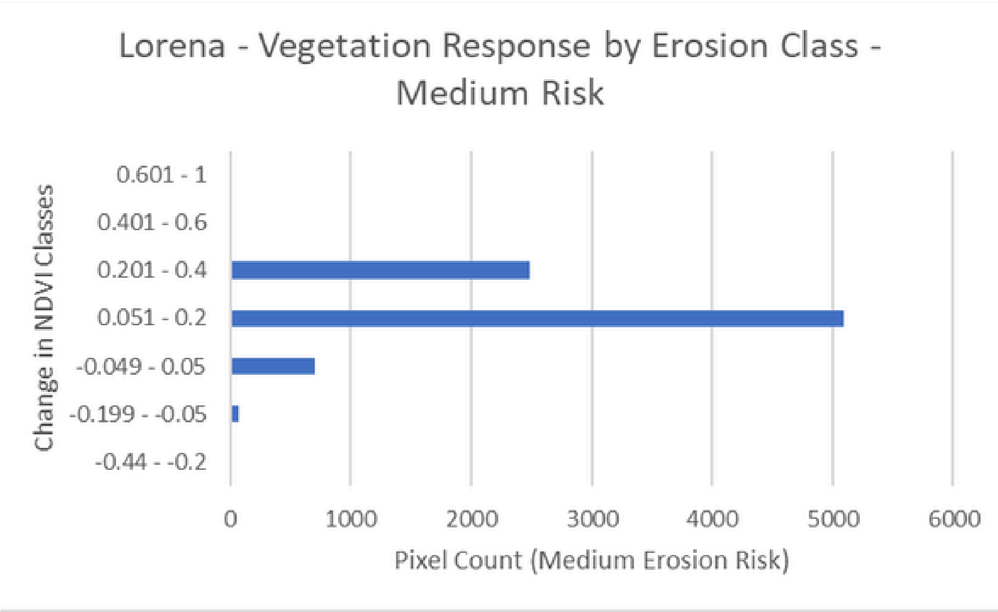
Goals for Studies in Erosion

To go beyond simple "before-after" greening, this project examined how the landscape itself shapes vegetation response. Using the Global Forest Watch erosion risk dataset, we evaluated whether areas prone to soil instability respond differently to major storm events. First, the erosion risk raster was downloaded and clipped to the Baja California Sur study area. Its original categories (0–5) were cleaned and reclassified into three intuitive classes: low, Medium, and High risk, to simplify comparison across storms. Each class represents distinct terrain and hydrological behavior; Low risk: stable uplands and flat desert plains; Medium risk: gentle slopes and transition zones; High risk: steep drainages, foothills, and erosion-prone fan surfaces.









Zonal Stats

To better understand these classes, I ran Zonal Statistics as Table for each storm's ΔNDVI raster. For every erosion class, ArcGIS calculated pixel count, minimum, maximum, range, mean ΔNDVI, standard deviation, median, and 90th percentile. These tables were exported to Excel and combined into a consolidated dataset, enabling multi-storm comparison. From that cleaned dataset, we developed summary bar charts showing:

1. Storm-specific ΔNDVI distribution across NDVI change bins
2. **Mean ΔNDVI by erosion class for all storms, which is the clearest cross-event indicator calculated**

Interpretation of Visuals

Erosion risk map:

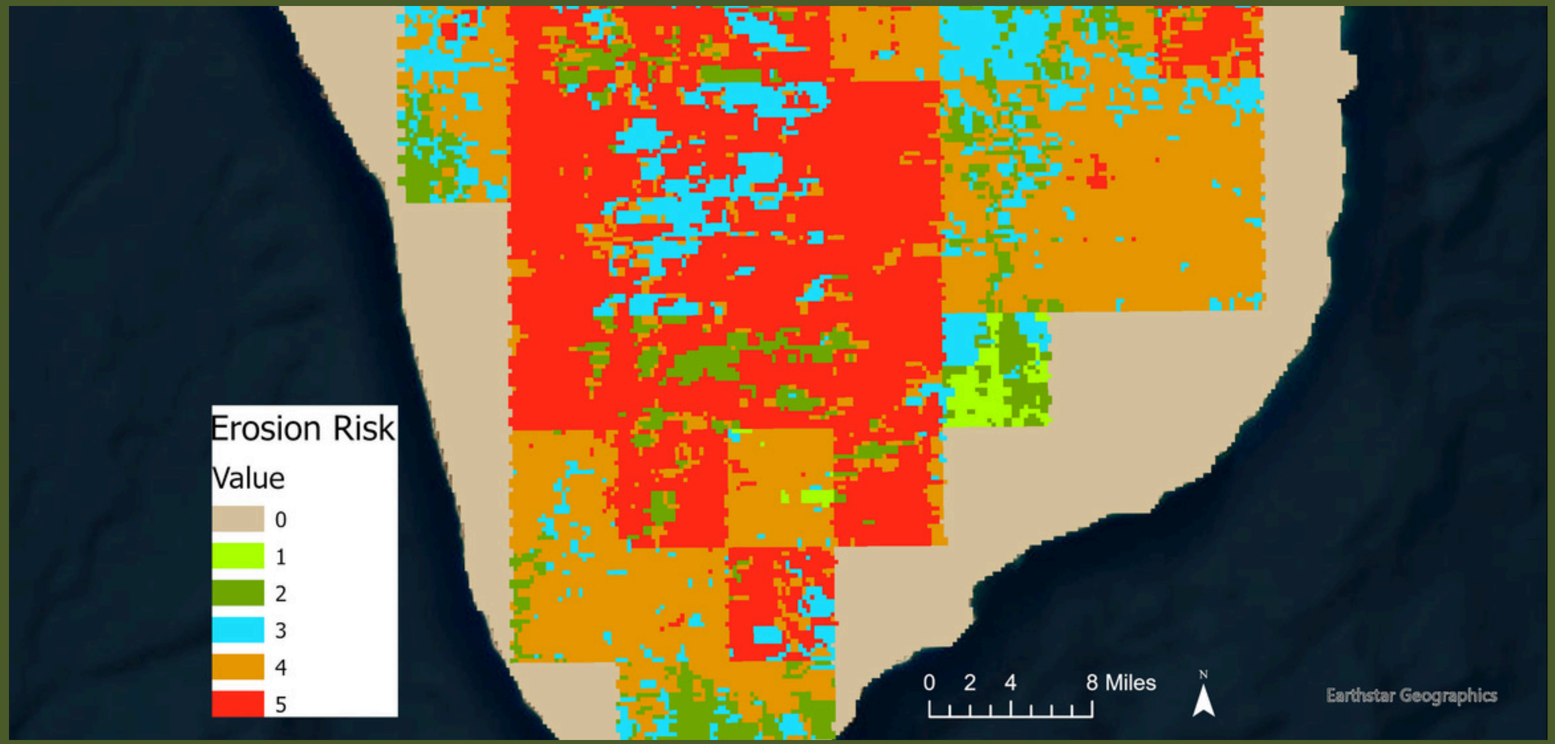
- Shows the spatial distribution of low, medium, and high-risk areas across the region. High-risk zones cluster along slopes, canyons, and alluvial fans (the very areas where rainfall concentrates during tropical storms).

Lorena's vegetation response by erosion class:

- These charts reveal that higher-risk areas contain a larger count of pixels in the strong-greening bins (0.05–0.4), demonstrating that Lorena's rainfall disproportionately activated vegetation in erosion-prone terrain.

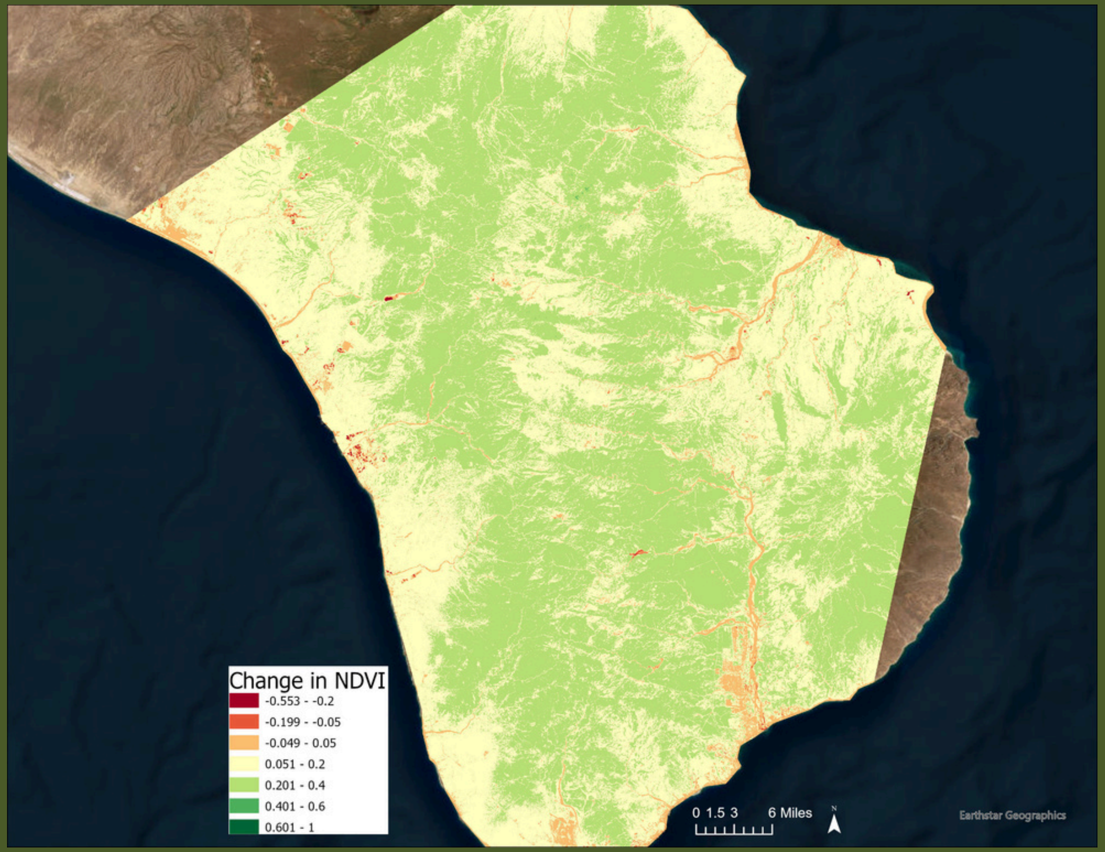
Mean ΔNDVI by erosion class (all storms):

- Across all four storm events, High-risk to erosion areas consistently show the strongest mean greening, followed by Medium, then Low. This was a remarkable discovery, suggesting that tropical rainfall pulses most strongly benefit landscapes with higher infiltration potential, complex topography, and better moisture retention.

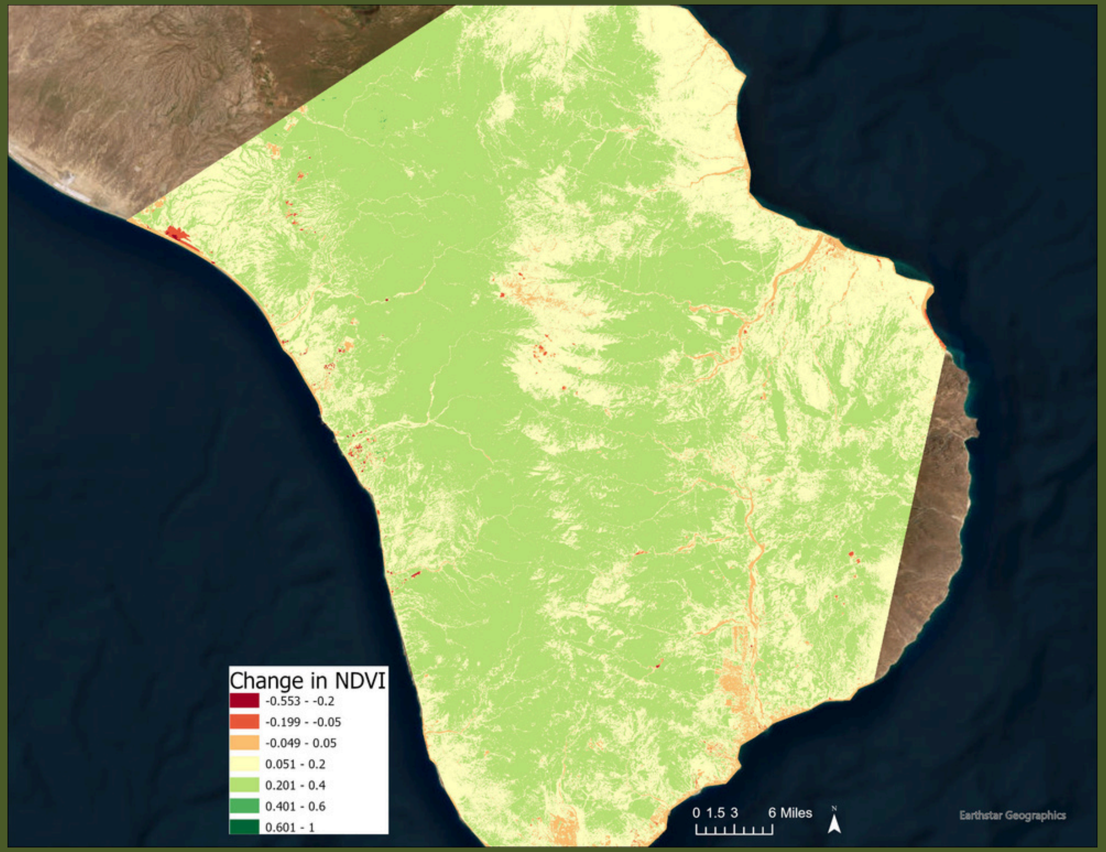


Comparing Vegetation Response and Weather

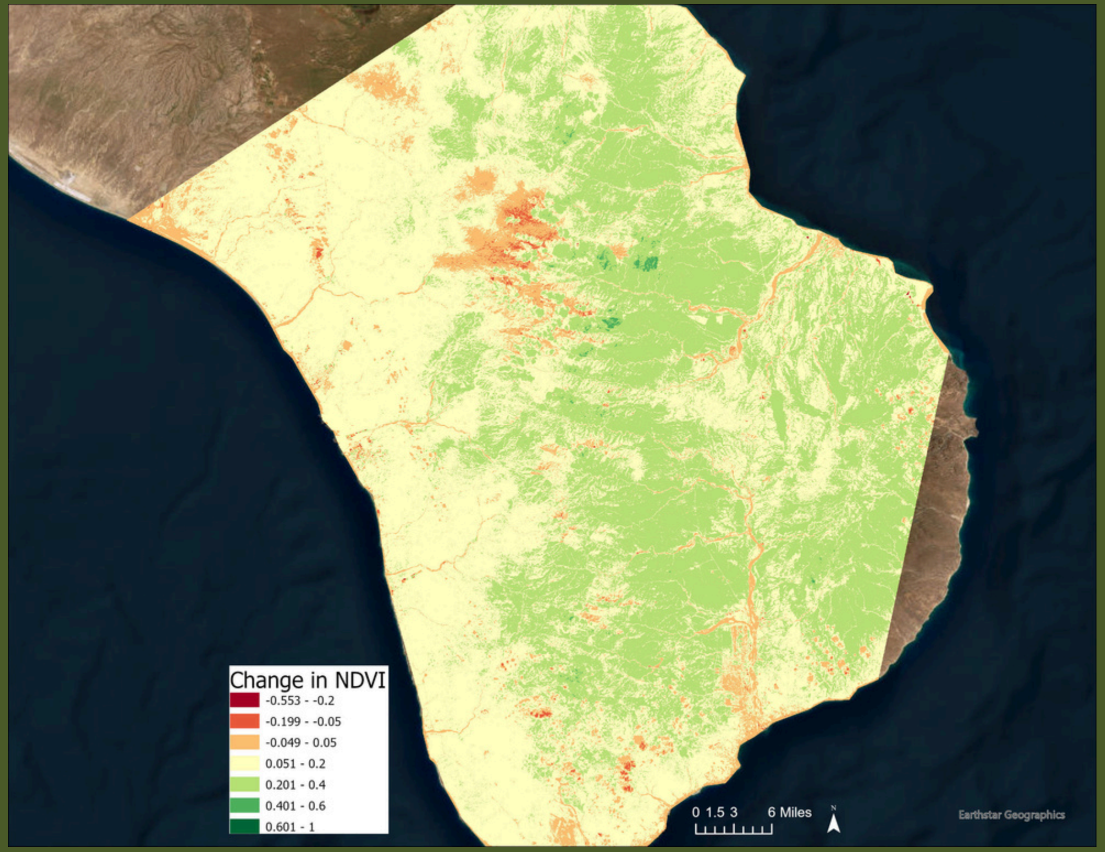
Proof of Concept



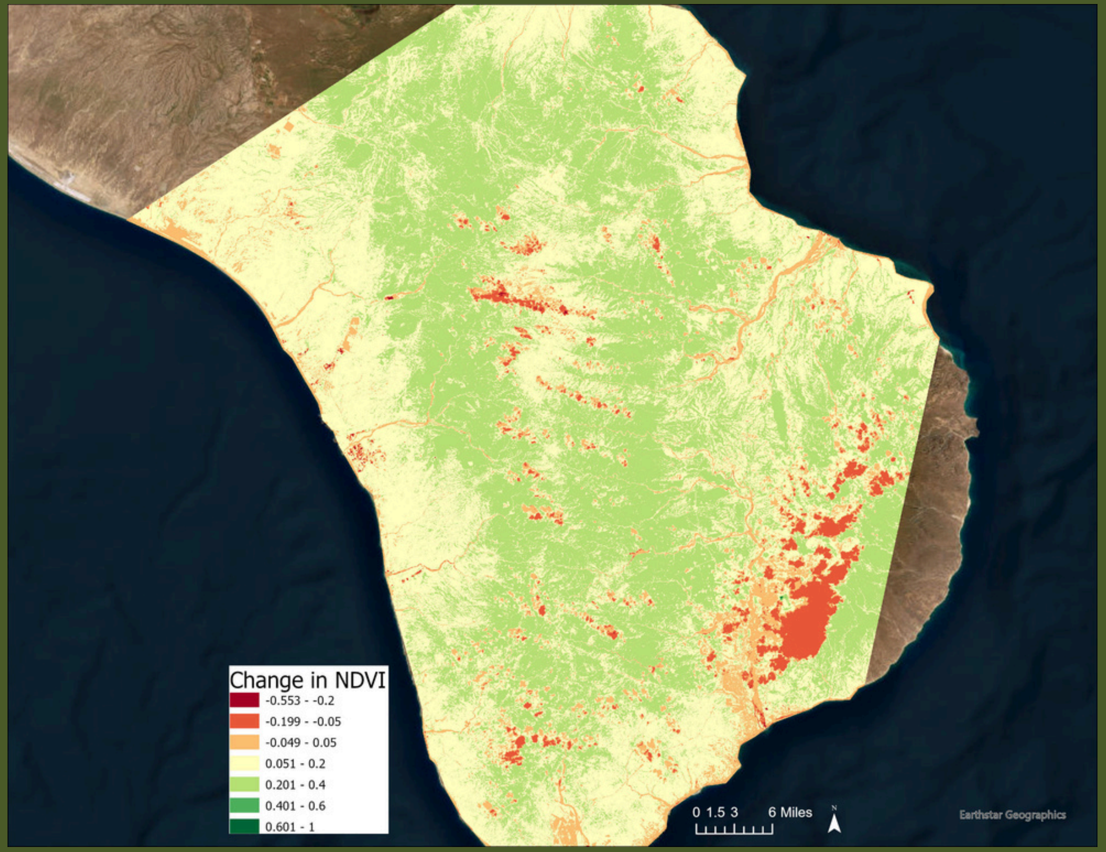
ΔNDVI Hurricane Olaf



ΔNDVI Hurricane Oliver



ΔNDVI Hurricane Lorena



ΔNDVI Hurricane Lidia

Meteorological Considerations

Viewing the four ΔNDVI maps together reveals how differences in rainfall totals and storm trajectories shape ecological outcomes across Southern BCS. While all of the storms triggered greening, the intensity and spatial footprint of that greening reflects both meteorology and landscape structure.

For example, Hurricane Lidia (2017) brought **150-200 mm** of rain to the Cabo-Santiago region, an event that is among the wettest in the dataset. Nevertheless, its ΔNDVI map displays more scattered reds and subdued greens, which is a not signature of weak muted vegetation response, but of cloud contamination impacting one of the paired Landsat scenes. Cloud shadows artificially lowered NDVI in some areas, obscuring otherwise positive vegetation response. Strong positive values are still apparent across upland basins and foothill corridors, consistent with Lidia's extensive, slow-moving area of heavy rainfall.

Hurricane Lorena (2017) tracked north of Cabo before skirting the eastern peninsula, bringing **80-120 mm** of rainfall to the study area. The ΔNDVI footprint for Lorena is moderate in magnitude but far-reaching, with particularly strong greening on east-facing slopes oriented to the highest rainfall intensity. The Lorena greening signature reinforces the notion that storms even with more peripheral landfall positions may produce substantial ecological effects when moisture intersects topography.

Hurricane Olaf (2021) delivered 100-150 mm of rainfall during a direct landfall near San José del Cabo, producing a clear and coherent greening signature across foothills and alluvial fans. Its ΔNDVI pattern shows how efficiently the landscape responds when a high-rainfall event strikes areas with strong infiltration potential. Olaf behaves exactly as expected for a direct-hit hurricane: substantial rainfall, widespread positive ΔNDVI, and a greening footprint that aligns closely with the storm's track and rainfall distribution.

Unanswered Questions

The 2025 Lorena/Oliver hurricane, however, is far more surprising. Despite bringing only 40-70 mm of rainfall, the lowest total among the storms in this study, Oliver produced the strongest and most extensive ΔNDVI pulse in the entire series. This raises an important question that our analysis cannot yet fully resolve: Why did a storm with comparatively modest rainfall generate the greatest vegetation response? The result may reflect antecedent moisture, soil infiltration, or subtle differences in how rainfall was distributed across topography. Regardless of the cause, Oliver highlights that in hyper-arid ecosystems, storm intensity is not always synonymous with post-storm bloom.