Florida Keys Coral Reef Health Assessment: An Analysis of CREMP Data (1996-2023)

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1. Introduction: Understanding Our Underwater Cities

Coral reefs, like the vibrant ones in the Florida Keys National Marine Sanctuary, are essential underwater ecosystems, bustling with life and crucial for coastal protection and economies. To gauge their health, we analyzed nearly three decades (1996-2023) of detailed monitoring data from the Coral Reef Evaluation and Monitoring Project (CREMP). This report aims to clearly present the key trends in coral health – how much coral covers the seafloor, the variety of species, the condition of individual corals – and explore influencing factors like location and water temperature. Our goal is to make these complex findings accessible to a broad audience, including decision-makers and stakeholders without a background in data analysis, to foster a shared understanding of the state of these vital natural resources.

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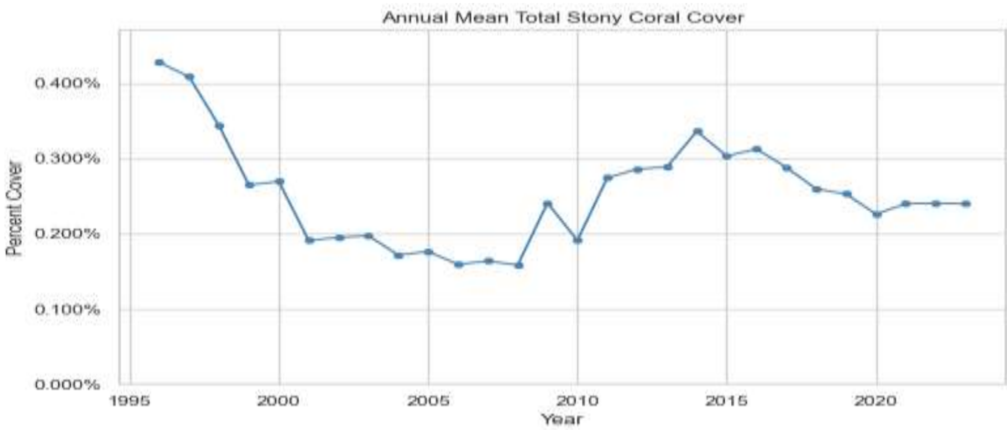
2. Key Findings & Data Visualizations

This section highlights the main discoveries from our analysis, directly addressing the evaluation criteria for the datathon. Each point is supported by data visualizations.

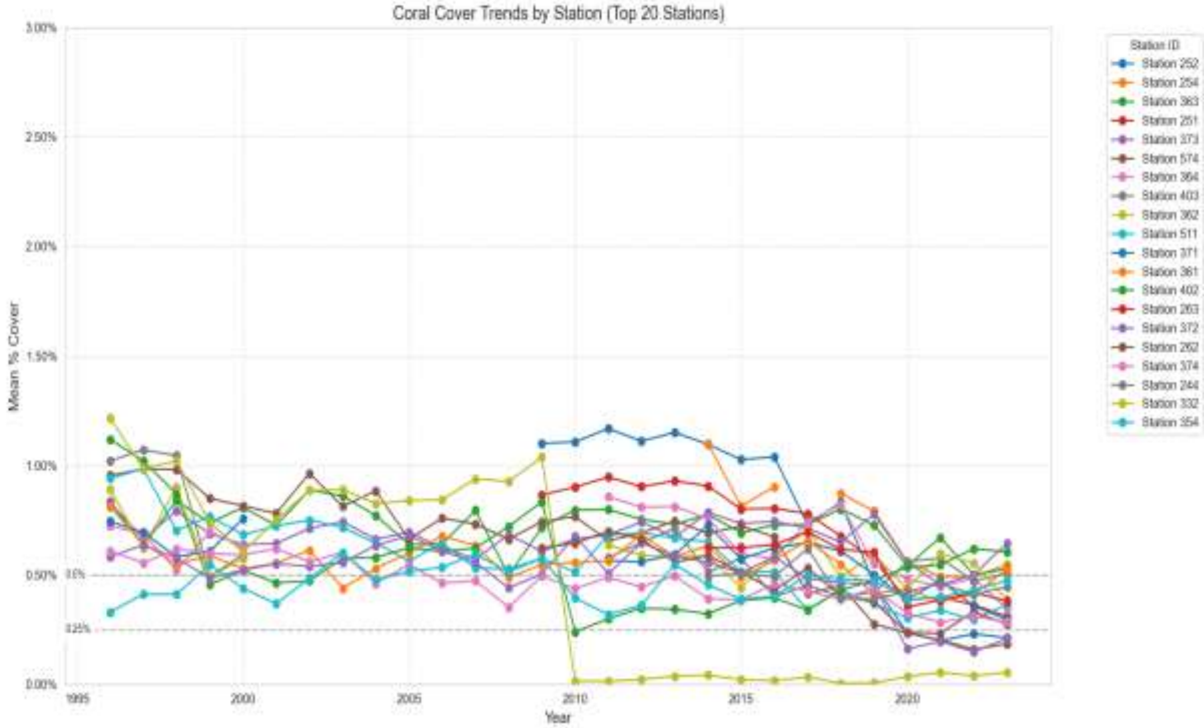
2.1 Stony Coral Cover Trends: A Significant Decline

- **Overall Decline:** Since 1996, there has been a marked decrease in the average percentage of the seafloor covered by stony corals across the sanctuary. This is evident in the overall annual mean trend.
- **Visualization 1:**



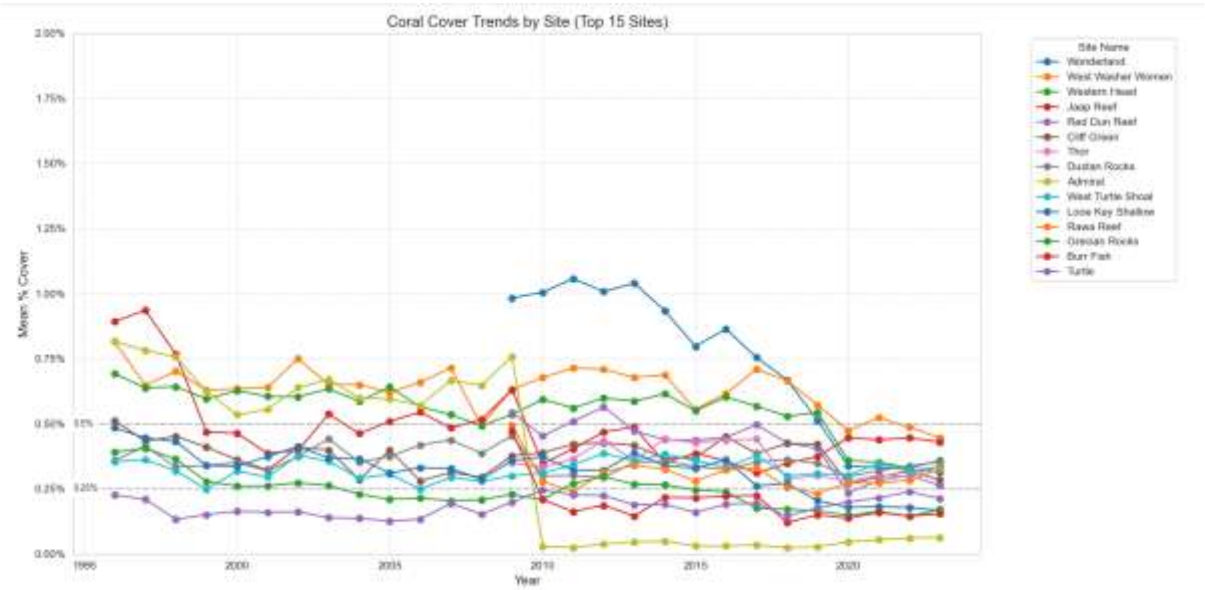
Caption: This line graph shows the average stony coral cover each year. A sharp decline occurred in the late 1990s, followed by fluctuations at lower levels, indicating a persistent reduction from historical coverage.

- **Station-Level Variability:** While the overall trend is down, the rate and pattern of decline vary significantly between individual monitoring stations and sites.
- **Visualization 2:**



  - *Caption:* This plot tracks average coral cover over time for a selection of stations with historically higher cover. It highlights the diverse trajectories at the local level.

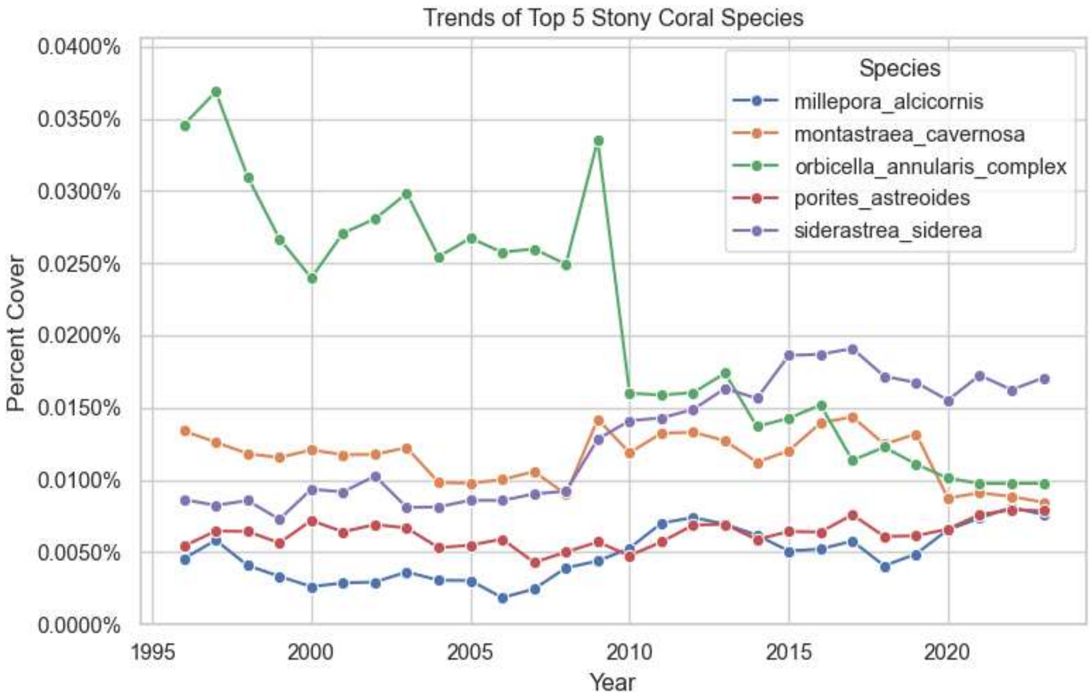
- **Visualization 3:**



- *Caption:* Similar to the station plot, this shows trends for broader monitoring sites, again emphasizing local differences in coral cover changes.

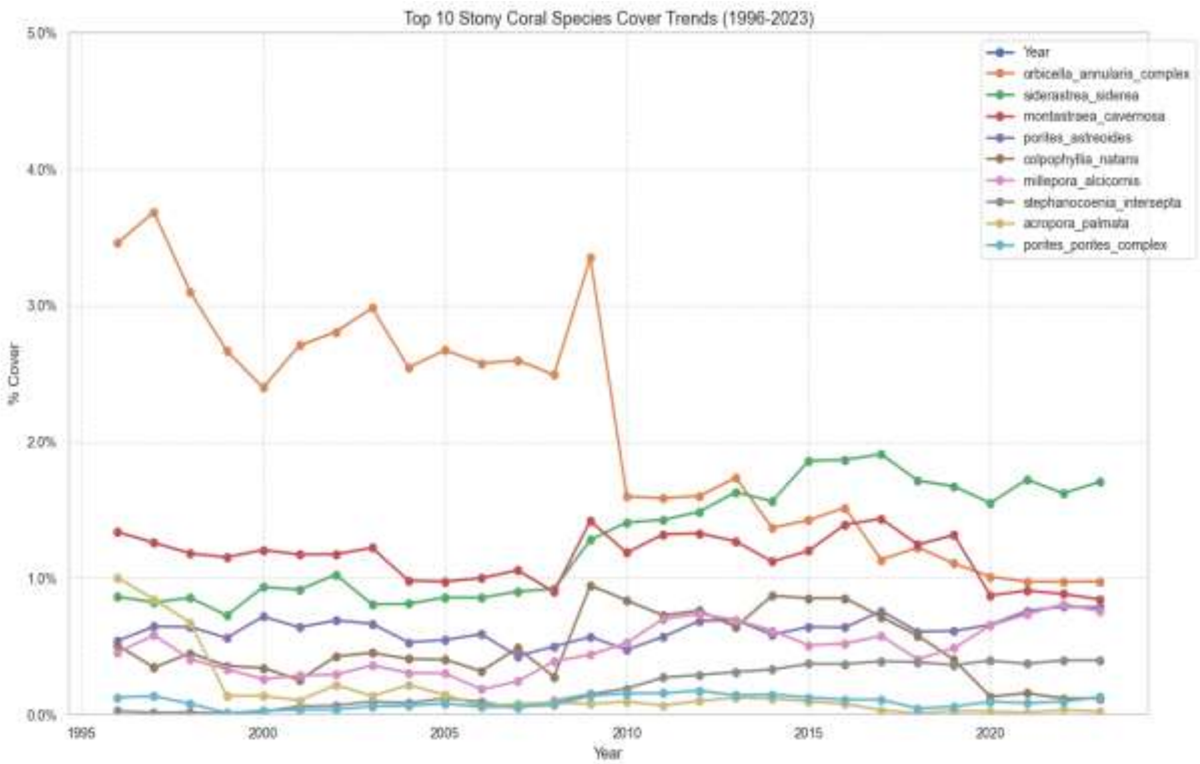
- **Species-Specific Trends:** Different stony coral species exhibit different long-term patterns, with some historically dominant species showing steeper declines than others.

  - **Visualization 4:**



Caption: This tracks the five most abundant stony coral species, showing varying decline rates and trajectories over time.

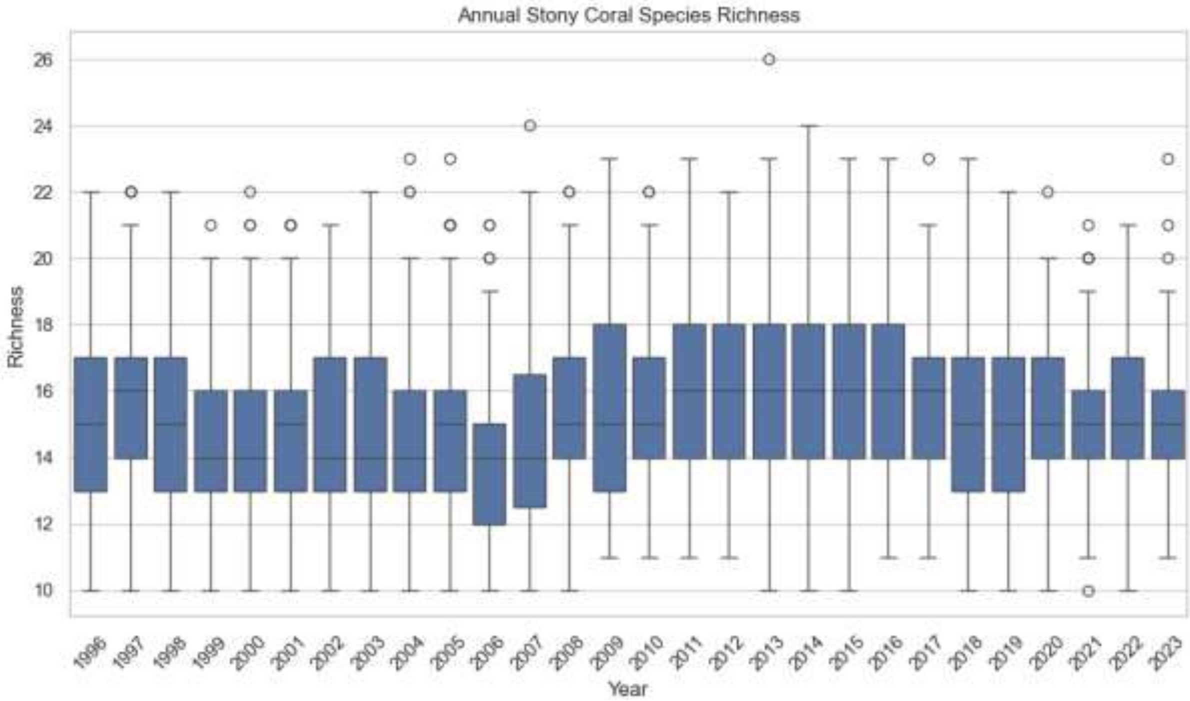
- **Visualization 5:**



- *Caption:* Expanding to the top 10 species provides a broader view of species-specific changes in abundance.

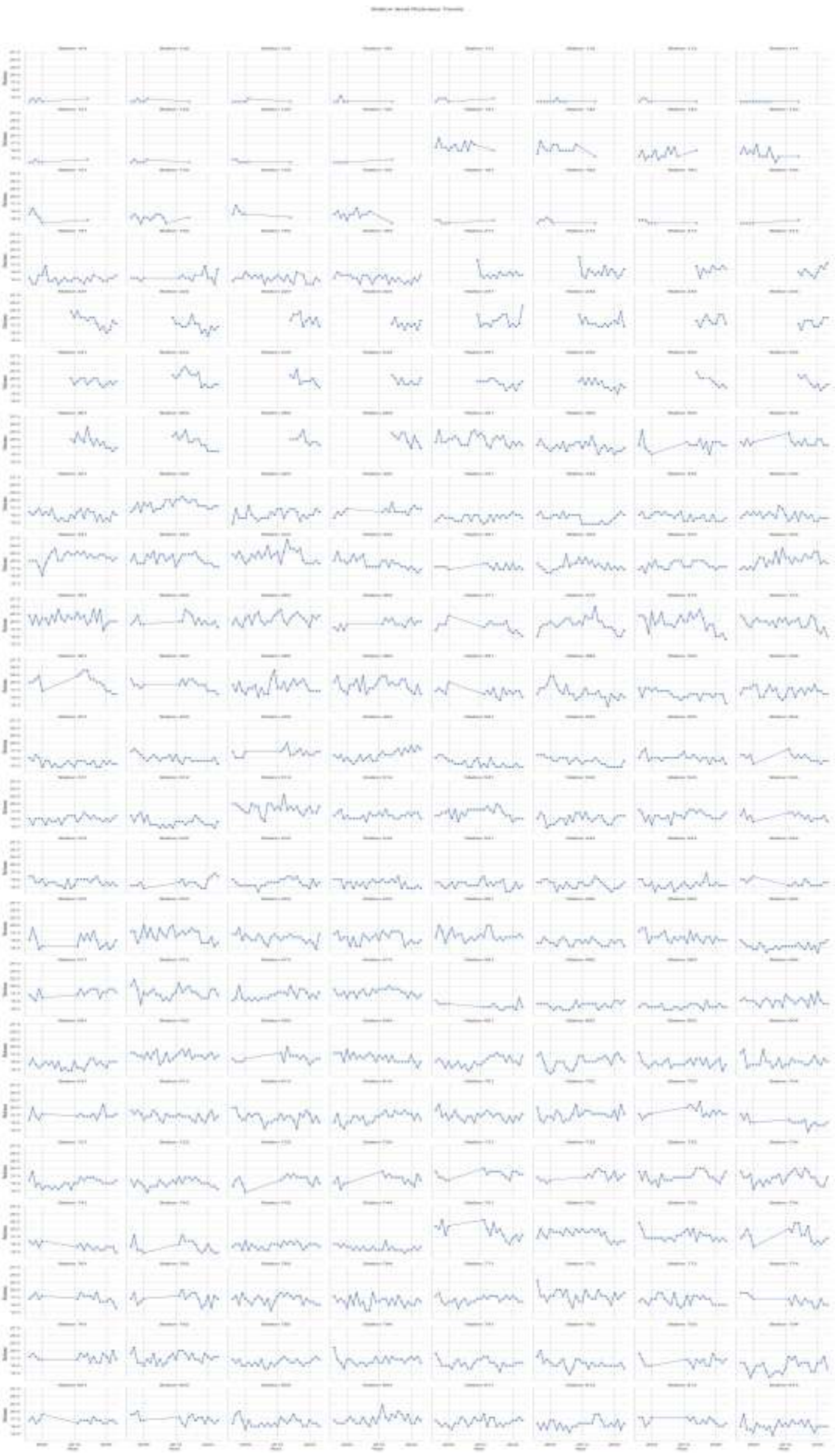
2.2 Species Richness Trends: Fluctuations Amidst Pressure

- **Sanctuary-Wide Fluctuation:** The average number of different stony coral species (richness) per station has fluctuated annually across the sanctuary, without a consistent long-term increase or decrease evident in the overall average.
- **Visualization 6:**



  - *Caption:* This boxplot shows the distribution of species counts across stations each year. While the median fluctuates, the overall range hasn't shown a drastic unidirectional shift, but variability within years is notable.
  - **Station-Level Variation:** Individual stations show diverse trends in richness over time, with some increasing, some decreasing, and others remaining relatively stable.

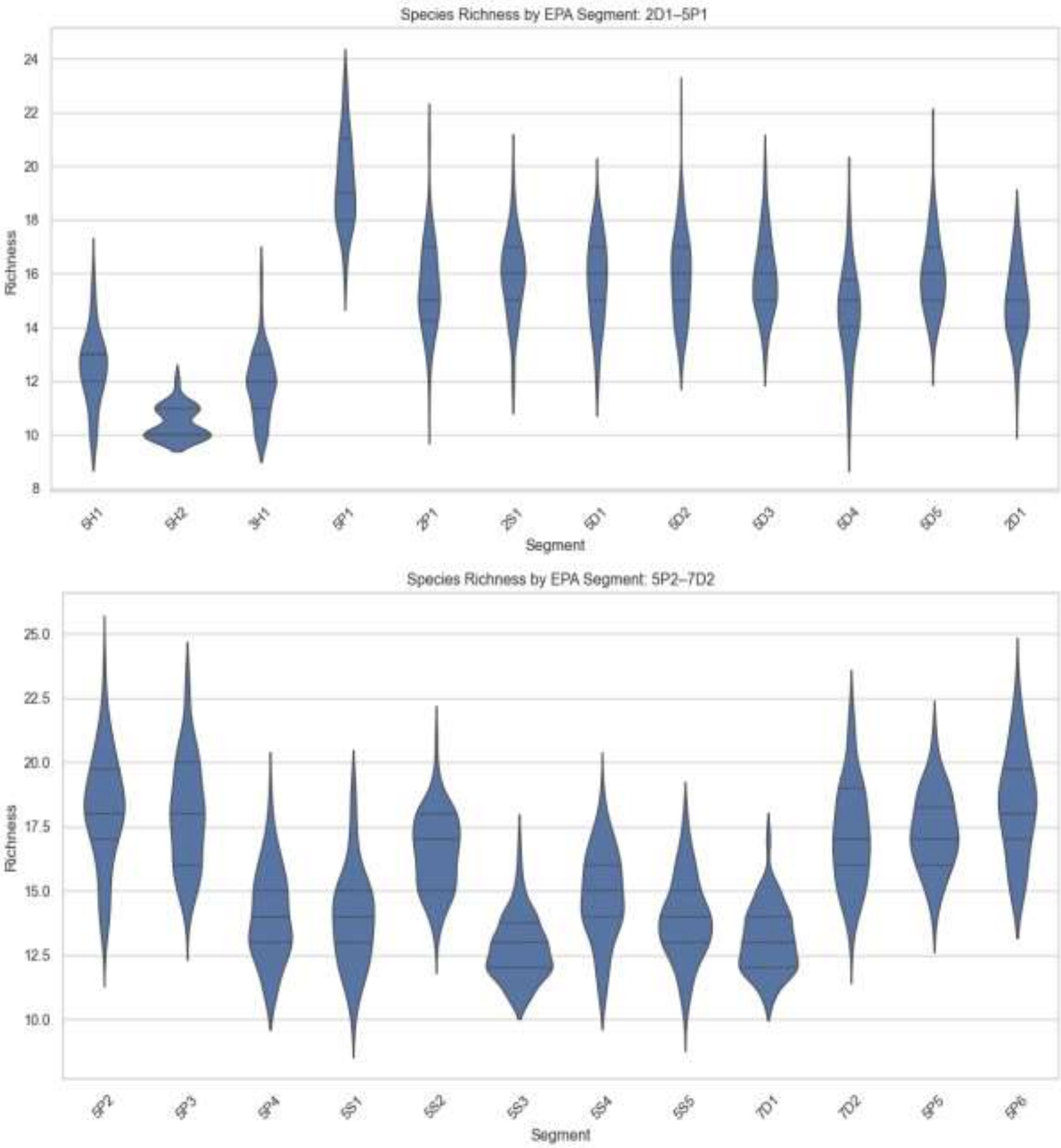
    Visualization 7:

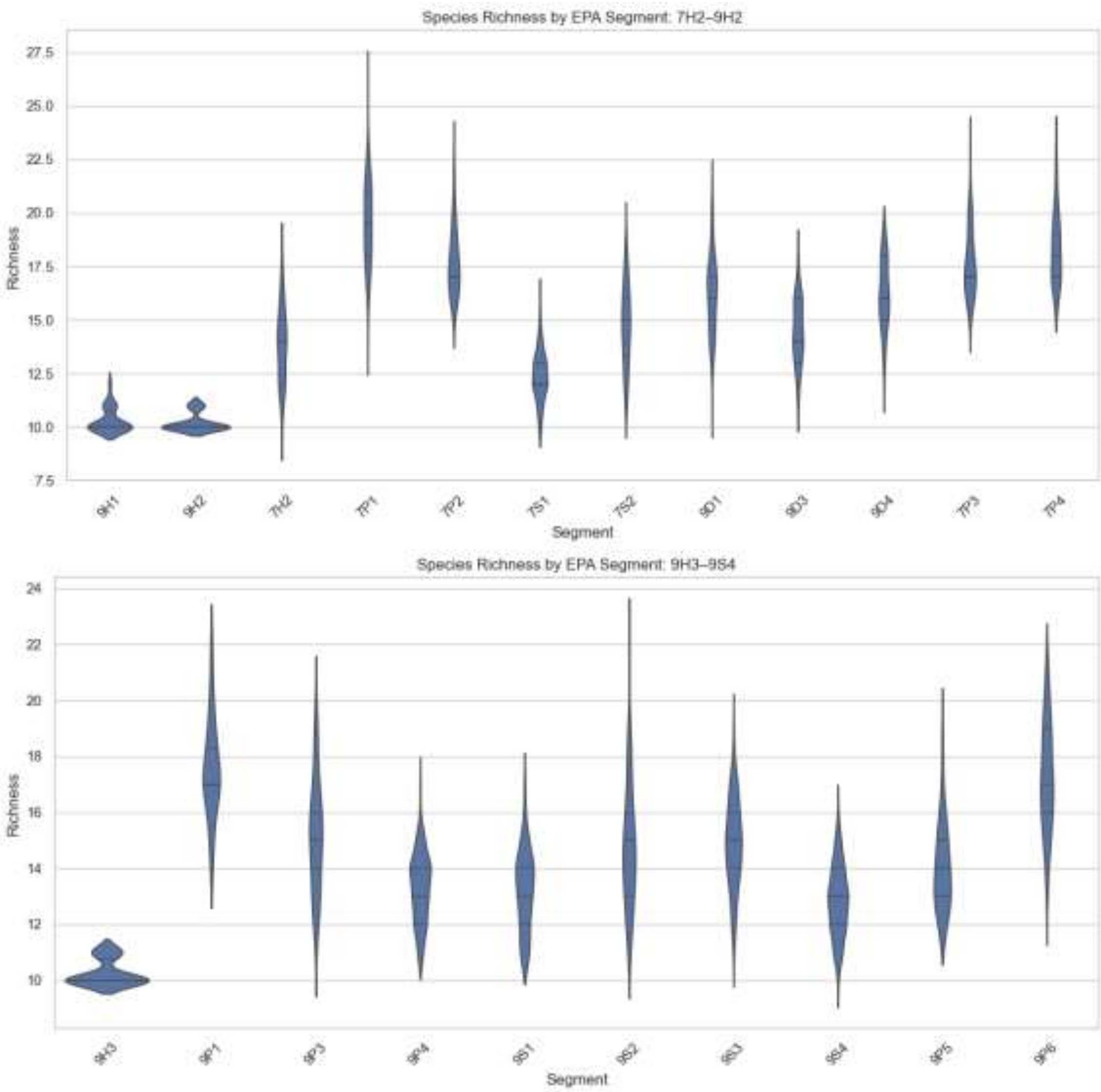


- *Caption:* These small plots display richness trends for each individual station, illustrating the high degree of local variation.

- **Spatial Richness Differences:** There are significant differences in average richness between geographic locations (EPA segments and stations).

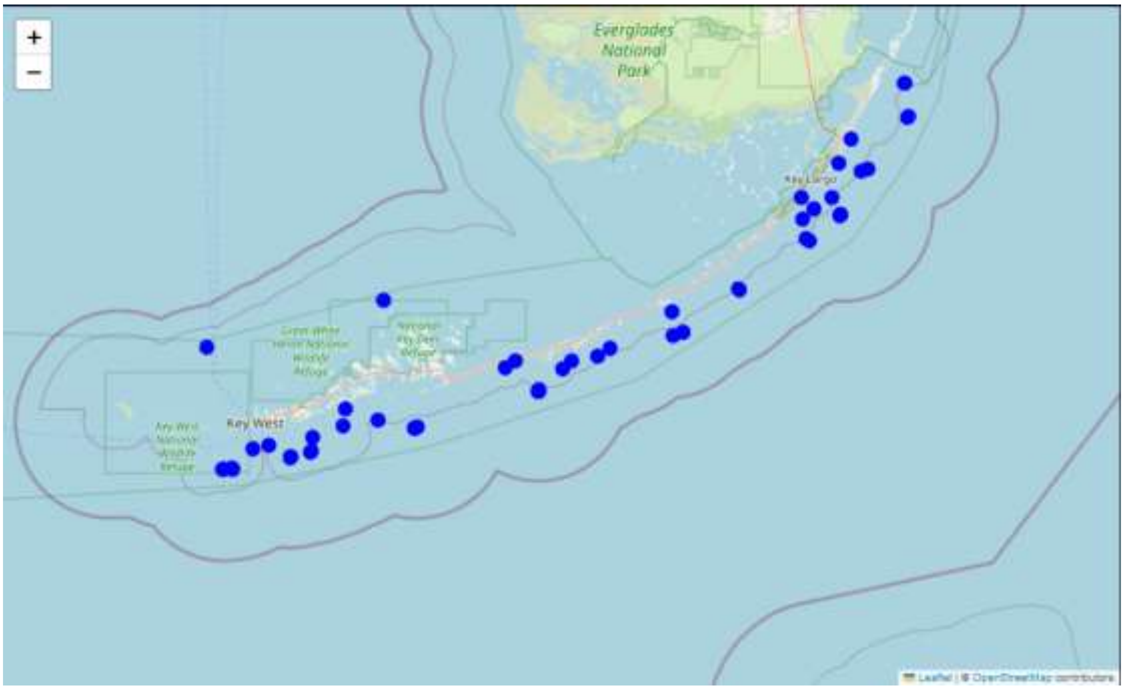
- **Visualization 8:**





- *Caption:* These violin plots (split for readability) show the distribution of richness values within different EPA segments, highlighting segments that typically support higher or lower diversity.

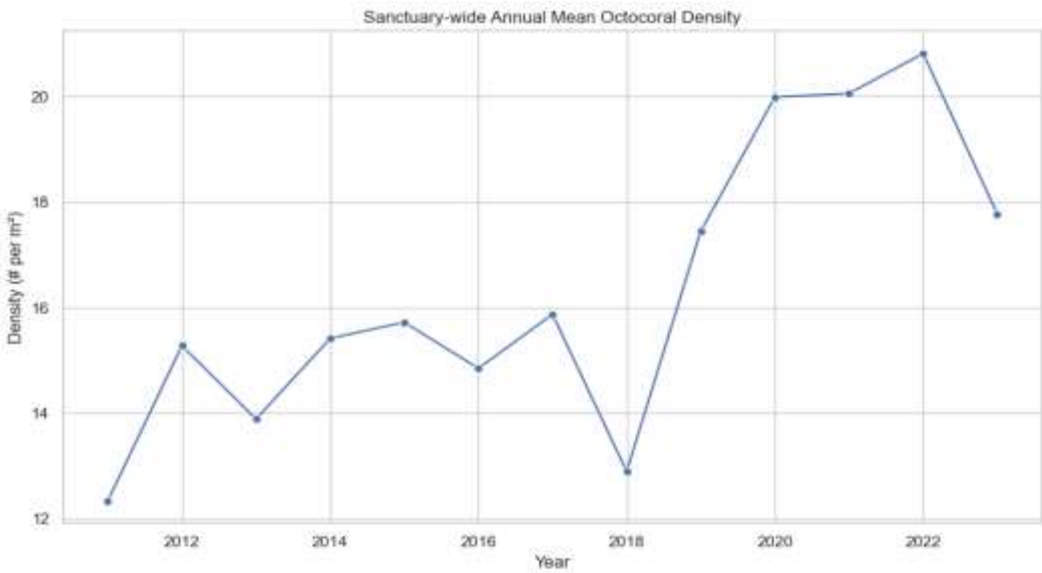
- **Visualization 9:**



  - *Caption:* This map visually displays the average species richness at each station, allowing for identification of geographic patterns in diversity. (Circle markers represent stations, popups show average richness).

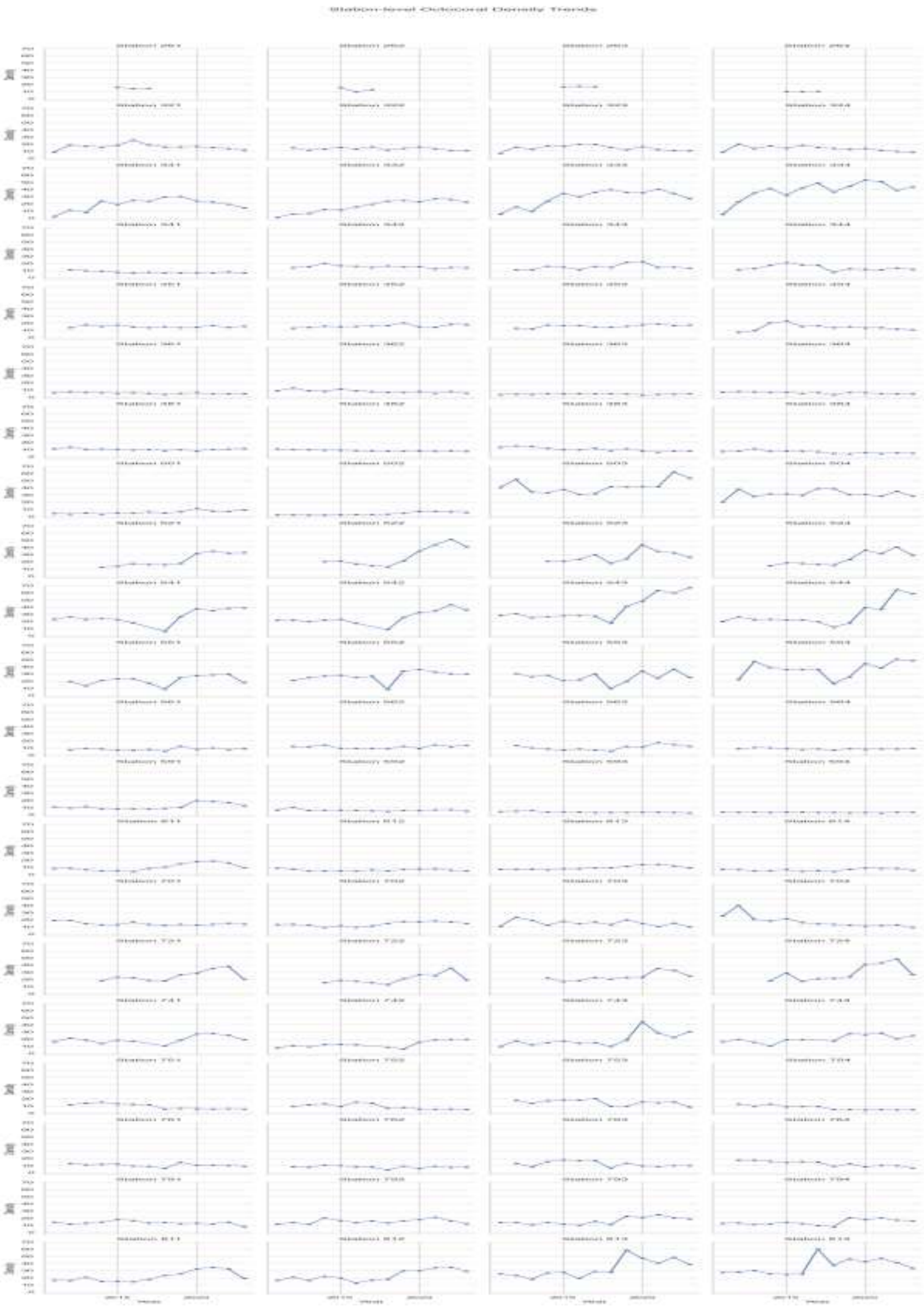
2.3 Octocoral Density Dynamics: A Contrasting Trend?

- **Overall Increase:** In contrast to stony corals, the average density of octocorals (soft corals) showed a general increasing trend sanctuary-wide between 2011 and 2022, though with high variability and a recent dip.
  - **Visualization 10:**



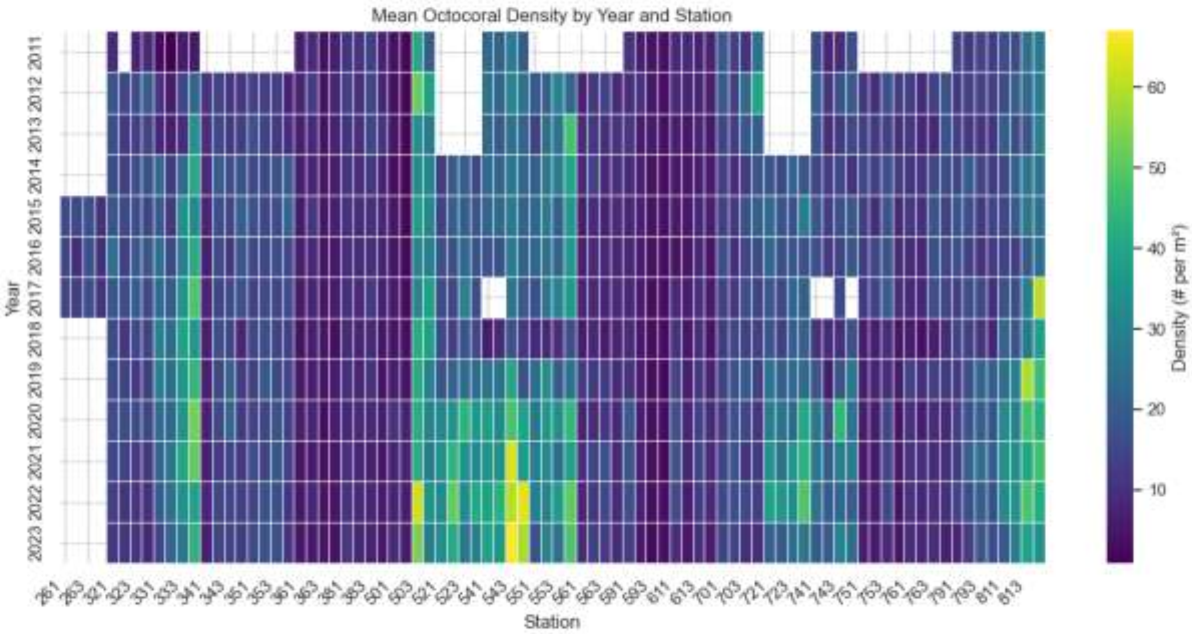
Caption: This line graph shows the average number of octocoral colonies per square meter across the sanctuary, indicating a general rise over the period shown.

- **High Station/Temporal Variability:** Octocoral density varies greatly from station to station and year to year.
- **Visualization 11:**



- *Caption:* These plots show the diverse trends in octocoral density at individual stations over time.

- **Visualization 12:**

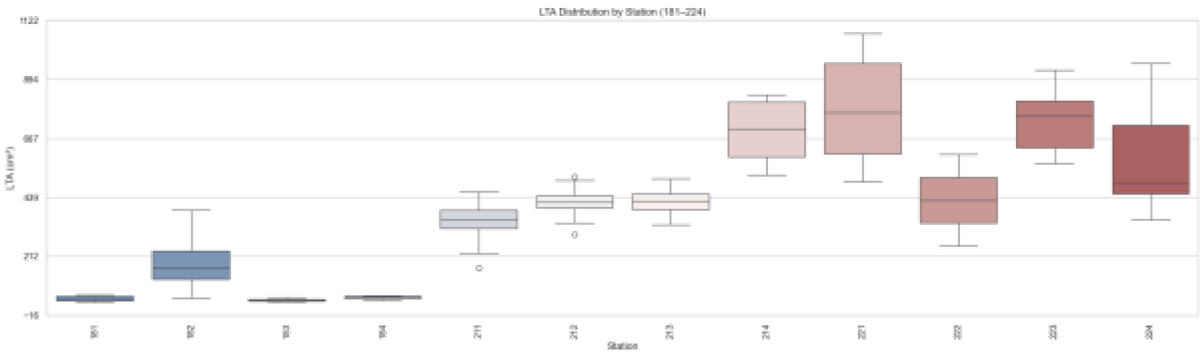


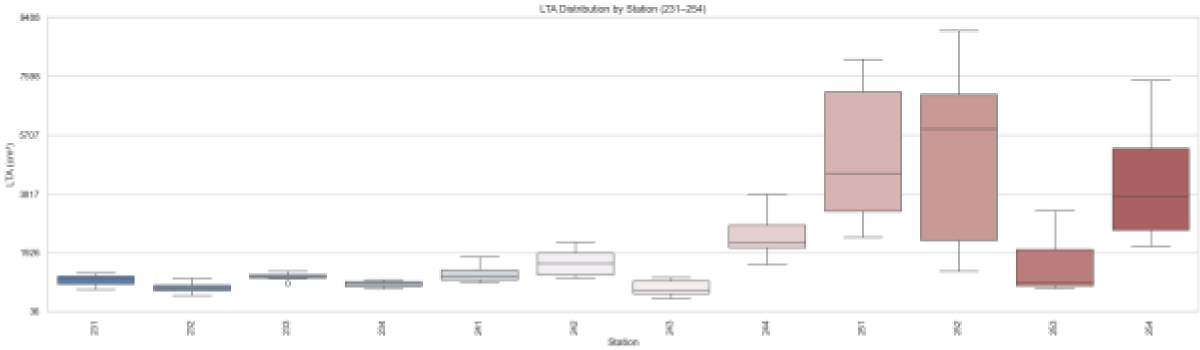
- *Caption:* This heatmap visually represents density across stations (columns) and years (rows). Brighter colors indicate higher density, revealing strong spatial and temporal patterns.

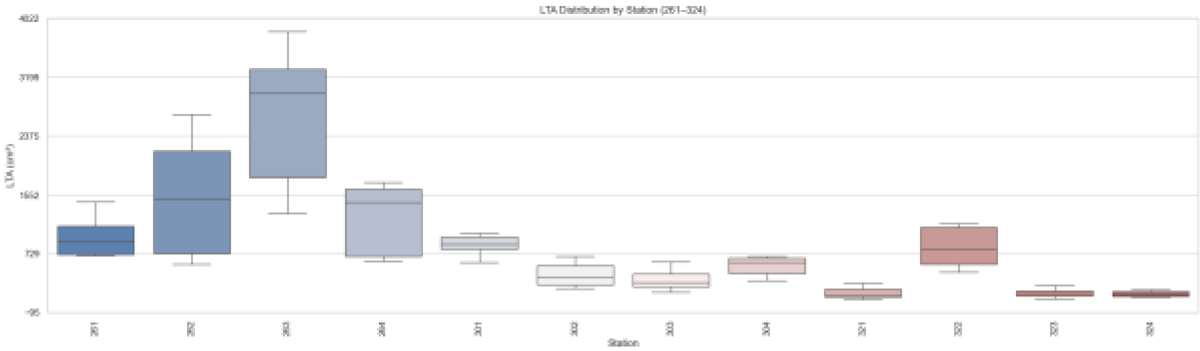
2.4 Living Tissue Area (LTA) Differences: Coral Size & Health

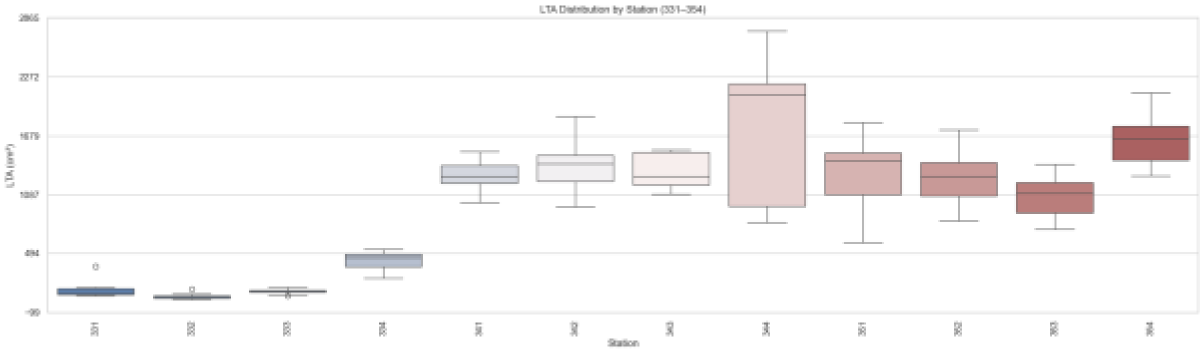
- **Significant Site Differences:** The average Living Tissue Area (LTA) of stony corals, an indicator of coral size and health, varies significantly between different monitoring stations and broader EPA segments.

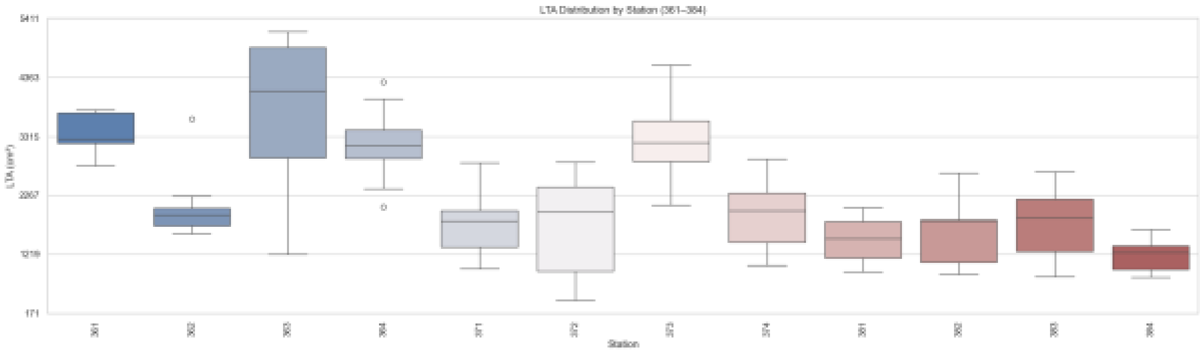
- **Visualization 13:**

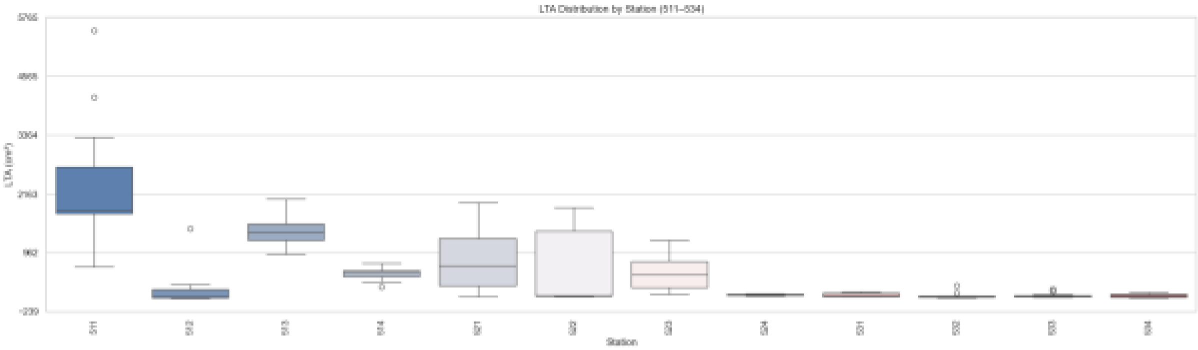


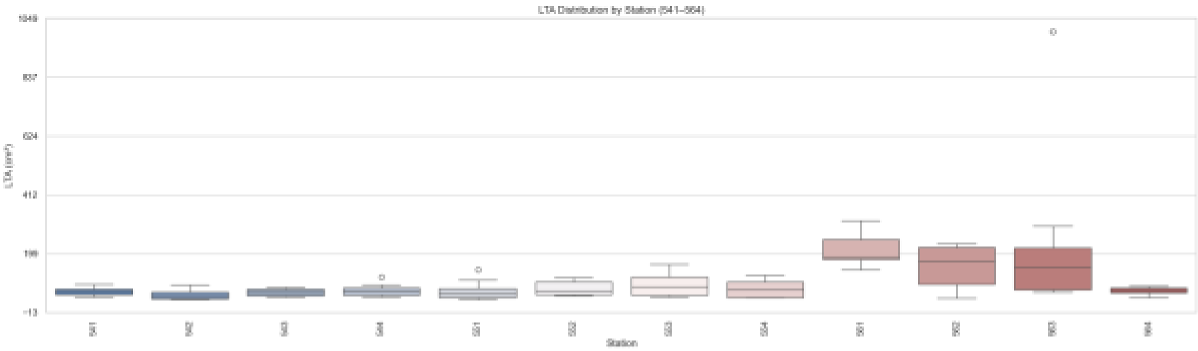

LTA Distribution by Station (231–254)
LTA (cm²)
Station

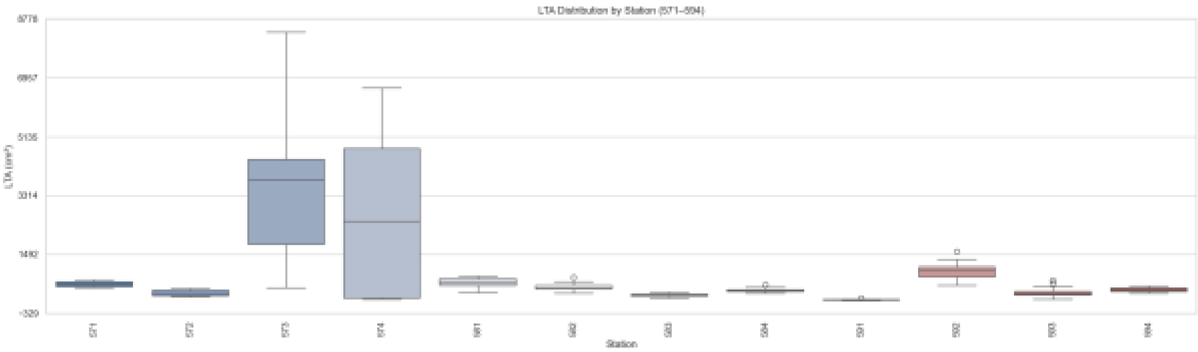

LTA Distribution by Station (261–324)
LTA (cm²)
Station

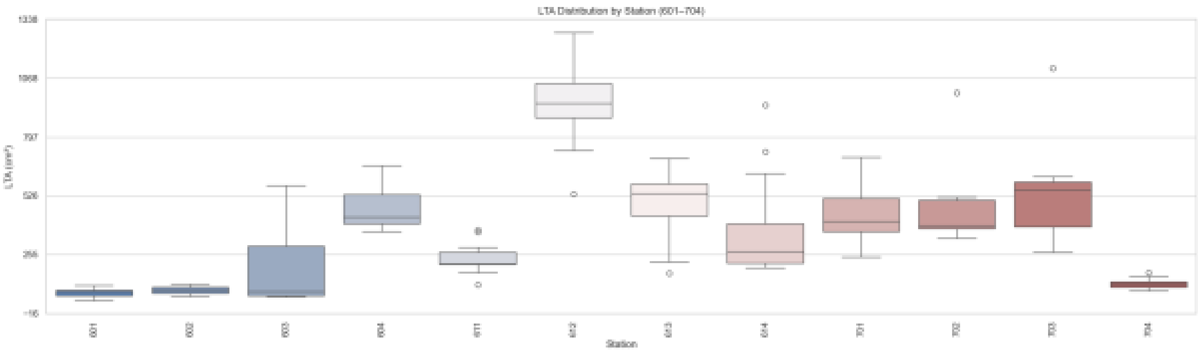

LTA Distribution by Station (331–354)
LTA (cm²)
Station

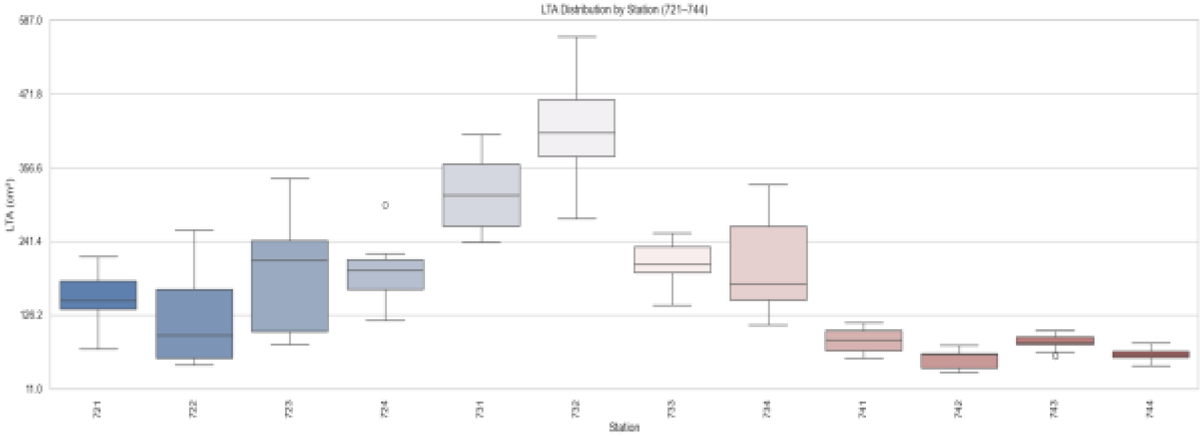

LTA Distribution by Station (361–384)
LTA (cm²)
Station

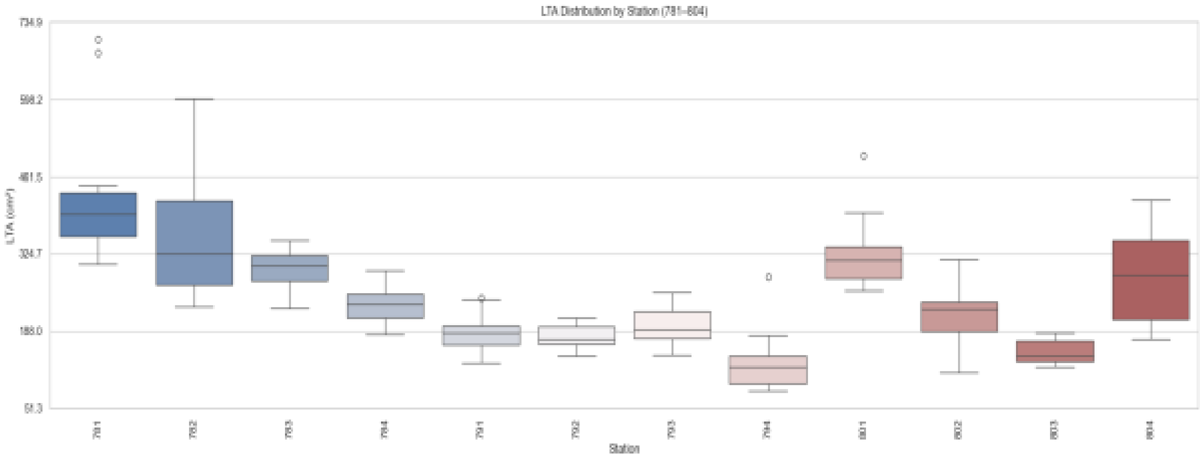

LTA Distribution by Station (511–534)
LTA (cm²)
Station

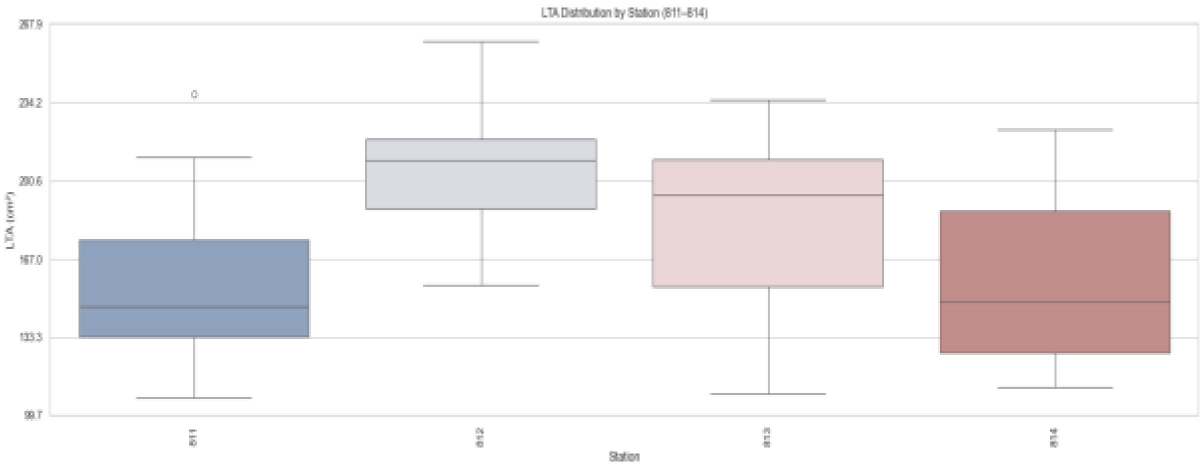

LTA Distribution by Station (541–564)
LTA (cm²)
Station


LTA Distribution by Station (571–594)
LTA (cm²)
Station


LTA Distribution by Station (601–704)
LTA (cm²)
Station

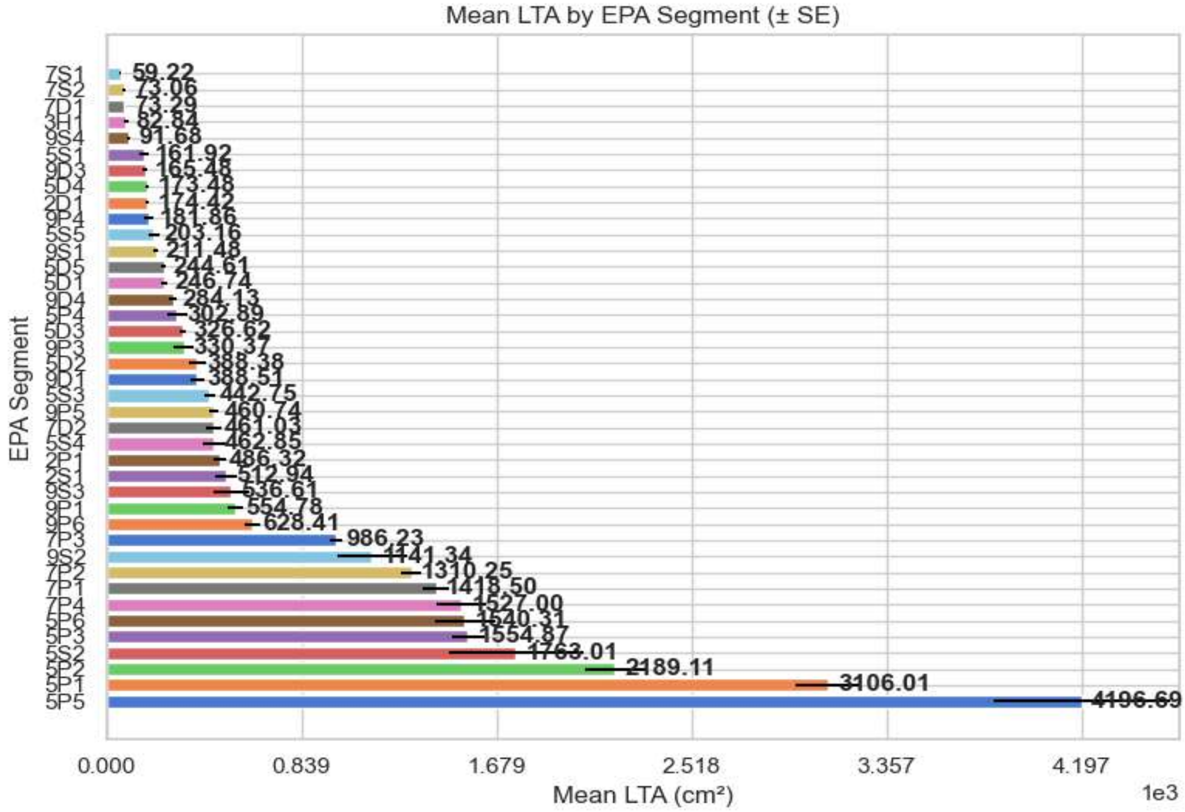






- *Caption:* These boxplots (split by station groups) compare the distribution of average LTA values across stations, showing substantial differences in typical coral size.

- **Visualization 14:**



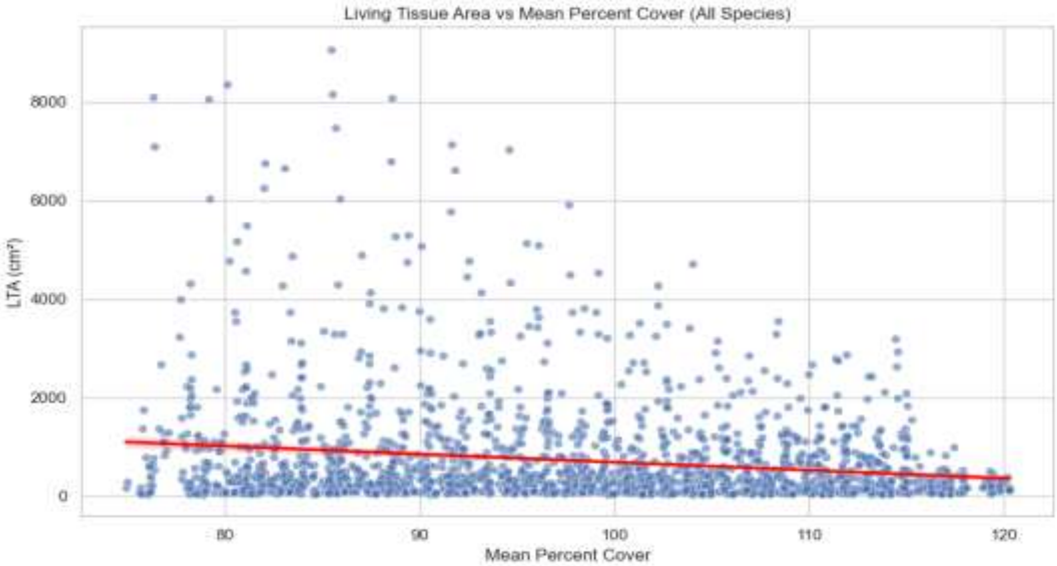
  - *Caption:* This bar chart ranks EPA segments by average LTA, highlighting segments with typically larger or smaller corals.

- **Overall LTA Decline:** Similar to cover, the average LTA across the sanctuary has shown a general decline over the period analyzed (2011-2023).

- **Visualization 15:**

- *Caption:* This line graph shows the decreasing trend in average LTA over time, suggesting corals are, on average, getting smaller or covering less area individually.

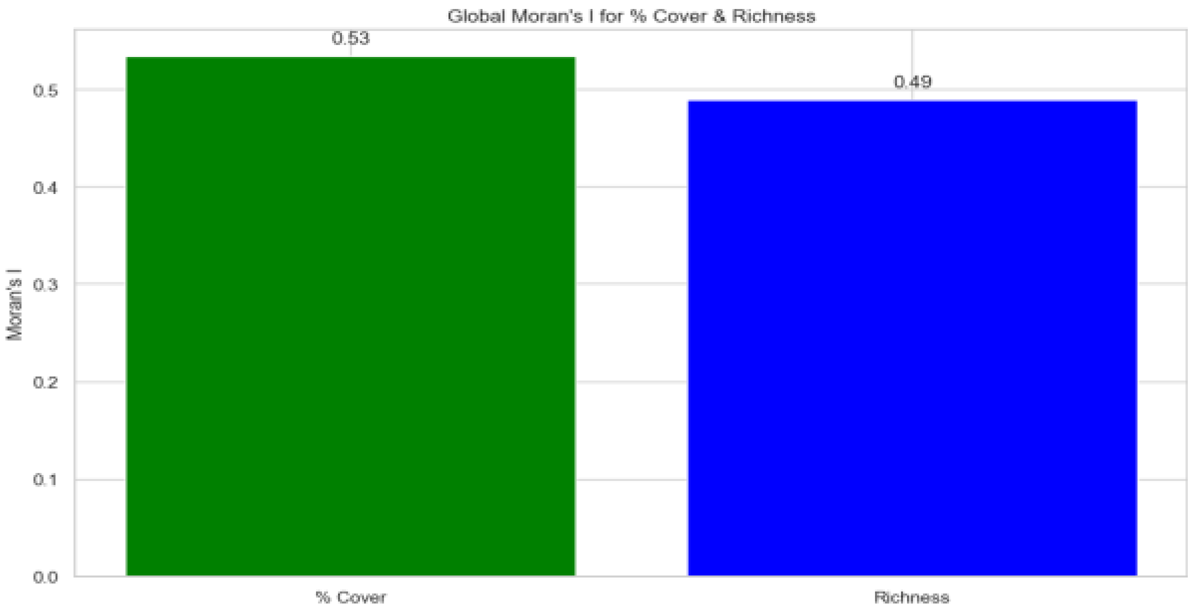
Visualization 16:



- *Caption:* This line + scatter graph shows the decreasing trend in average LTA over time, suggesting corals are, on average, getting smaller or covering less area individually.

2.5 Spatial Patterns: Geography of Reef Health

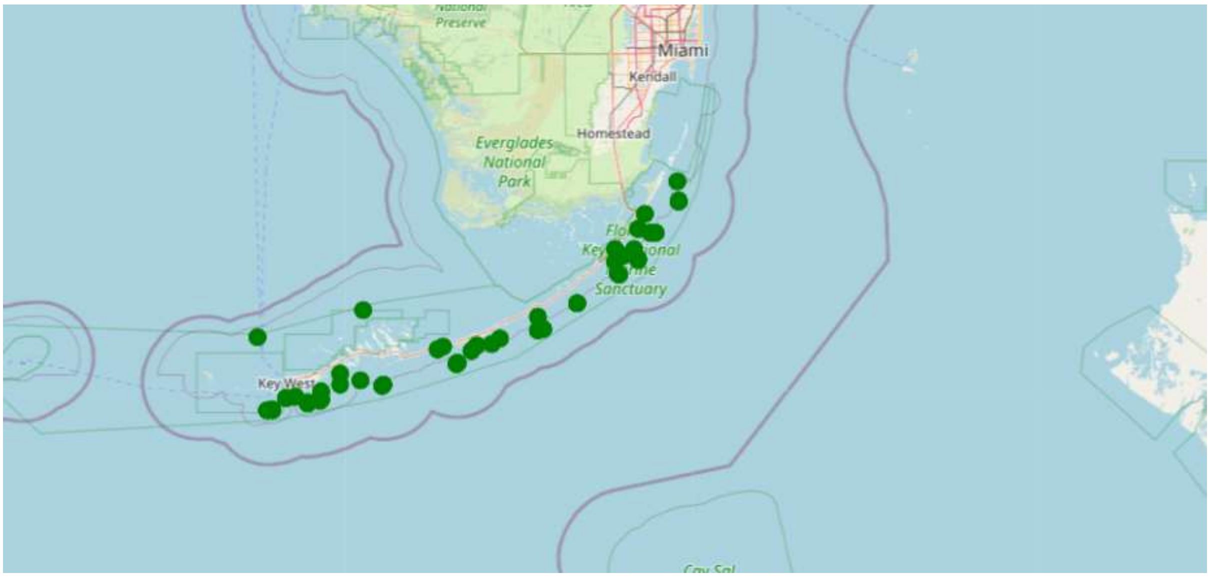
- **Clustering Confirmed:** Statistical analysis (Moran's I) confirms that both stony coral percent cover and species richness exhibit significant positive spatial autocorrelation. This means high-value areas tend to cluster together, as do low-value areas.
- **Visualization 17:**



- *Caption:* The positive Moran's I values indicate that stations with similar cover or richness levels are geographically closer than would be expected by chance.

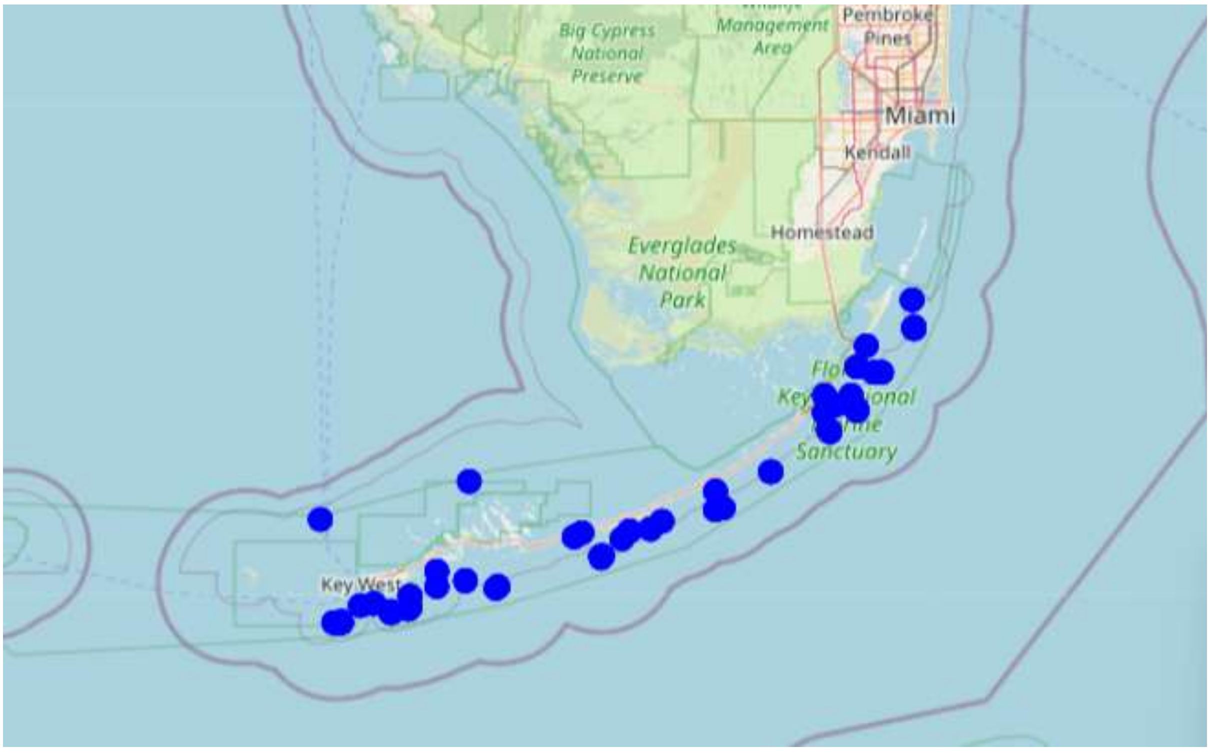
- **Mapping Cover and Richness:** Maps reveal the geographic distribution of average cover and richness across stations.

- **Visualization 18:**



- *Caption:* Map showing average stony coral percent cover at each station.

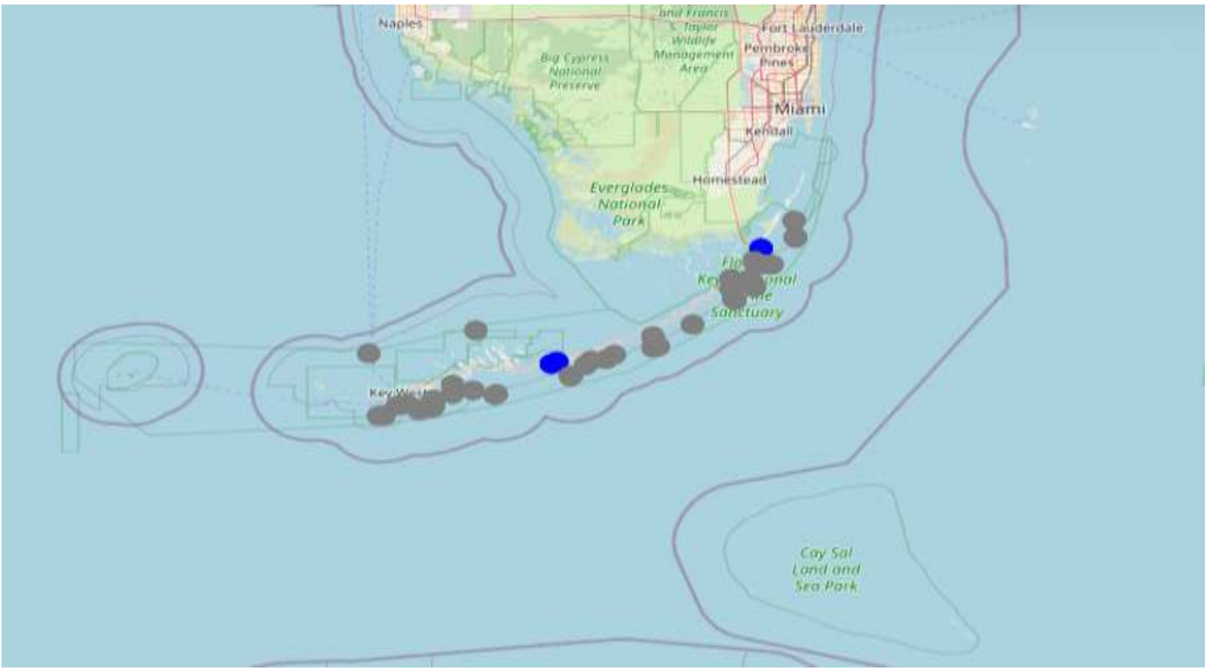
- **Visualization 19:**



- *Caption:* Map showing average stony coral species richness at each station.

- **Hotspots Identified:** Local Gi* analysis identified statistically significant hotspots (clusters of high cover) and coldspots (clusters of low cover) for stony coral percent cover.

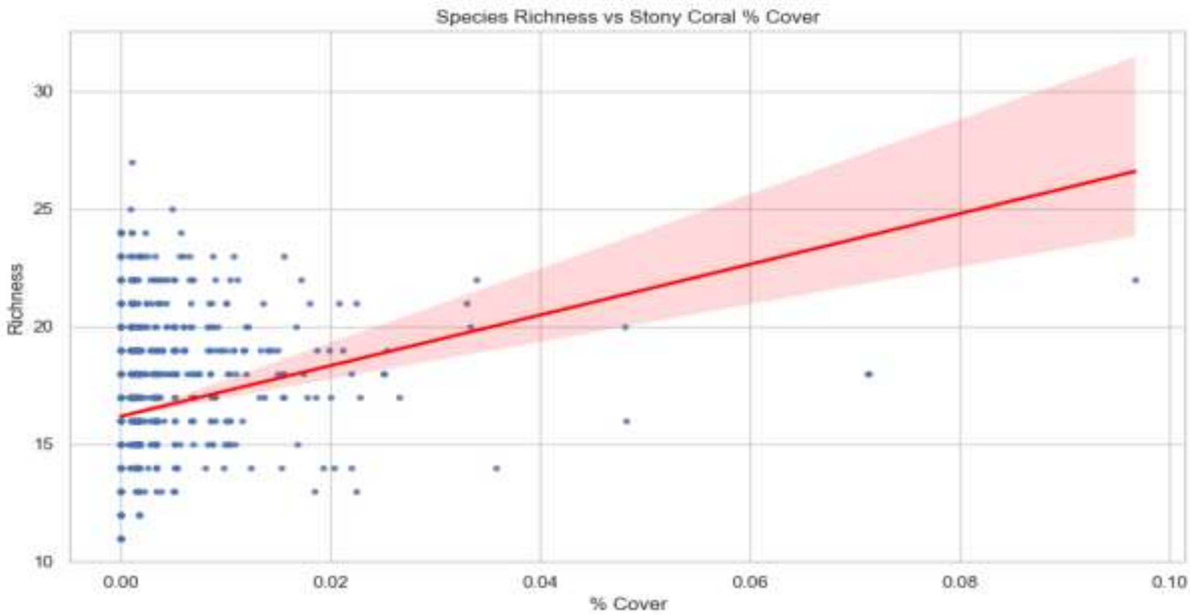
- **Visualization 20:**



  - *Caption:* This map pinpoints areas of statistically significant high (red) or low (blue) stony coral cover clusters, highlighting areas of particular concern or relative health. Here we have 3 blue spots indicating **statistically significant cold spots** for stony coral cover.

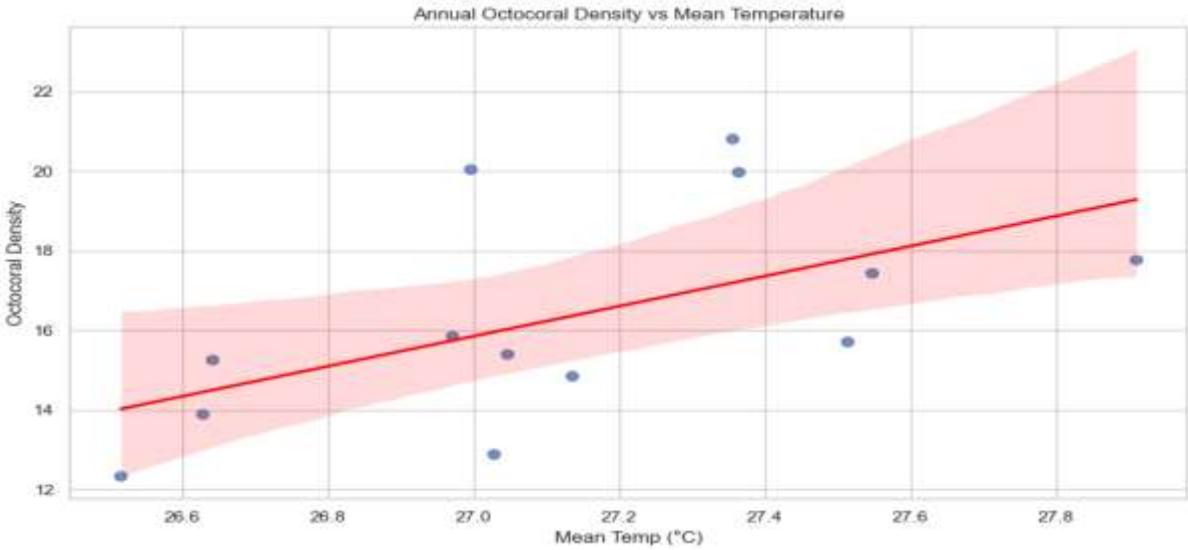
2.6 Key Relationships: Interacting Factors

- **Cover and Richness Link:** A positive relationship exists between stony coral percent cover and species richness, although with considerable variability.
- **Visualization 21:**



  - *Caption:* The regression line suggests that as percent cover increases, species richness tends to increase, though many factors influence this relationship.

- **Octocoral Density and Temperature:** There is a positive correlation between average annual octocoral density and average annual water temperature across the sanctuary.
- **Visualization 22:**

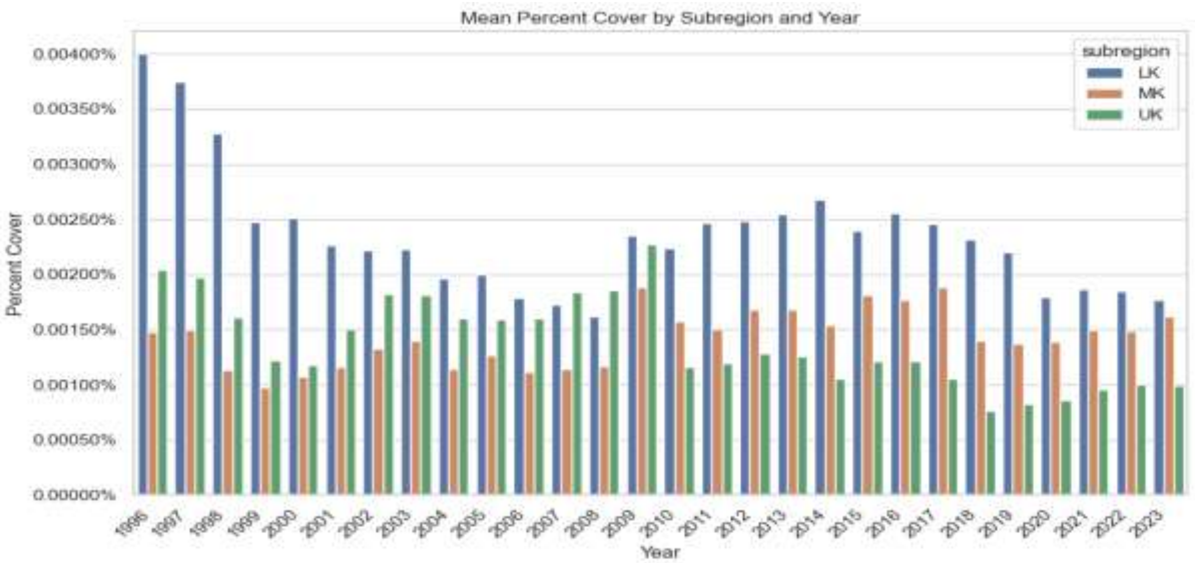


  - *Caption:* This plot shows a tendency for higher octocoral density in warmer years, although the relationship is not perfect.

- **Temperature and Other Metrics:** Temperature variables (mean, min, max, variability) correlate significantly with various biological metrics, including specific species abundances, LTA, and cover (details in Appendix A).

2.7 Regional Comparisons: A Patchwork Quilt

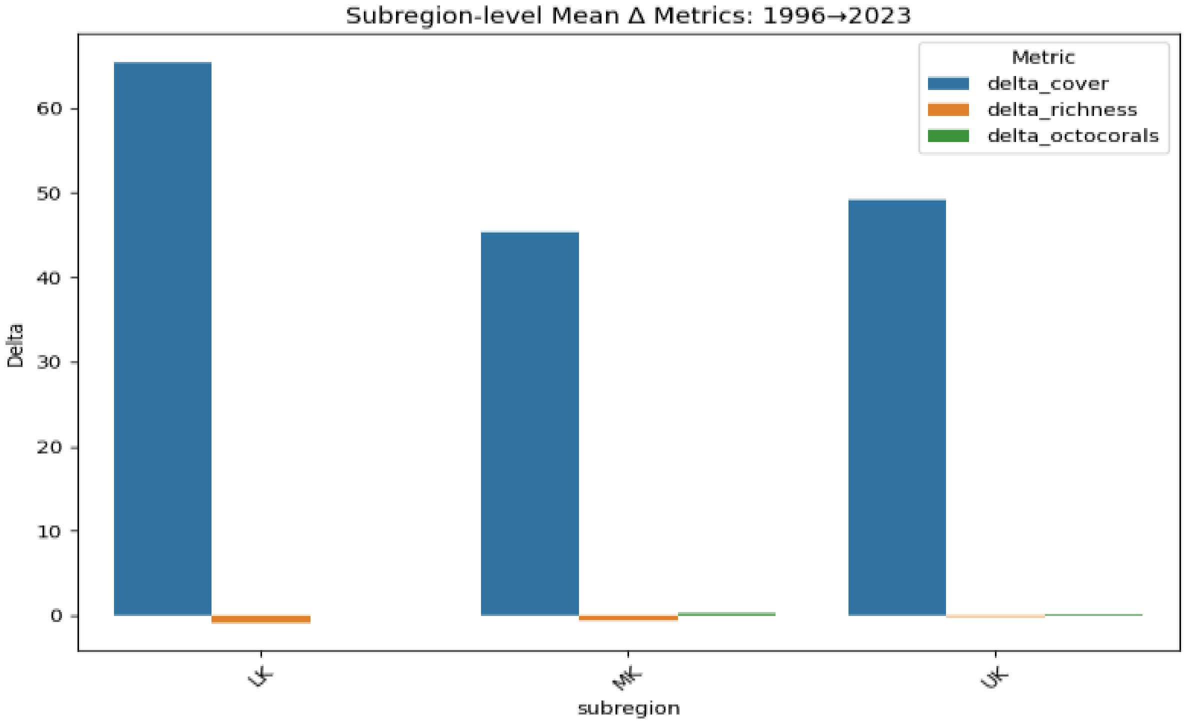
- **Subregional Cover Trends:** Stony coral cover levels and trends differ between the Upper Keys (UK), Middle Keys (MK), and Lower Keys (LK).
- **Visualization 23:**



- *Caption:* This bar chart illustrates the different historical and recent average cover levels in the three main key regions.

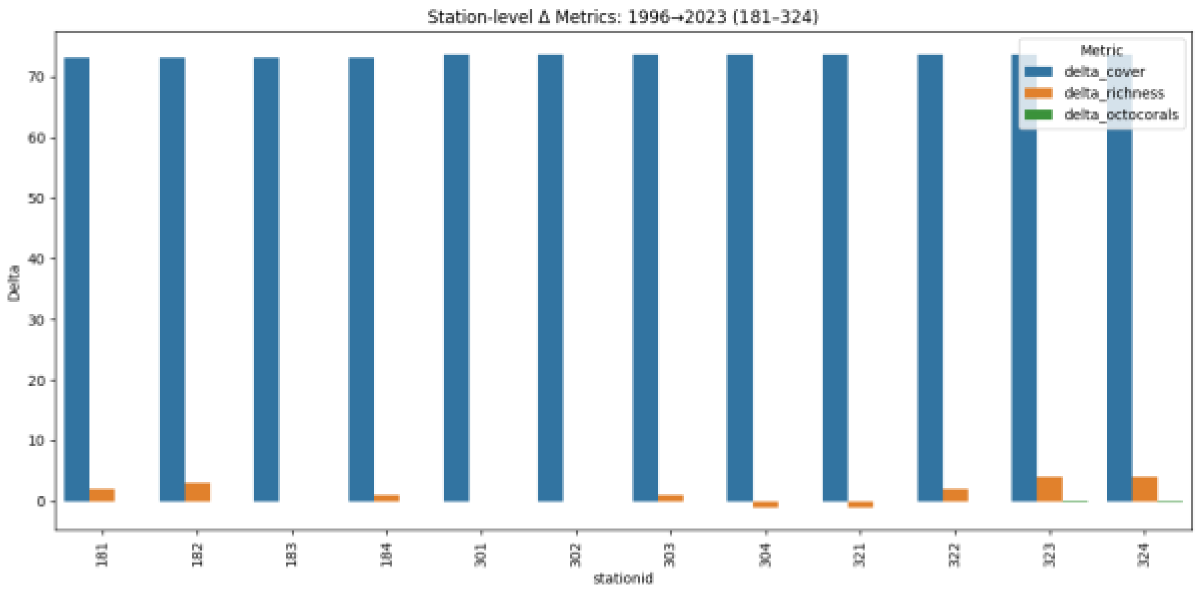
- **Differential Change (Delta):** The magnitude of change in cover, richness, and octocoral density between 1996 and 2023 varies significantly by subregion and station.

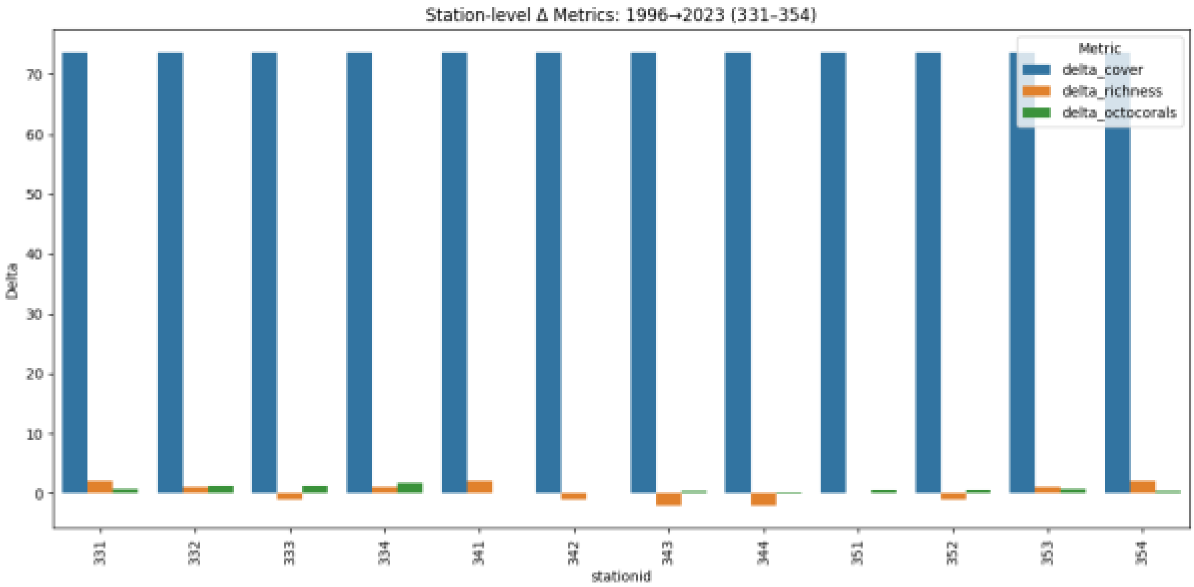
- **Visualization 24:**



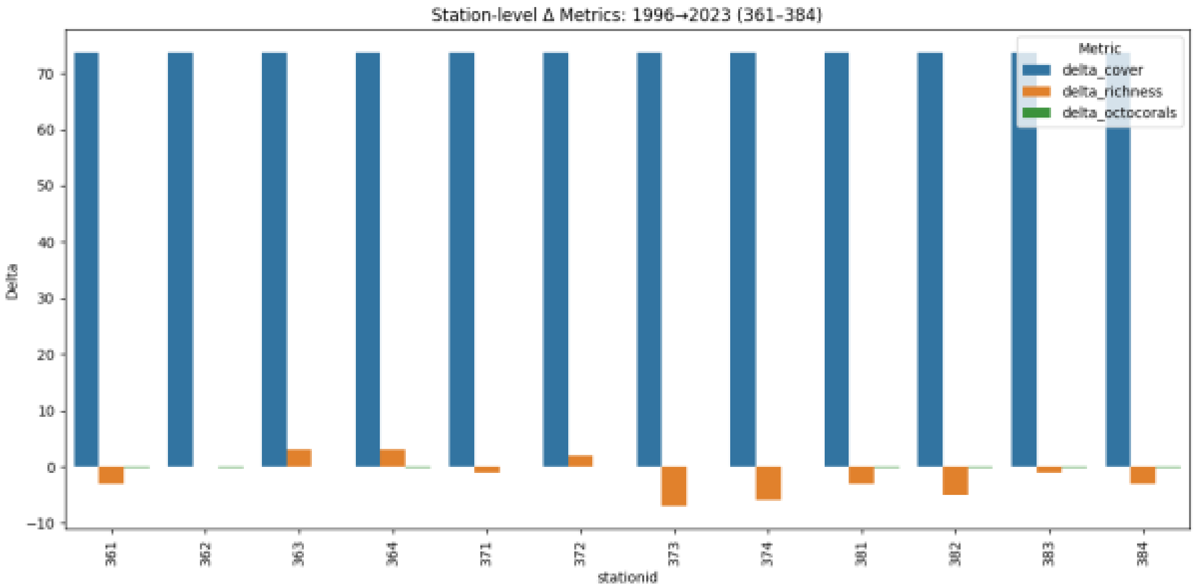
- *Caption:* This chart summarizes the average change per subregion, showing significant cover loss (blue) across all regions.

- **Visualization 25:**





Station-level Δ Metrics: 1996→2023 (331–354)
Metric
delta_cover
delta_richness
delta_octocorals
Delta
stationid
331
332
333
334
341
342
343
344
351
352
353
354



Station-level Δ Metrics: 1996→2023 (361–384)
Metric
delta_cover
delta_richness
delta_octocorals
Delta
stationid
361
362
363
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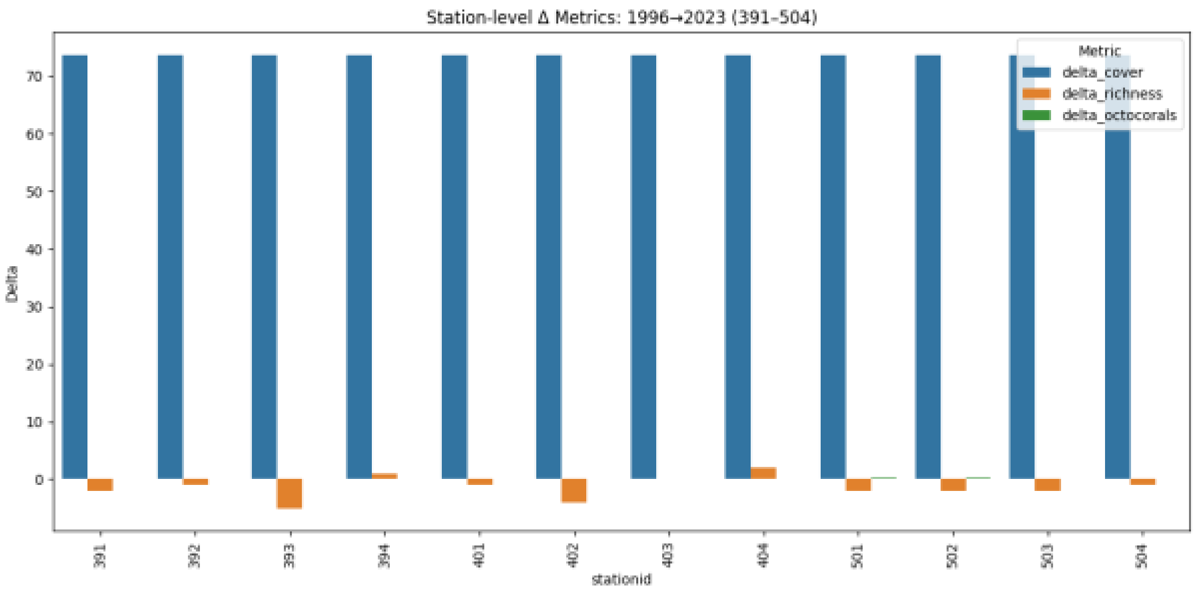
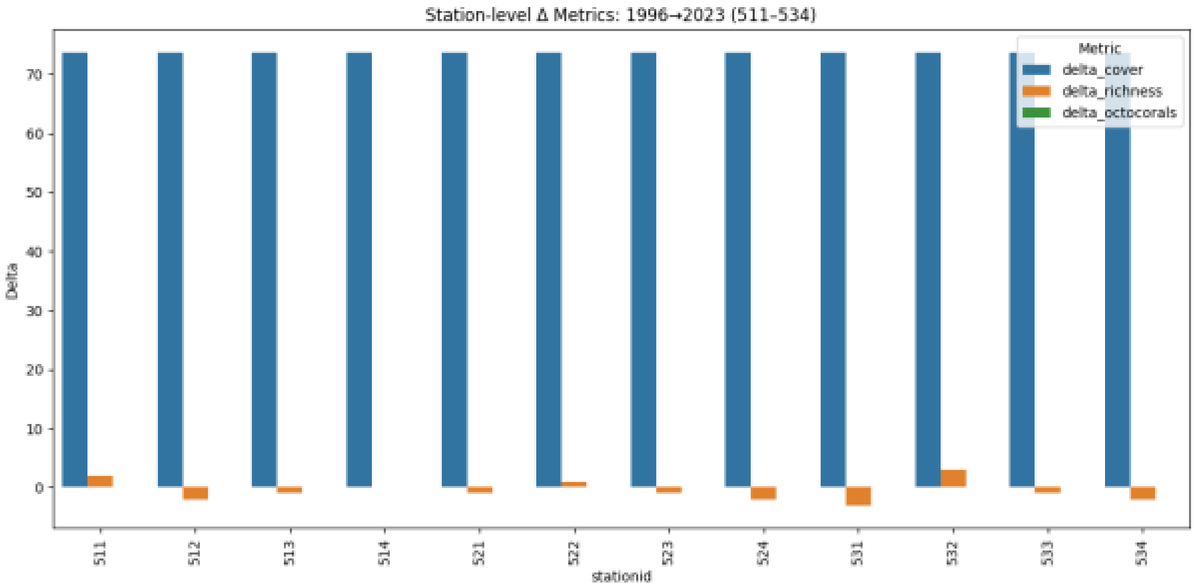
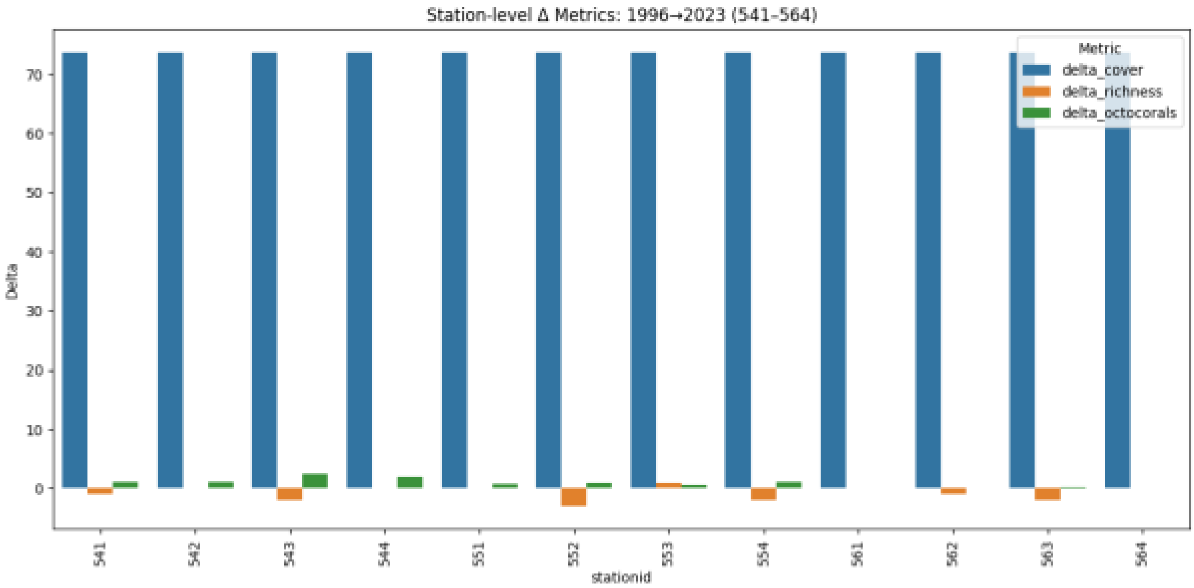
384



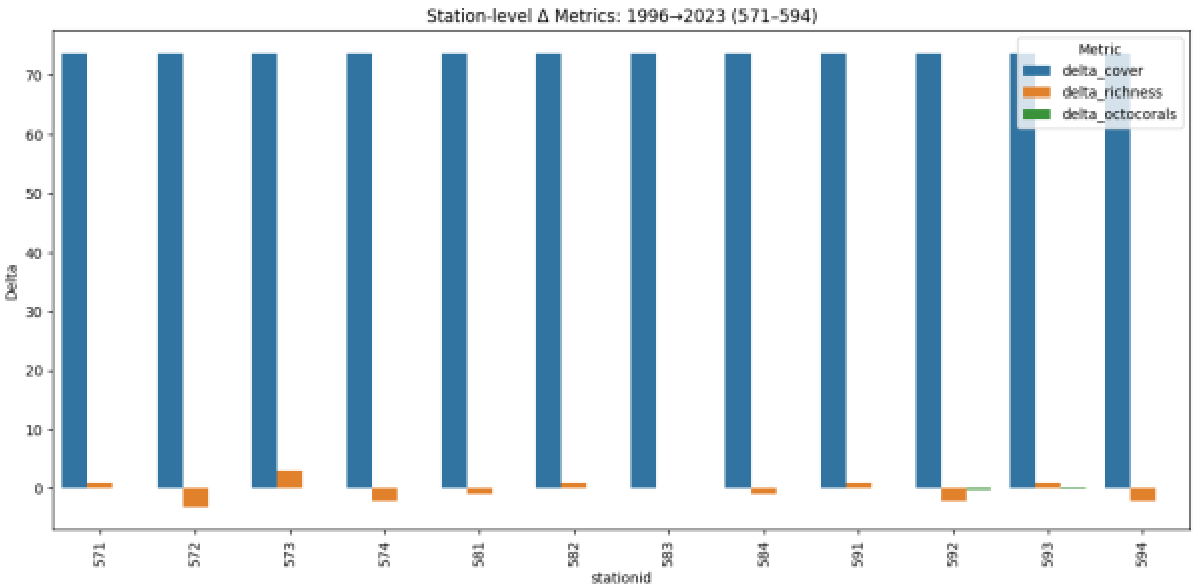
Station-level Δ Metrics: 1996→2023 (391–504)
Metric
delta_cover
delta_richness
delta_octocorals
Delta
stationid
391
392
393
394
401
402
403
404
501
502
503
504



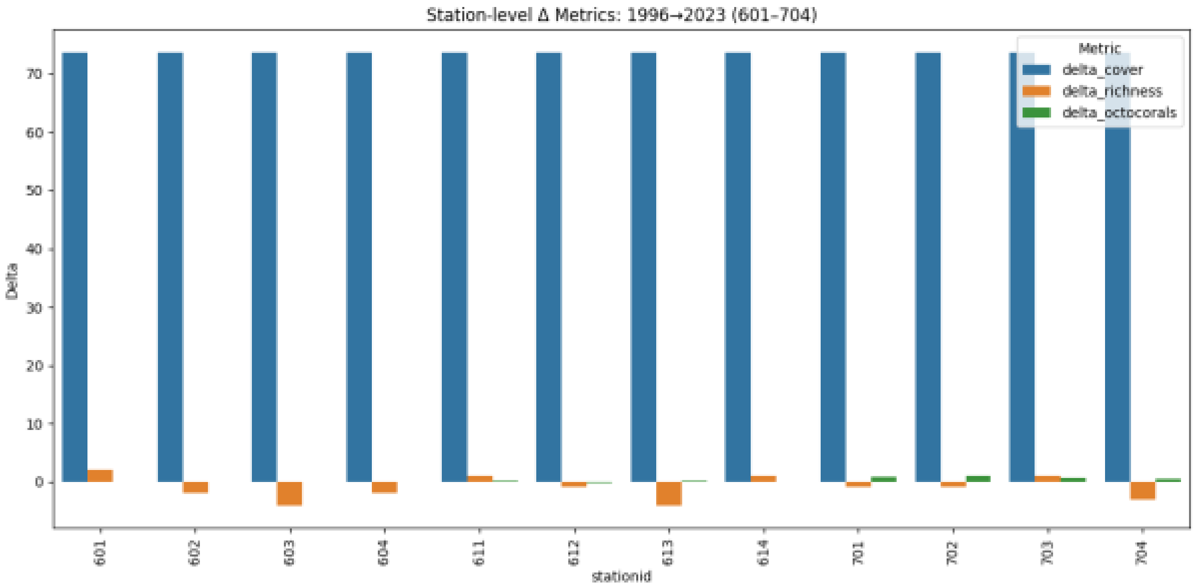
Station-level Δ Metrics: 1996→2023 (511–534)
Metric
delta_cover
delta_richness
delta_octocorals
Delta
stationid



Station-level Δ Metrics: 1996→2023 (541–564)
Metric
delta_cover
delta_richness
delta_octocorals
Delta
stationid



Station-level Δ Metrics: 1996→2023 (571–594)
Metric
delta_cover
delta_richness
delta_octocorals
Delta
stationid


Station-level Δ Metrics: 1996→2023 (601–704)
Metric
delta_cover
delta_richness
delta_octocorals
Delta
stationid
601
602
603
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611
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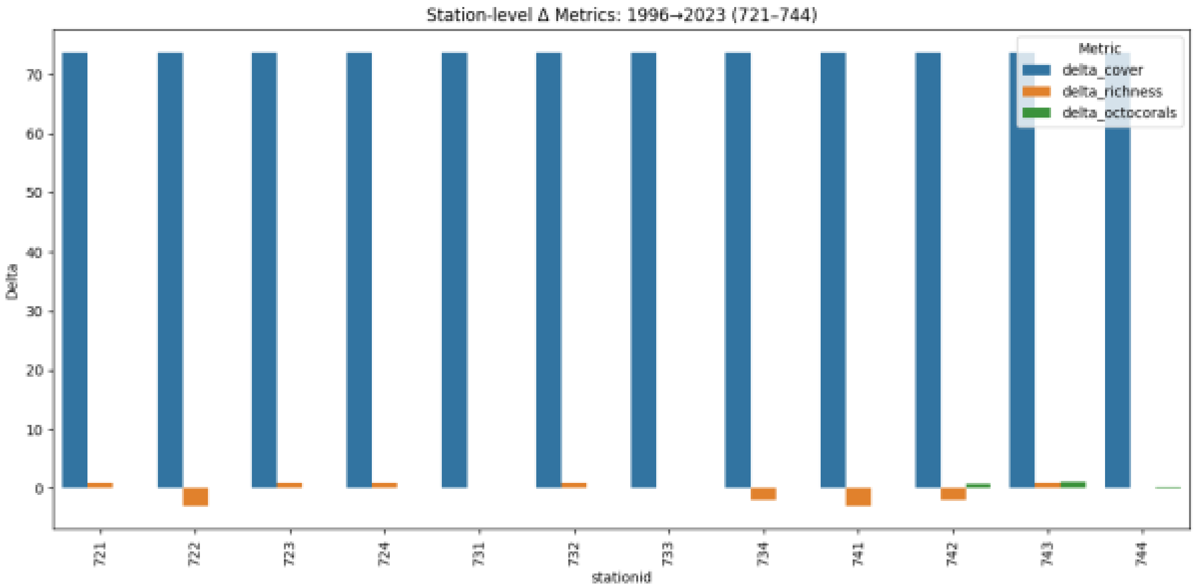
614
701
702
703
704


Station-level Δ Metrics: 1996→2023 (721–744)
Metric
delta_cover
delta_richness
delta_octocorals
Delta
stationid
721
722
723
724
731
732
733
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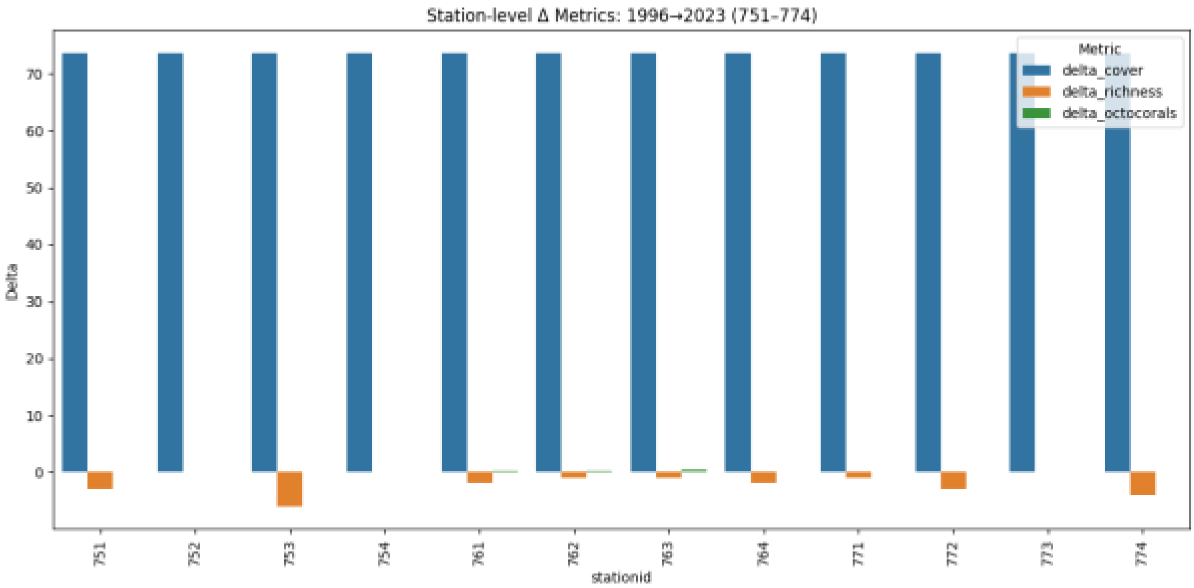
741
742
743
744


Station-level Δ Metrics: 1996→2023 (751–774)
Metric
delta_cover
delta_richness
delta_octocorals
Delta
stationid
751
752
753
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761
762
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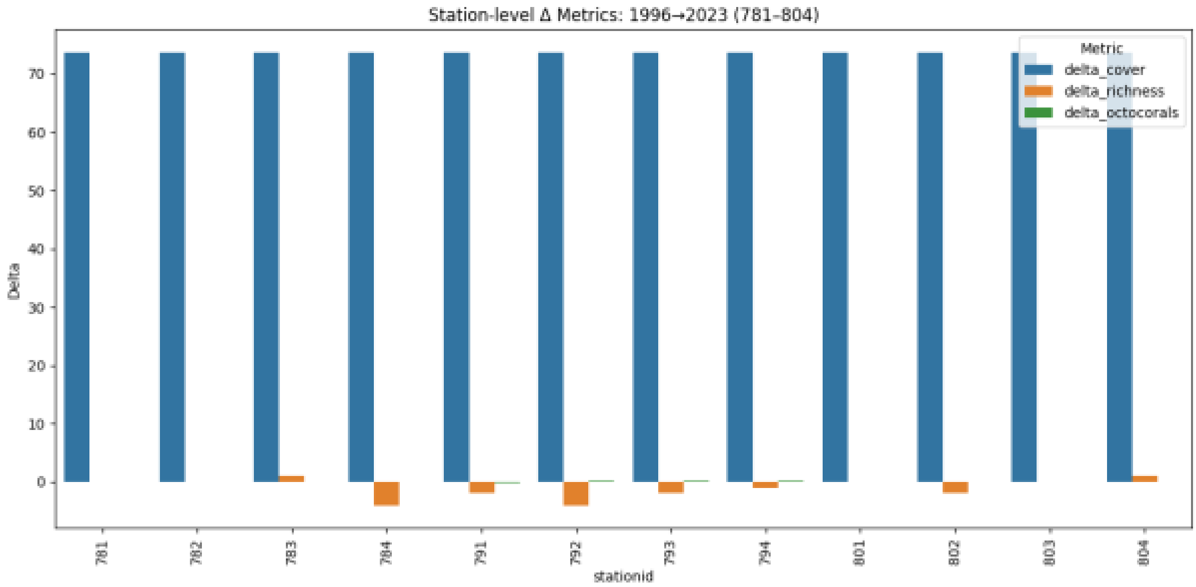
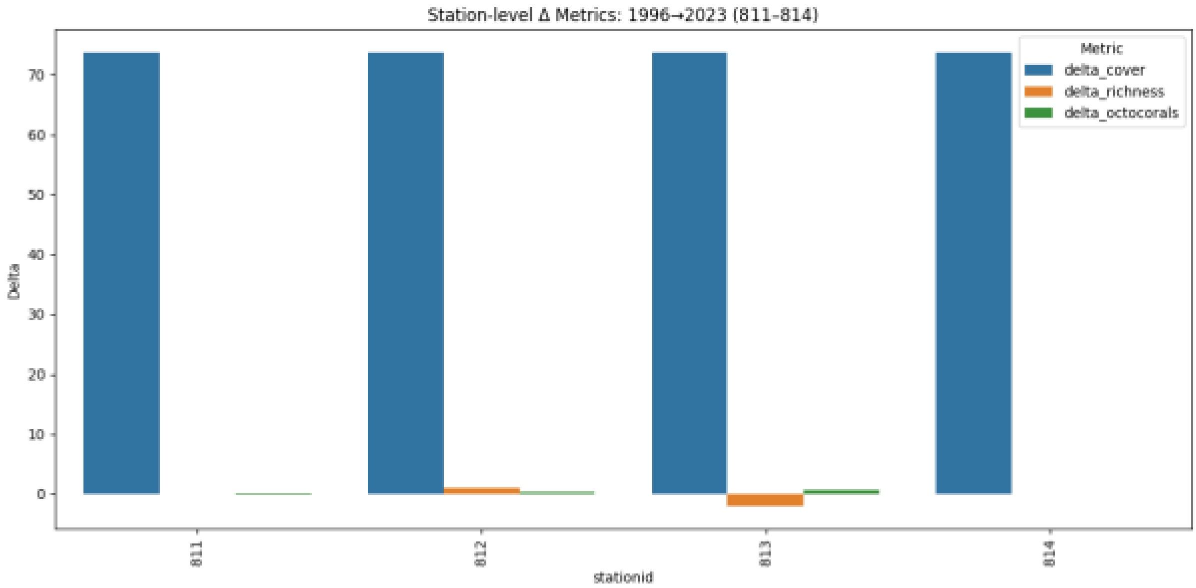
764
771
772
773
774



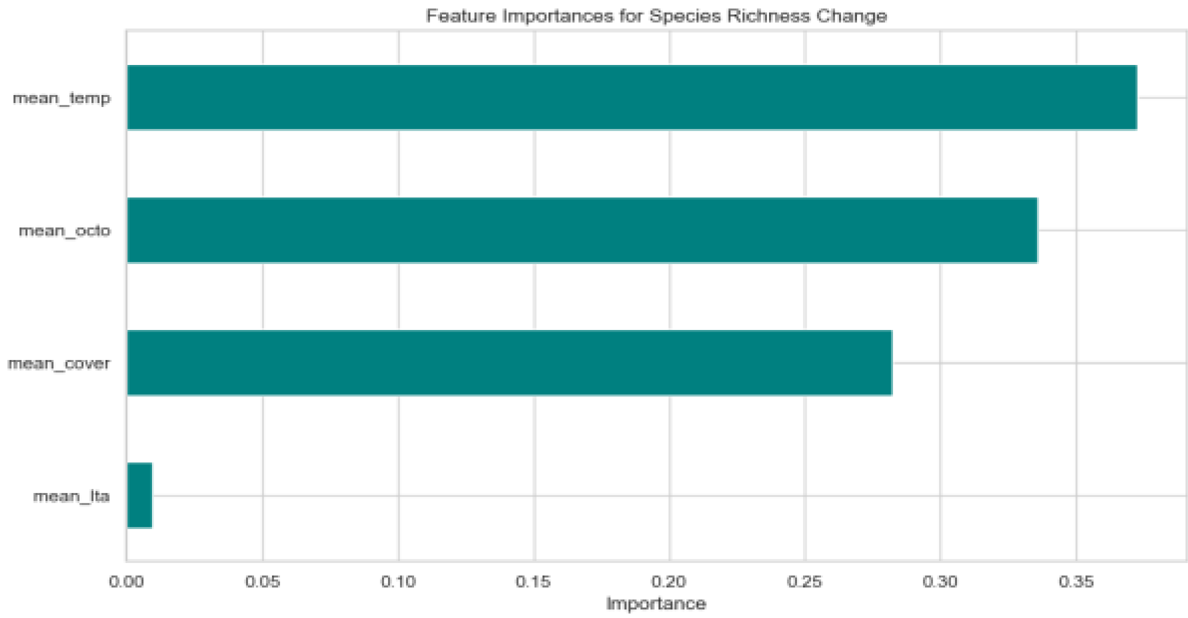


- *Caption:* These detailed charts show the station-by-station change, highlighting the large variation even within regions.

- **Multi-Metric Regional Health:** A combined view using normalized metrics for coral cover, octocoral density, and species richness reveals distinct regional profiles.
- **Visualization 26:**
  [Placeholder: Describe Regional Health Assessment Radar Chart - HTML - e.g., "Insert screenshot or description of regional_health_assessment.html"]
  - *Caption:* A radar chart comparing regions across key health indicators shows relative strengths and weaknesses (e.g., one region might have higher richness but lower cover). (Generated as HTML: regional_health_assessment.html)

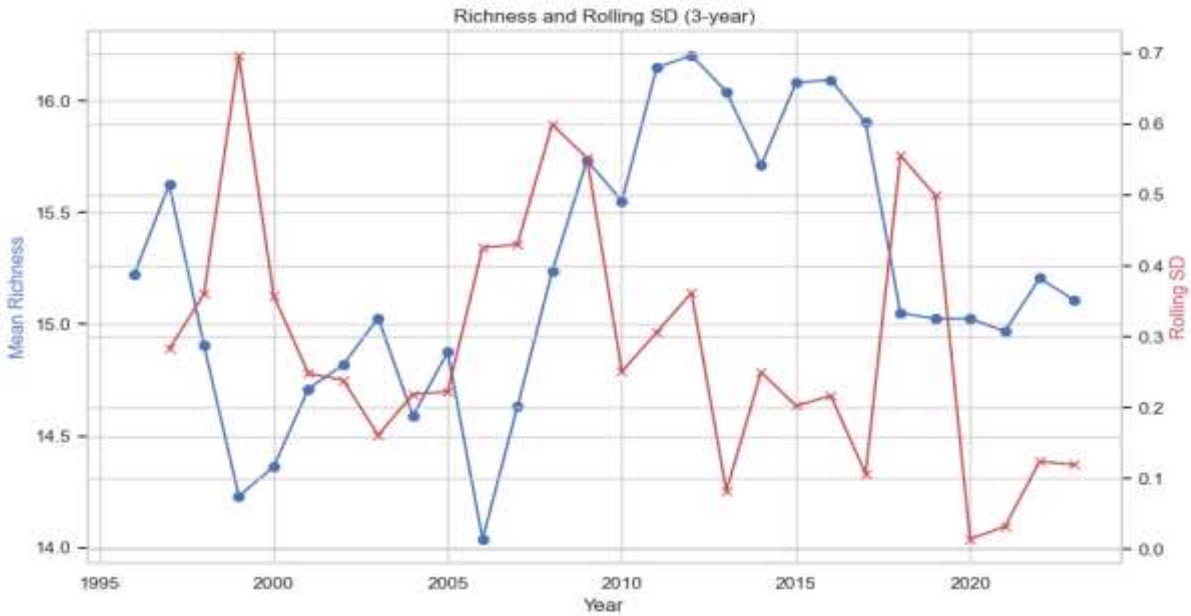
2.8 Drivers, Indicators, and Risk Factors

- **Drivers of Richness Change:** A Random Forest model identified mean temperature, mean octocoral density, and mean coral cover as key factors influencing station-level changes in stony coral richness over the study period.
- **Visualization 27:**



  - *Caption:* This bar chart ranks the importance of different factors in predicting richness change, with temperature and octocoral density appearing most influential in this model.

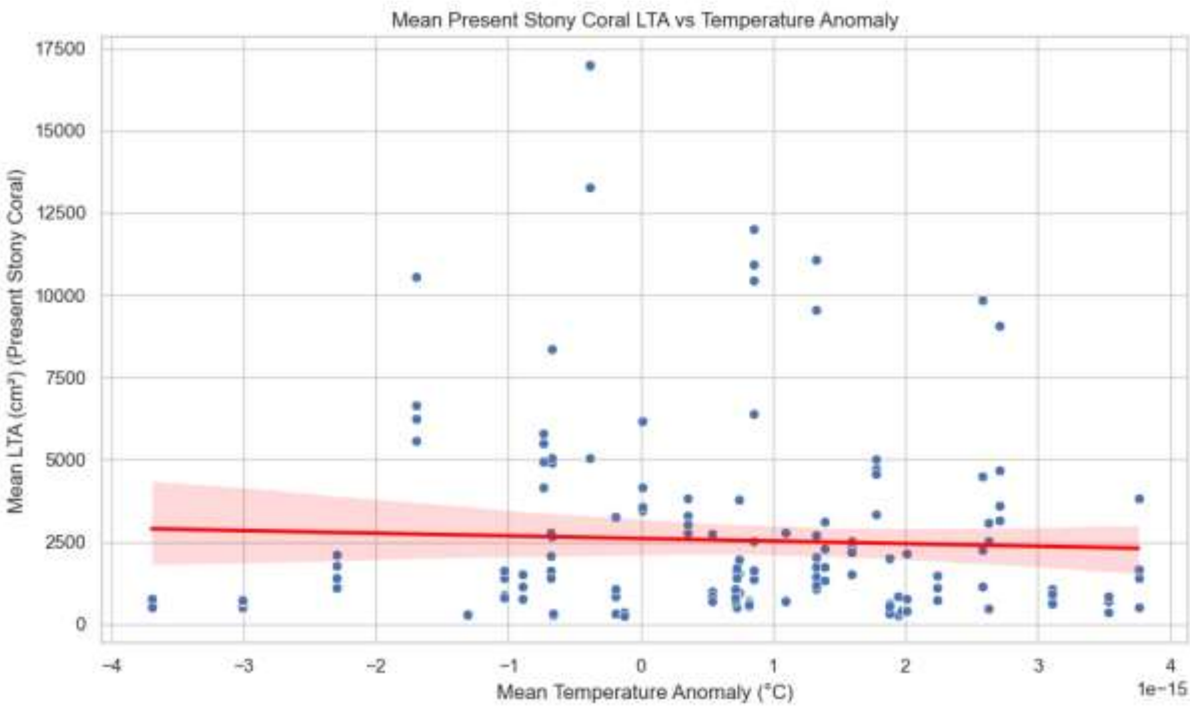
- **Variability as Early Warning:** Increased year-to-year variability (rolling standard deviation) in richness sometimes preceded larger shifts in the overall richness trend, suggesting it could potentially serve as an early indicator of instability.
- **Visualization 28:**



- *Caption:* Peaks in the red line (variability) sometimes occur near turning points or periods of change in the blue line (average richness).

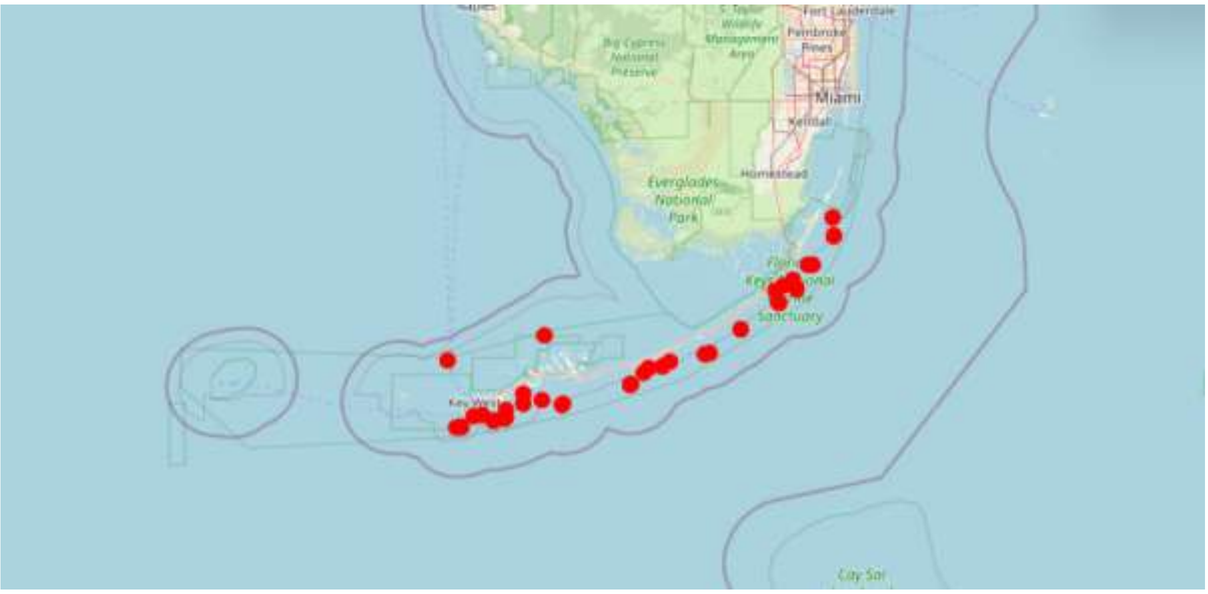
- **LTA Sensitivity to Warming:** Stations where stony coral LTA showed a stronger negative response to temperature anomalies (warmer-than-average conditions) were identified as potentially higher risk.

Visualization 29:



Caption: This plot shows a slight negative relationship overall between LTA (of present corals) and temperature anomalies.

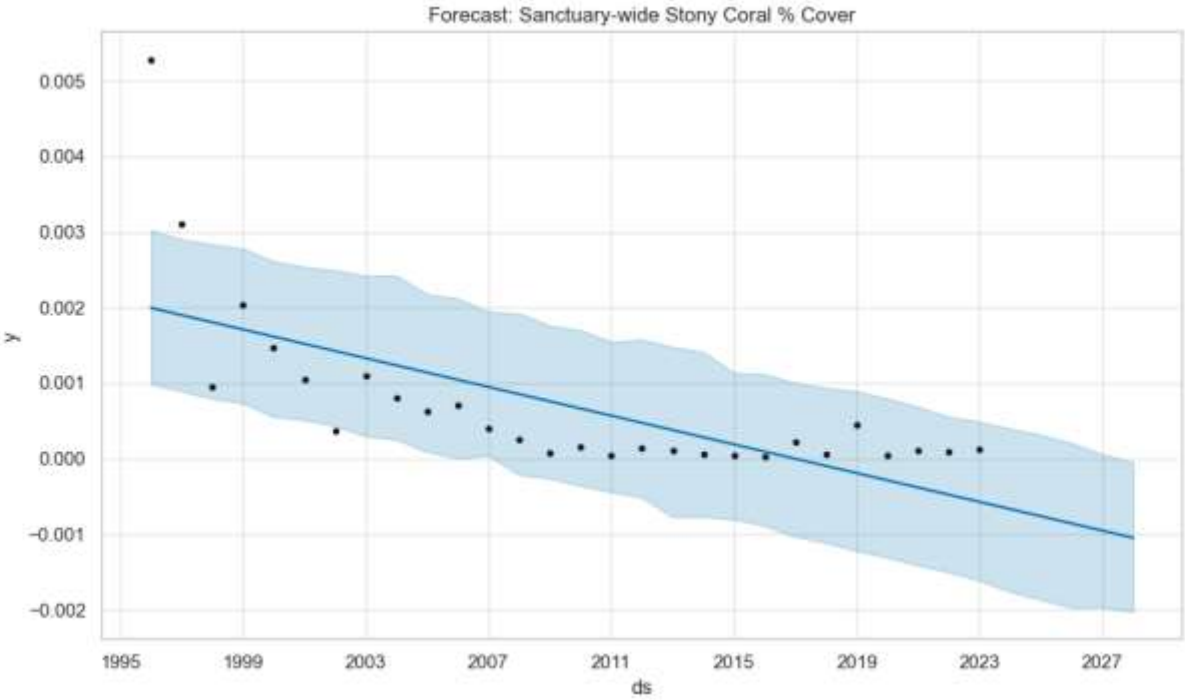
- **Visualization 30:**



- *Caption:* This map highlights stations based on their calculated LTA sensitivity to warming (risk score), identifying potentially more vulnerable locations.

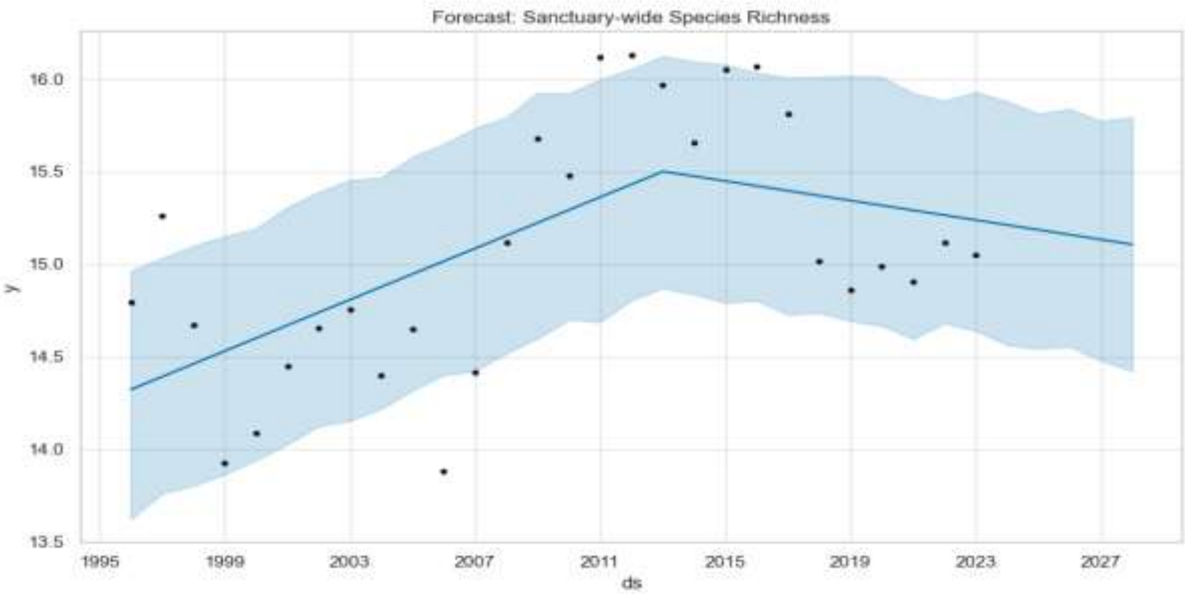
2.9 Future Outlook: Projections and Uncertainty

- **Forecasted Trends:** Time-series models (Prophet) projecting trends five years forward suggest a continued slight decline or stabilization at current low levels for both sanctuary-wide stony coral cover and species richness, based on historical patterns.
- **Visualization 31:**



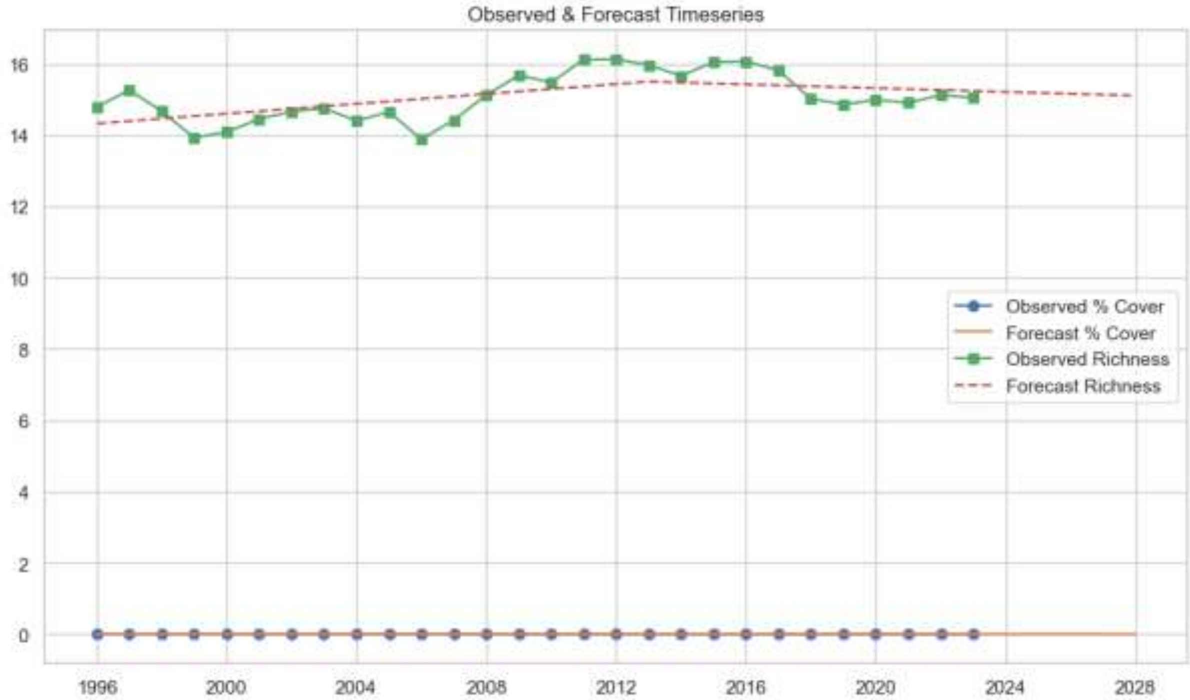
- *Caption:* Forecast showing the projected trend for percent cover (black line) and the uncertainty range (blue shading).

- **Visualization 32:**



- *Caption:* Forecast showing the projected trend for species richness and its uncertainty range.

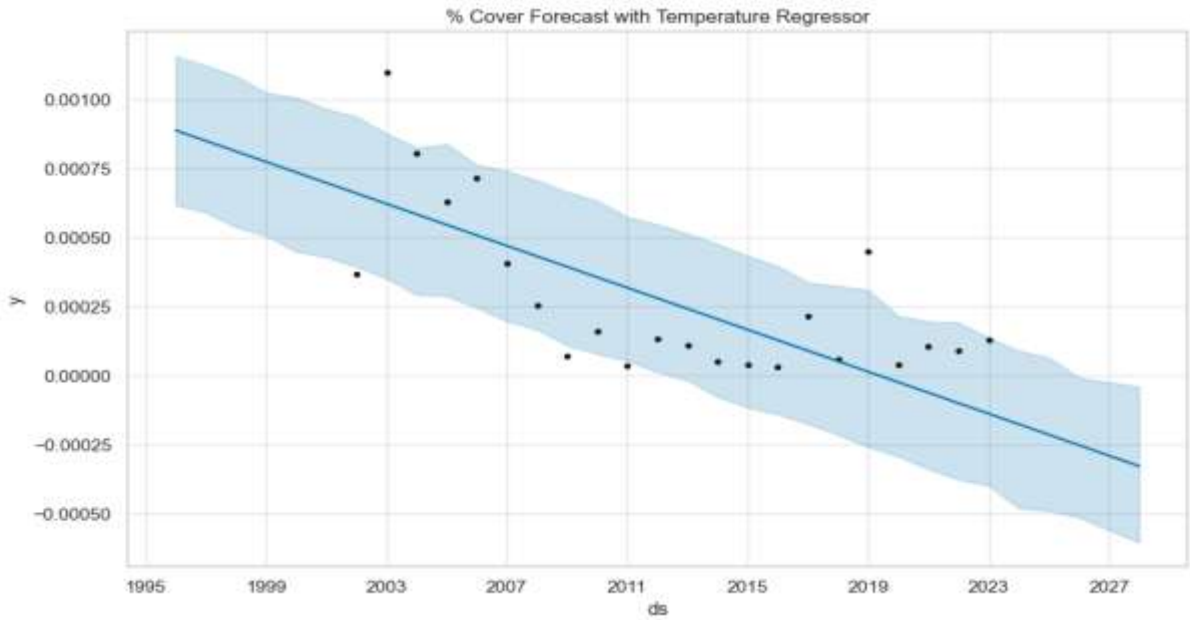
- **Visualization 33:**



  - *Caption:* This plot combines historical data and future forecasts for both cover and richness.

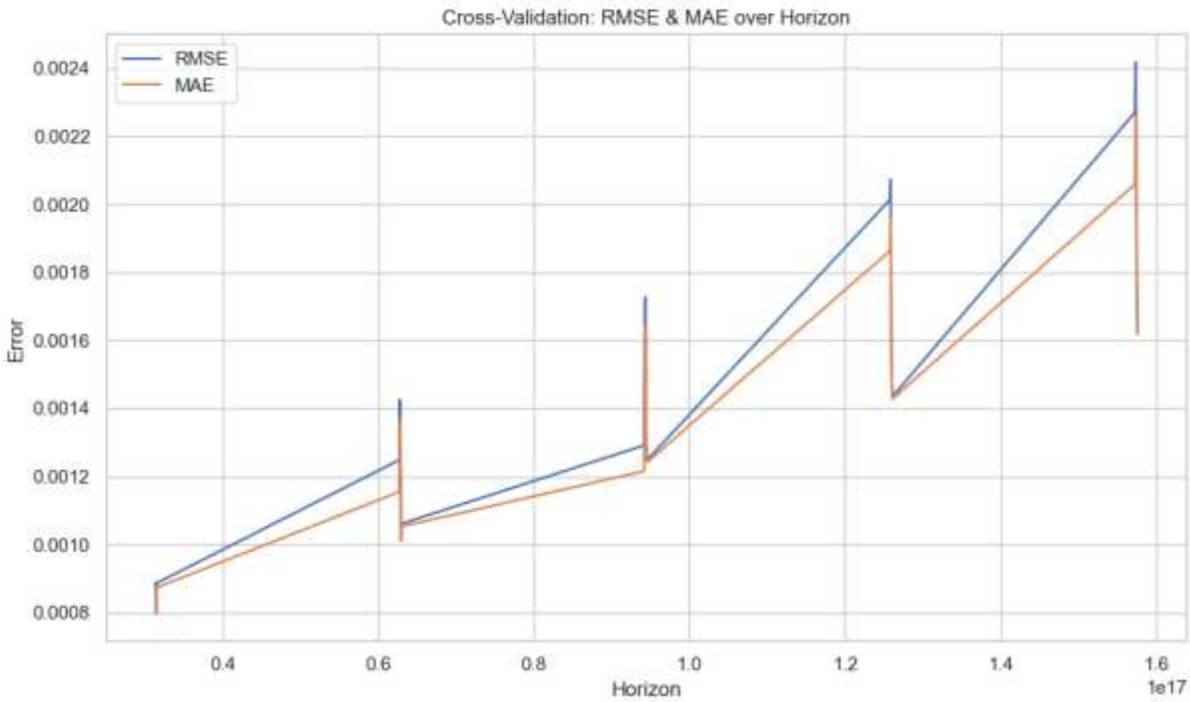
- **Model Considerations:** Adding temperature as an explicit predictor did not drastically change the cover forecast in this analysis, but forecast uncertainty increases significantly over longer horizons. Station-level forecasts were also generated.

- **Visualization 34:**



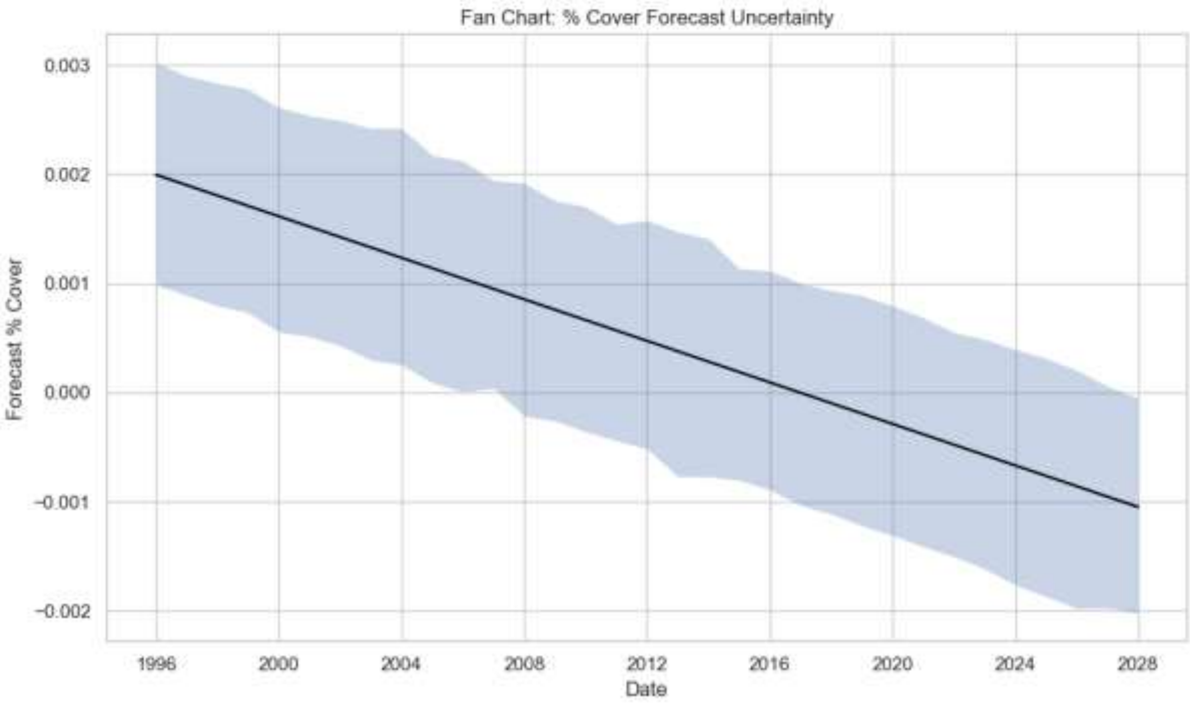
- *Caption:* The forecast for percent cover when explicitly including temperature as a predictive factor.

- **Visualization 35:**



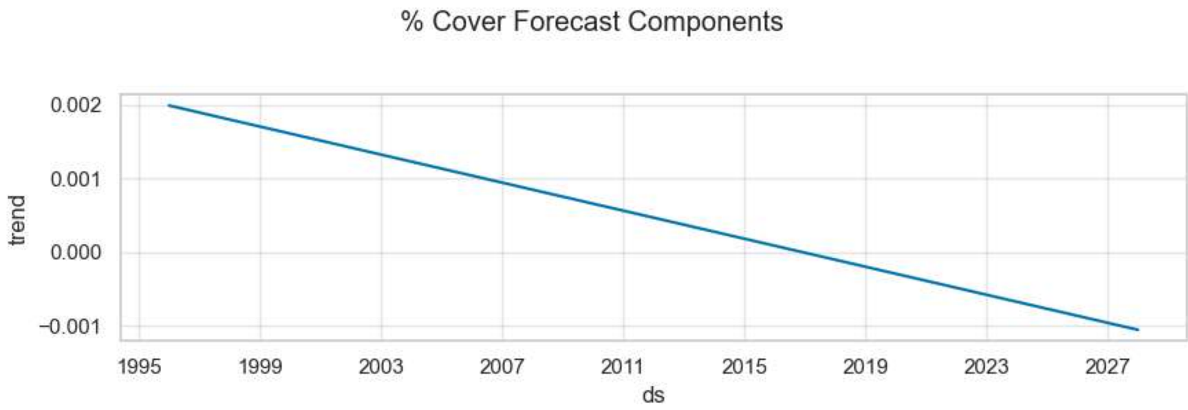
- *Caption:* Shows how prediction error tends to increase when forecasting further into the future.

- **Visualization 36:**



- *Caption:* Visually represents the widening range of possible outcomes for the percent cover forecast over time.

- **Visualization 37:**



  - *Caption: This* figure breaks down the percent cover forecast into its underlying components, including the long-term trend and any recurring seasonal patterns. It means the % cover will decline.

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3. In-depth Analysis: Understanding the 'Why' and 'How'

Here we delve deeper into the analysis methods and what the results mean in simpler terms, structured around the datathon criteria.

3.1 Exploratory Analysis (Sections 3-7)

- **What we did:** We looked at how key reef health measures changed over time (1996-2023) and differed across nearly 200 monitoring stations spread throughout the Keys. We tracked stony coral cover (like lawn coverage), species richness (variety of coral types), octocoral density (number of soft corals), and LTA (size/health of stony corals). We also mapped these patterns geographically.

- **Key Insight:** The big story is the drop in stony coral cover and LTA. It's like parts of the underwater city are shrinking or becoming less robust. Richness is holding steadier *on average* sanctuary-wide, but this hides a lot of local variation – some places lost variety, others didn't as much. Soft corals seem to be playing by different rules, showing periods of increase.

- **Analogy:** Imagine tracking trees in many parks across a city for 30 years. We found fewer large, old trees overall (lower LTA, lower cover), but the total number of *different kinds* of plants might fluctuate without a clear city-wide drop (richness). Meanwhile, maybe shrubs (octocorals) increased in some parks.

3.2 Relationships and Correlations (Sections 4, 5, 9)

- **What we did:** We looked for statistical connections (correlations) between different reef characteristics and environmental factors like temperature and depth. We checked if factors tended to increase or decrease together.

- **Key Insight:** Reefs are complex systems. We found that areas with more coral cover often had more species (Sec 4.4). Octocoral density showed a positive link with average annual temperature (Sec 5.3), while stony coral LTA showed a slight negative link with temperature *anomalies* (unusually warm periods compared to normal for that spot, Sec 10.3). Many other factors like depth, location, and specific species abundances were also interconnected (See Appendix A for details from Sec 9).

- **Analogy:** Finding correlations is like noticing that ice cream sales and crime rates both go up in the summer. They are correlated, likely because both are influenced by a third factor (hot weather), not because ice cream causes crime. Similarly, while octocorals and temperature are correlated, it doesn't automatically mean warmth *causes* more octocorals – other factors could be involved.

3.3 Regional Comparison (Sections 3, 5, 6, 8)

- **What we did:** We grouped the stations by subregion (Upper, Middle, Lower Keys) and compared their average coral cover, richness, density, and how much these metrics *changed* between 1996 and 2023 (the 'delta'). We also used a radar chart to visually compare regions across multiple health indicators.
- **Key Insight:** The Florida Keys reef tract is not uniform. The UK, MK, and LK have different baseline levels of coral cover and experienced the overall decline differently (Sec 3.3, Sec 8.2). Some regions might be doing relatively better in terms of richness but worse in cover, or vice-versa, as visualized in the regional health assessment (Sec 8 HTML plot). Station-level analysis (Sec 8.1 plots) shows even greater variability within regions.
- **Analogy:** Think of comparing different neighborhoods in a city. Some might have more parks (higher cover potential), some might have more diverse plant life (higher richness), and the changes over 30 years (like tree loss) wouldn't be the same everywhere.

3.4 Future Outlook (Sections 10, 11)

- **What we did:** We used statistical models (Random Forest, Prophet) to identify potential drivers of change and project recent trends forward. Random Forest helped rank factors influencing richness changes. Prophet created forecasts for cover and richness, accounting for past trends. We also looked for 'early warning signals' like increased variability before a major shift and calculated a 'risk score' based on LTA's response to temperature anomalies.
- **Key Insight:** Temperature consistently emerges as an important factor influencing reef health, both in historical correlations (Sec 9) and as a driver of richness change (Sec 10.1). While forecasts based on past data predict stabilization at low levels or continued slight decline for stony corals (Sec 11), there's significant uncertainty. Monitoring variability (Sec 10.2) and identifying stations sensitive to warming (Sec 10.4) might offer ways to anticipate future problems.
- **Analogy:** Forecasting reef health is like weather forecasting. We use past data and models to predict the future, but the further out we look, the less certain we are. Identifying factors like temperature is like knowing clouds often bring rain, but doesn't guarantee it will rain tomorrow at your exact house. Early warnings (like variability) are like noticing the barometer dropping sharply.

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4. Conclusion & Actionable Recommendations

Summary: Our analysis of nearly three decades of CREMP data provides invaluable insights into the long-term dynamics of the Florida Keys coral reefs. The most significant finding is the substantial decline in stony coral cover and LTA since 1996, contrasted by periods of increase in octocoral density. Reef health is highly variable spatially, with specific locations acting as relative hotspots or coldspots, and different regions showing distinct health profiles across multiple metrics. Temperature, depth, and geographic location are key interconnected factors influencing these patterns. While historical trend-based forecasts suggest a challenging near-term future for stony corals, understanding the drivers, spatial patterns, and potential early warning signs offers pathways for informed action.

Implications: The decline in stony corals is concerning as they form the essential structure of the reef ecosystem. This loss impacts biodiversity, coastal protection, and industries reliant on healthy reefs. The relative success of octocorals highlights potential shifts in the reef community composition. The spatial variability suggests that some areas may be more resilient or face different pressures than others.

Recommendations:

1. **Prioritize Monitoring & Research:** Continue and enhance long-term monitoring (like CREMP). Focus research on understanding the mechanisms behind observed resilience in hotspot areas and specific species.
2. **Spatially-Explicit Management:** Use the identified hotspots/coldspots (Map 7.4) and regional health profiles (HTML Radar Chart) to tailor management actions, potentially focusing resources on protecting resilient areas or restoring degraded ones.
3. **Address Key Stressors:** Given the identified links between temperature anomalies/variability and coral health metrics (LTA decline, richness drivers, octocoral density - Sec 9.2, 10.1, 10.3), support broader climate mitigation efforts. Locally, consider strategies to mitigate thermal stress where feasible (e.g., managing factors affecting water flow or local shading). Monitor 'high-risk' stations (Map 10.4) closely during warming events.
4. **Investigate Early Warning Indicators:** Further validate the potential use of variability metrics (like rolling SD of richness - Graph 10.2) as operational early warning signals for management intervention.
5. **Adaptive Management:** Recognize the potential for ecosystem shifts (e.g., increased octocorals - Graph 5.1) and adapt management goals and strategies accordingly, considering the changing nature of the reef community.

Understanding these complex underwater cities is the first step towards protecting them for the future.

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5. Appendix

Supporting details from the analysis.

A. Significant Correlations (|r| >= 0.3, Section 9 Output Summary)

- **Note:** The following lists summarize pairs of variables found to be significantly correlated (|correlation coefficient r| ≥ 0.3) in the merged dataset combining biological and environmental data aggregated by site and year. This highlights key interactions but is not exhaustive. Categories (e.g., [SCOR LTA], [Temperature], [Station Var]) indicate the source/type of variable.

- **Non-Temperature Correlations:** Numerous significant correlations were found between biological variables (e.g., LTA of different stony coral species like *Colpophyllia natans* and *Montastraea cavernosa*, r=0.63; *Siderastrea siderea* and *Stephanocoenia intersepta*, r=0.72) and between biological variables and station characteristics (e.g., Depth and *Madracis decactis* LTA, r=0.68; Depth and the octocoral *Pseudopterogorgia bipinnata* density, r=0.68). Density of the octocoral *Pseudoplexaura porosa* showed strong positive correlations with the LTA of several stony corals, including *Montastraea cavernosa* (r=0.76) and *Siderastrea siderea* (r=0.73). Geographic coordinates (Latitude/Longitude) also showed correlations with various biological metrics, reflecting broader spatial gradients.
- **Temperature Correlations:** Temperature metrics showed significant correlations with biological and station variables. For example, temperature variability (temp_std) was negatively correlated with depth (r=-0.46) and positively correlated with the LTA of *Siderastrea siderea* (r=0.42) and the density of the octocoral *Pseudoplexaura porosa* (r=0.61). Conversely, temp_std was strongly negatively correlated with internal database ID indices (potentially reflecting sampling time/effort changes over years with different temperature variability patterns, e.g., r=-0.73 with oid_). Mean, min, and max temperatures were highly correlated with each other, as expected (e.g., temp_mean vs temp_min, r=0.94).