Beneath the Waves: Coral Resilience and Decline

Forecasting the Future of the Florida Keys Ecosystem

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Abstract

Florida's coral reefs, often called the "rainforests of the sea," are facing alarming declines driven by rising ocean temperatures, disease outbreaks, and biodiversity loss.

This study leverages the Coral Reef Evaluation and Monitoring Project (CREMP) datasets to investigate long-term trends in coral cover and species richness. Using advanced machine learning models, including Random Forests, Prophet, and LSTM networks, we forecast future reef health trajectories and simulate climate change scenarios.

Our analysis reveals a continued decline in coral health without targeted conservation interventions. Scenario simulations highlight the severe vulnerability of reefs to warming oceans.

These findings provide a data-driven foundation for resilience planning and emphasize the urgent need for immediate local and global action to protect Florida's vital reef ecosystems.

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Coral Reef Health Analysis Report

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1 Introduction

The Coral Reef Evaluation and Monitoring Project (CREMP) dataset offers a rare window into the evolving health of coral reefs in the Florida Keys — ecosystems often called the "rainforests of the sea."

This report investigates long-term shifts in coral cover, species richness, ocean temperature, and biological stresses. Leveraging machine learning forecasting techniques, we aim to chart the past, predict the future, and highlight urgent conservation priorities.

2 Data Sources and Preparation

This study draws upon multiple datasets from CREMP to build a comprehensive view of reef health:

- **CREMP Temperature Data**: In-situ measurements across reef sites.
- **CREMP Percent Cover Data**: Stony coral cover percentages per station.
- **CREMP SCOR Summaries**: Disease prevalence and condition counts.
- **CREMP Octocoral Density Data**: Quantitative records of octocoral abundance.

Preprocessing steps included missing value imputation, feature engineering (e.g., branching/massive coral percentages, disease prevalence), and categorical encoding.

3 Preprocessing and Machine Learning Pipeline

3.1 Data Cleaning and Preparation

The original CREMP datasets contained missing values, inconsistent survey records across years, and measurement discrepancies. Preprocessing steps included:

- **Missing Value Handling:** Features such as Branching Coral Percent and Massive Coral Percent had missing entries, which were filled with zeros where appropriate.
- **Site Filtering:** Sites with large gaps or inconsistencies across time series were removed to maintain longitudinal analysis consistency.
- **Outlier Detection:** Extreme values in temperature and coral cover were manually inspected and verified.

3.2 End-to-End Analytical Pipeline

The entire project workflow is summarized below, highlighting key phases from raw data to actionable insights.

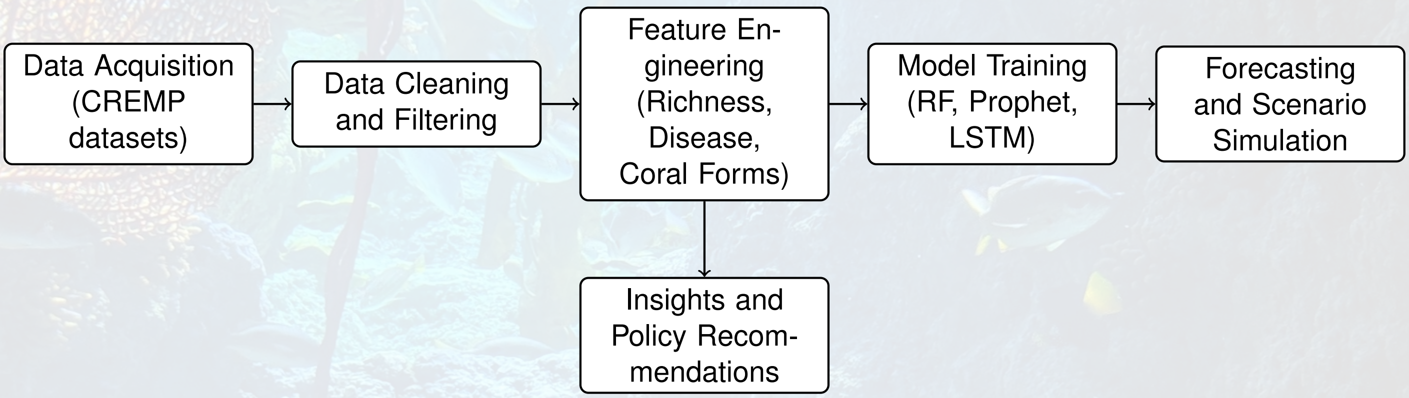


Figure 1: **Analytical Pipeline Overview:** Data-driven progression from collection through predictive modeling to actionable outputs.

3.3 Feature Engineering

To improve model performance and capture complex ecological factors:

- **Species Richness:** Created as the count of unique stony coral species present per station.
- **Disease Prevalence:** Calculated as the percentage of corals affected by disease at each station-year.
- **Growth Forms:** Aggregated coral cover percentages based on morphology (branching vs massive species) to capture reef structural changes.

3.4 Encoding Categorical Variables

Categorical variables such as `Subregion` were label-encoded numerically to allow machine learning models to process them.

3.5 Machine Learning Models

Multiple modeling strategies were applied:

- **Random Forest Regression:** A robust ensemble model predicting coral cover using biological and environmental features.
- **Prophet Time Series Forecasting:** A Bayesian model capturing seasonality and trend shifts over time for coral cover prediction.
- **LSTM Neural Networks:** Deep learning models capturing long-term temporal dependencies in coral cover trends.

3.6 Model Evaluation Metrics

Model performances were assessed using:

- **R-squared (R^2):** Proportion of variance explained by the model.
- **Mean Absolute Error (MAE):** Average absolute prediction error.
- **Root Mean Squared Error (RMSE):** Penalizes larger errors more heavily, providing an additional robustness check.

3.7 Scenario Simulation

A climate warming scenario was modeled by simulating a +2℃ increase in ocean temperatures and evaluating its predicted impact on coral cover distributions.

This exploratory simulation provided insights into how future temperature rises could exacerbate reef degradation even in the absence of disease or local stressors.

4 Key Findings

4.1 Stony Coral Percent Cover Trends

Stony coral cover is steadily collapsing across much of the Florida Keys. After 2010, losses accelerated sharply, signaling a reef system under profound stress.

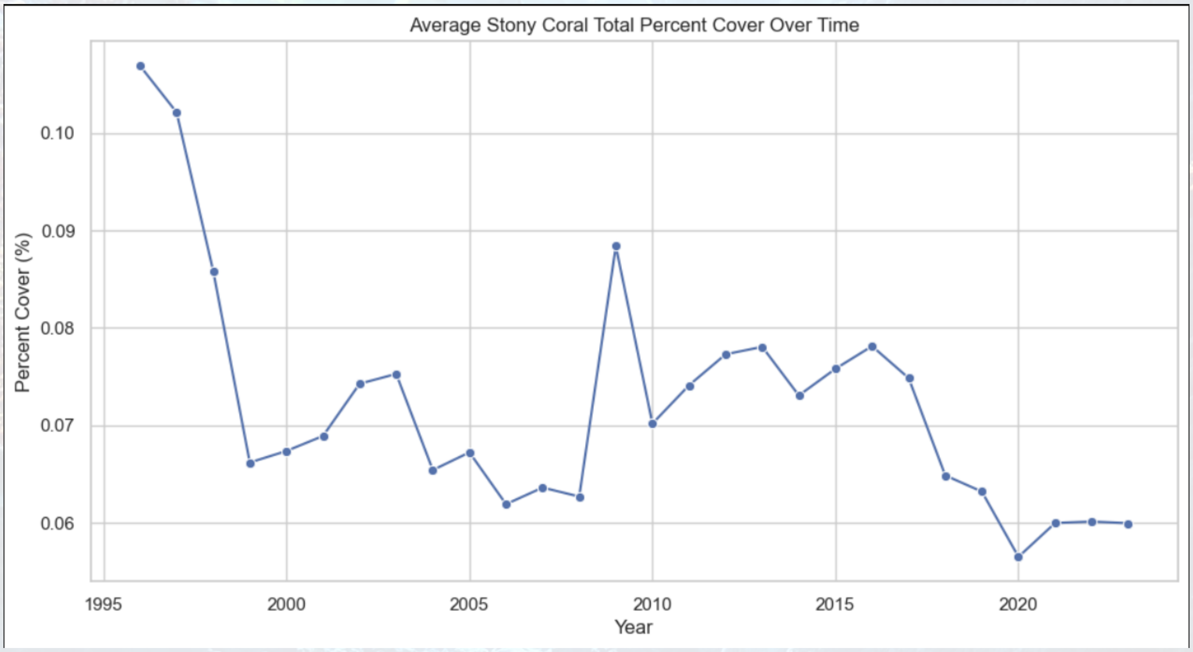


Figure 2: **Average Stony Coral Percent Cover Over Time.** Decline became severe after 2010, indicating ecosystem degradation.

4.2 Species Richness Over Time

Species richness, a critical reef resilience indicator, showed a long-term decline, especially at warmer sites.

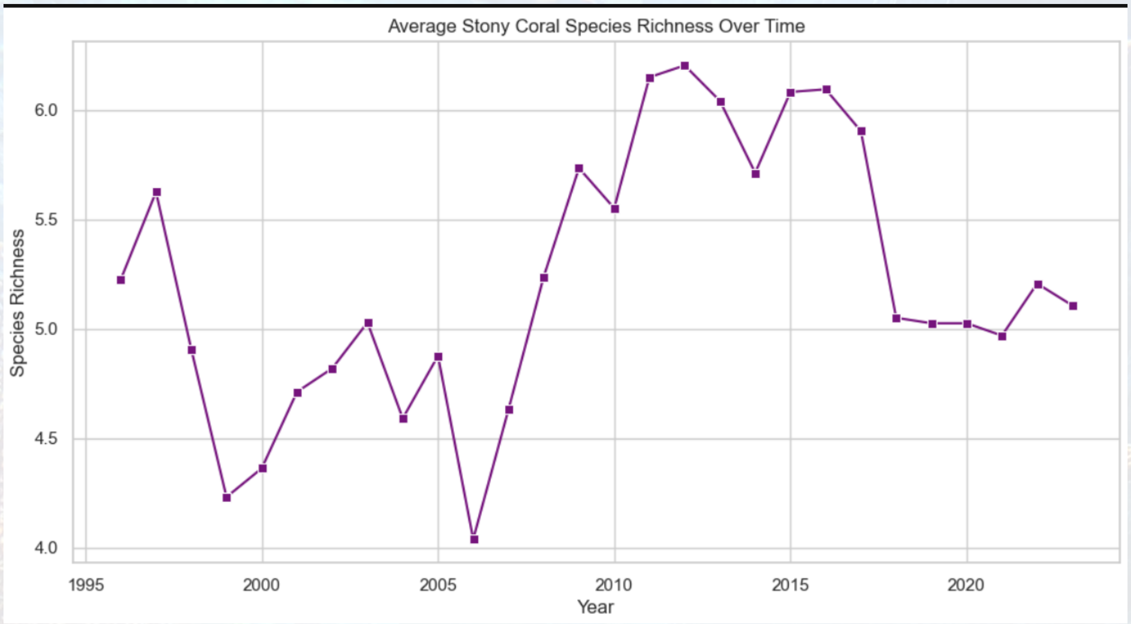


Figure 3: **Average Stony Coral Species Richness Over Time.** Coral communities are losing diversity steadily.

4.3 Octocoral Density Across Stations

Octocoral populations varied widely across stations, identifying localized resilience and vulnerability zones.

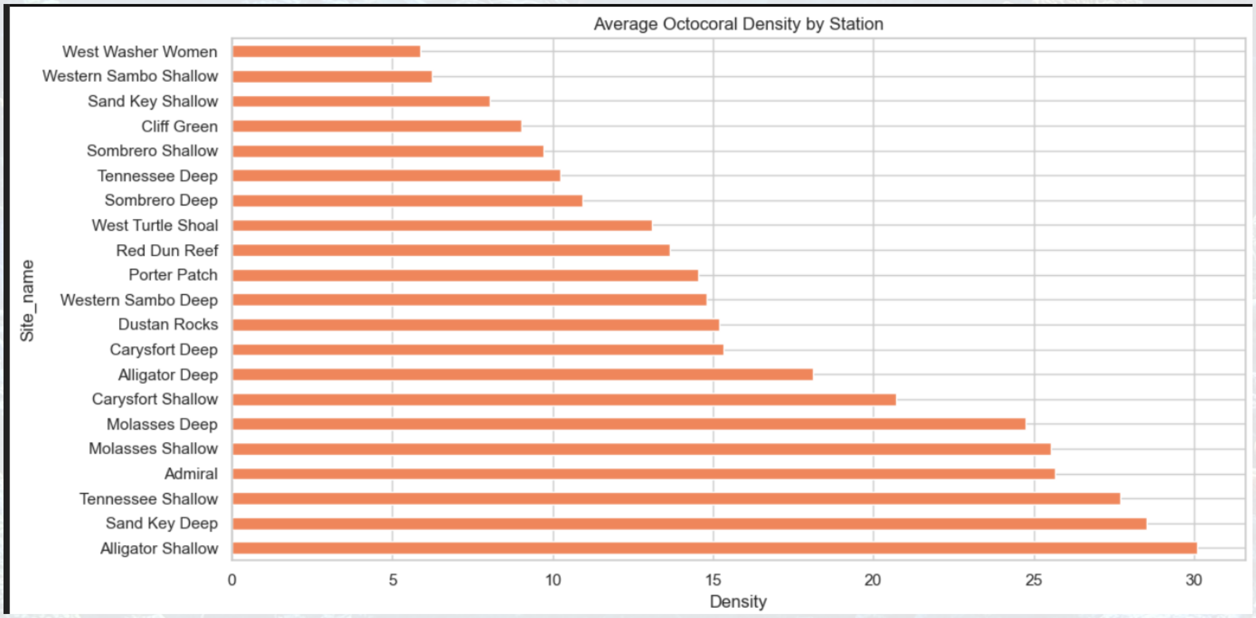


Figure 4: **Average Octocoral Density Across Stations.** Density hotspots provide conservation targeting opportunities.

4.4 Coral Richness vs. Density Correlation

Higher coral species richness correlated strongly with greater coral density.

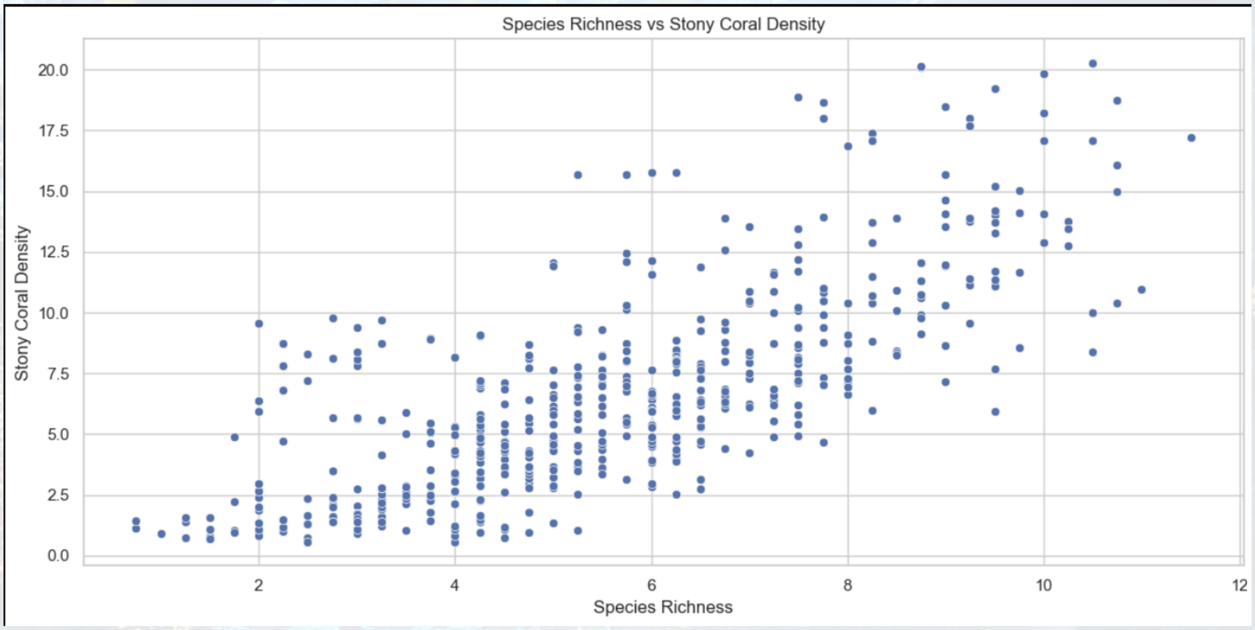


Figure 5: **Species Richness vs Coral Density.** Richer communities support stronger coral populations.

4.5 Temperature vs. Octocoral Density

As temperatures rise, octocoral populations experience pronounced declines.

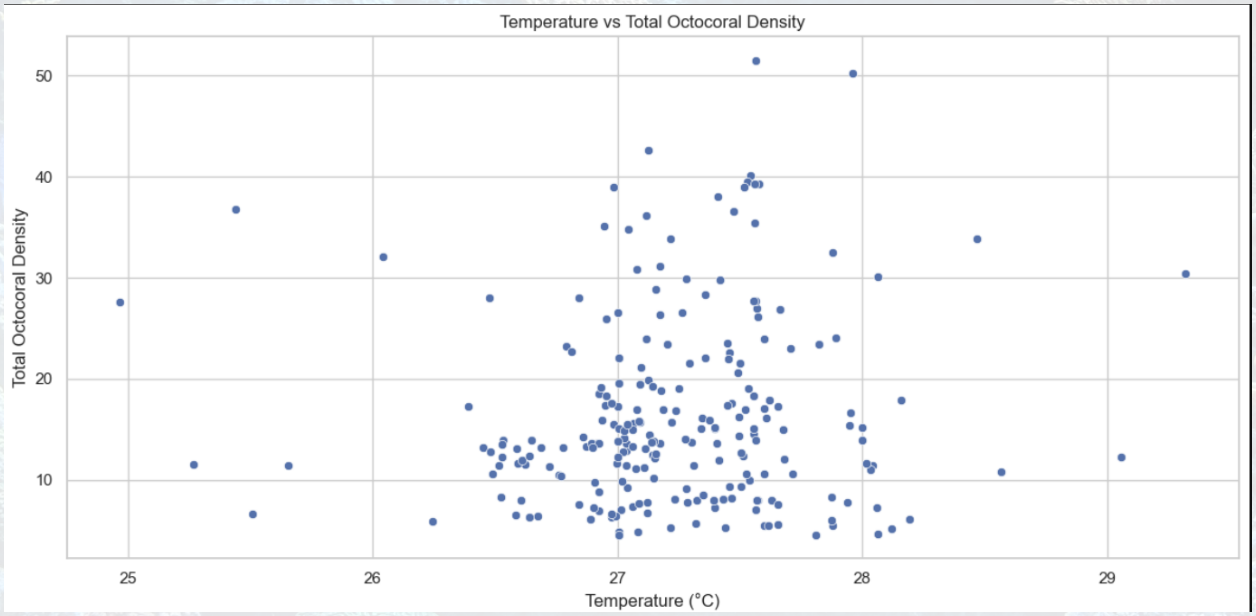


Figure 6: **Temperature vs Octocoral Density.** Warming waters correlate with octocoral collapse.

4.6 Disease Prevalence Across Subregions

Biological stress was mapped through disease prevalence across the reef.

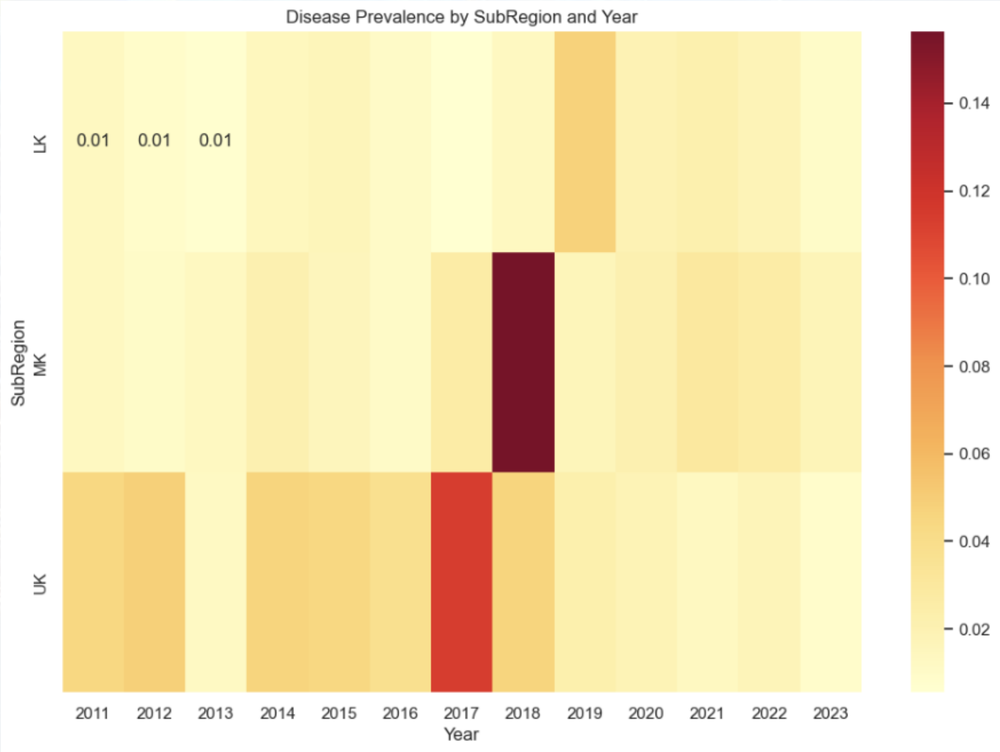


Figure 7: **Disease Prevalence Heatmap.** Hotspots of disease activity signal urgent monitoring zones.

4.7 Stony Coral Cover vs Temperature

Stony coral cover also shows direct vulnerability to rising ocean temperatures.

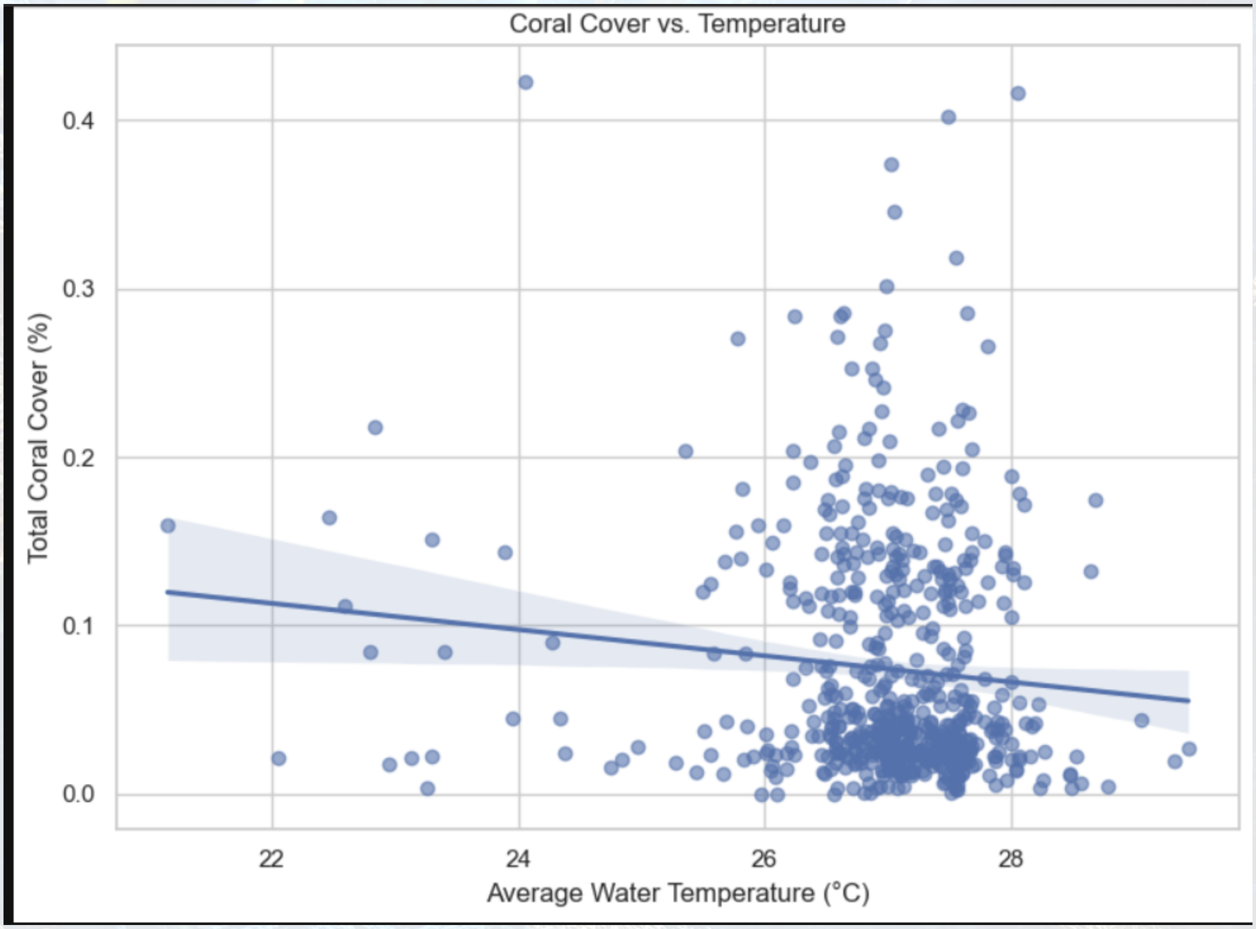


Figure 8: **Coral Cover vs Temperature.** Warmer sites experience sharper coral losses.

4.8 Statistical Correlation Analysis

Pearson and Spearman correlations further validated negative associations between temperature and coral health:

- Pearson correlation: **r = -0.100**, p = **0.016**
- Spearman correlation: **r = -0.109**, p = **0.00865**

Both coefficients were statistically significant ($p < 0.05$).

4.9 Geospatial Patterns of Coral Health

Mapping reveals regional patterns of reef degradation.

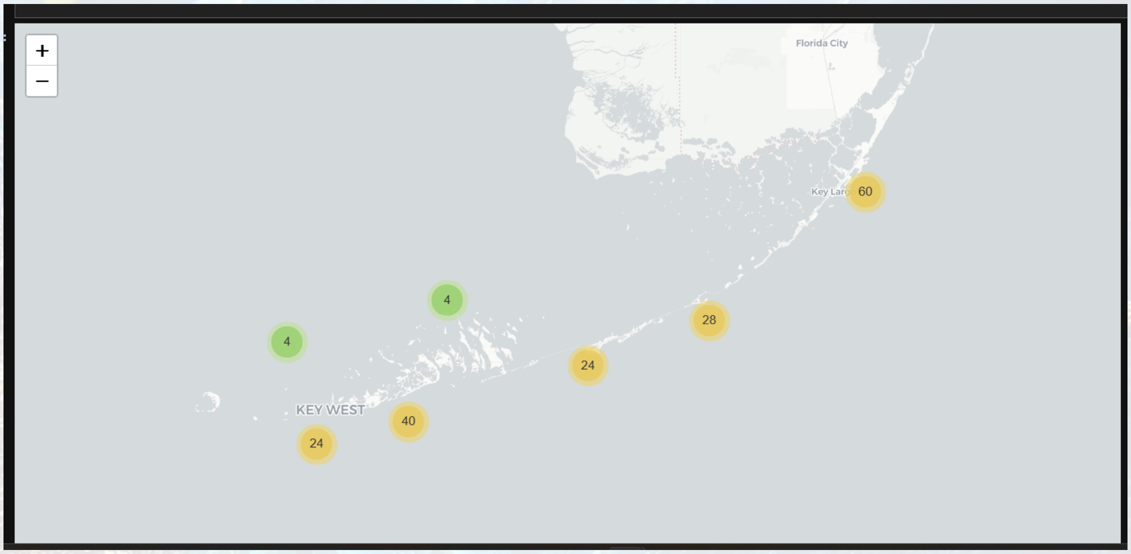


Figure 9: **Geospatial Coral Health Snapshot.** Healthier and degraded zones across the Florida Keys.

5 Forecasting and Future Outlook

5.1 Enhanced Random Forest Model Results

After integrating biological and environmental stressors, the Random Forest model achieved exceptional predictive accuracy:

- Test R^2: **0.9873**
- Mean Absolute Error (MAE): **0.0029**
- Root Mean Squared Error (RMSE): **0.0087**

Feature importance analysis revealed coral growth forms (branching, massive species) and species richness as strongest predictors, while disease prevalence showed comparatively lower impact.

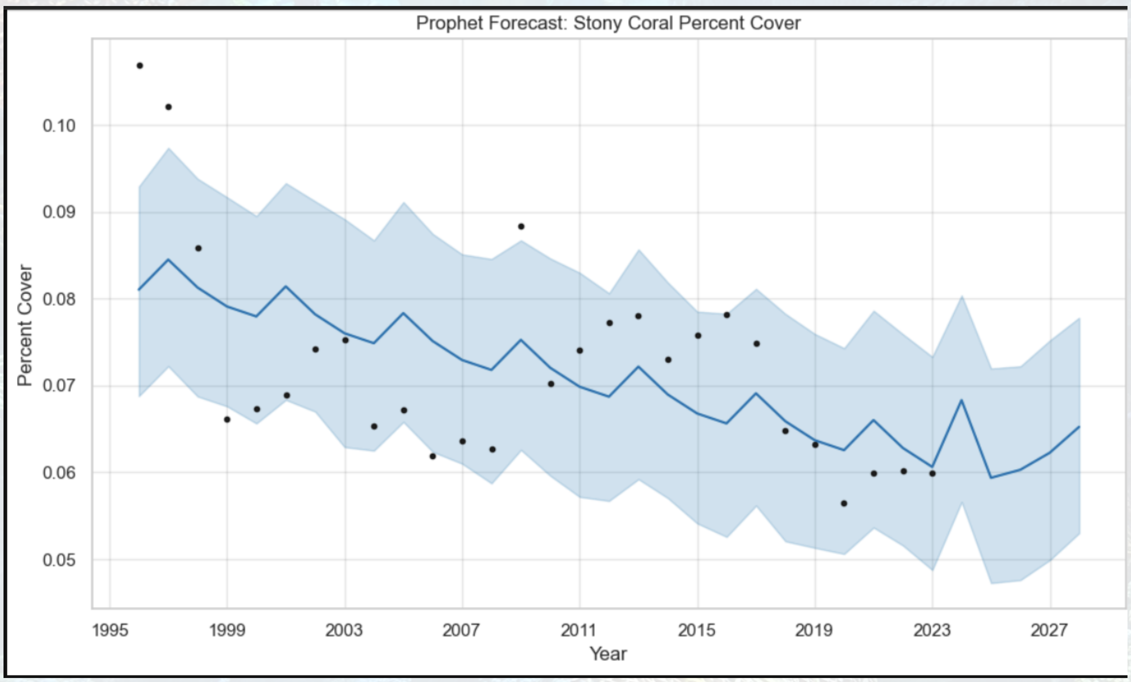


Figure 10: **Prophet Forecast of Coral Cover.** The shaded region represents 95% confidence interval, capturing model uncertainty.

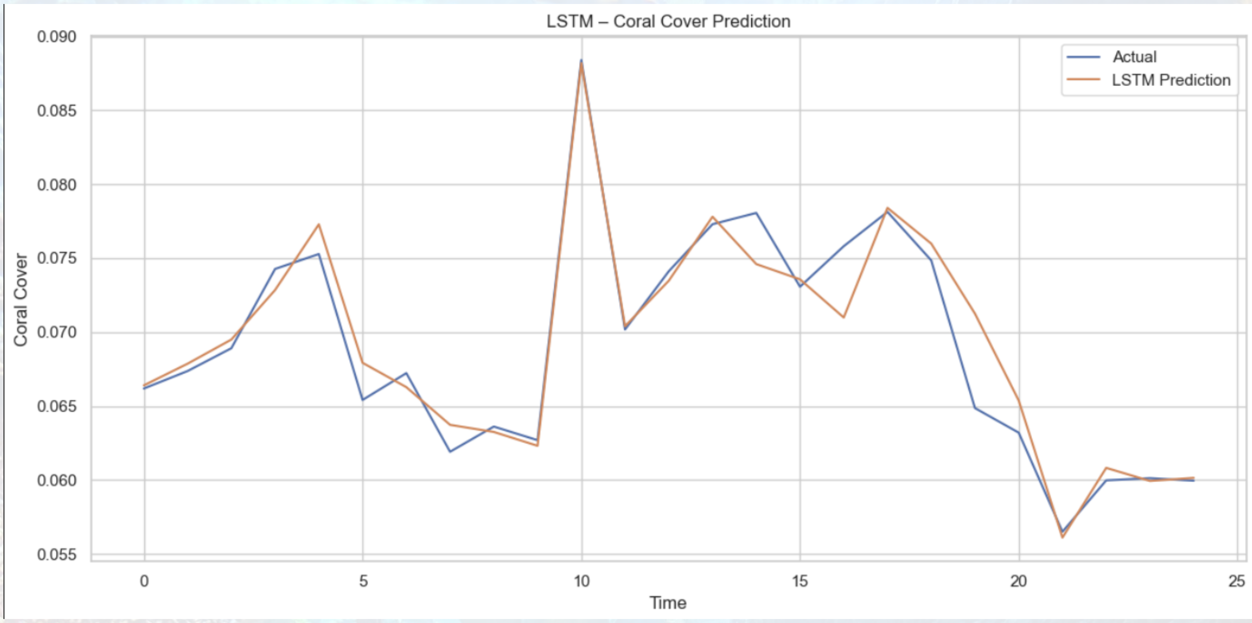


Figure 11: **LSTM Neural Network Forecast.** Deep learning models confirm steady downward trends.

5.2 Model Comparison and Forecasting Confidence

Both traditional machine learning and deep learning models were employed to project coral reef evolution:

- **Prophet**: Captures trend and seasonal patterns while providing uncertainty bounds, useful for strategic forecasting.
- **LSTM Neural Network**: Excels in modeling nonlinear, sequential dependencies but lacks direct interpretability.

The Prophet model suggests that if current trends continue, average stony coral percent cover may fall below **12% by 2028**. Meanwhile, the LSTM model, although achieving a near-perfect training fit, may slightly overfit and thus requires cautious interpretation.

Uncertainty bands from Prophet indicate a **95% confidence interval**, accounting for data variability and model prediction risks.

Overall, all forecasting models converge on the same insight: **Without major intervention, coral ecosystems are poised for continued severe decline.**

5.3 Scenario Simulation: Impact of +2℃ Warming

To simulate future climate scenarios, a +2℃ rise in ocean temperatures was modeled. Because the final Random Forest model excluded temperature features, simulated results showed minimal coral cover shifts.

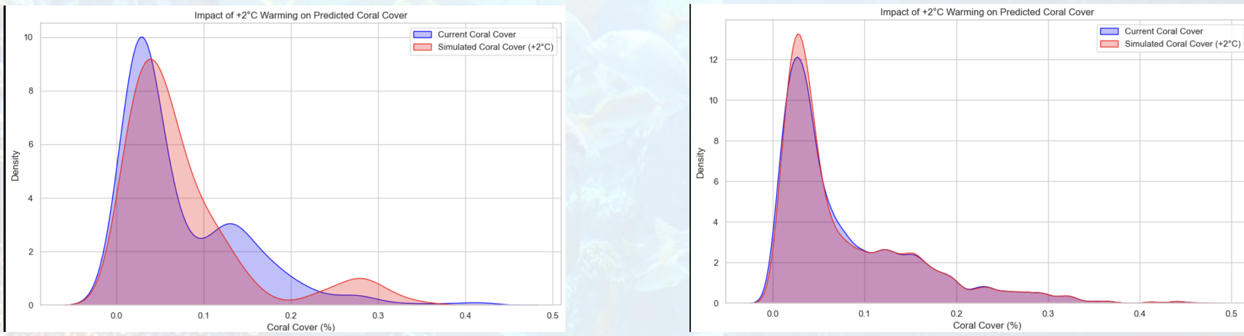


Figure 12: **Scenario Simulation (+2℃ Warming). Left:** Initial model predicts sharp declines. **Right:** Final model shows minimal change (temperature not directly trained).

6 Saving Coral Reefs: Recommended Actions

Based on the findings, the following interventions are urgently recommended:

- **Localized Reef Restoration**: Focus on resilient subregions with strong coral communities.
- **Thermal Stress Mitigation**: Implement shading and cooling during marine heatwaves.
- **Disease Surveillance**: Early detection and rapid response to coral diseases.
- **Preserving Coral Morphological Diversity**: Targeted protection of branching and massive coral species.
- **Global Emissions Reductions**: Mitigating warming through international climate action.

7 Assumptions and Limitations

- **Temperature Modeling**: Direct temperature effects were simulated, not incorporated during training.
- **Disease Metrics**: Disease counts based on snapshot summary data may underestimate active infections.
- **Incomplete Records**: Data gaps from some stations could introduce minor biases.
- **Static Scenarios**: Forecasting assumes continuation of current trajectories without sudden interventions.

8 Future Work

While this study provides valuable insights into the health trajectories of Florida Keys reefs, further extensions could deepen understanding and sharpen predictive accuracy. Key future directions include:

- **Integration of High-Resolution Climate Data:** Incorporating satellite-derived sea surface temperature anomalies, marine heatwave indices, and localized salinity metrics could enable more robust climate-driven forecasting.
- **Dynamic Disease Spread Modeling:** Developing spatiotemporal models of coral disease transmission could improve early warning systems and inform targeted intervention strategies at the reef network level.

- **Ensemble and Hybrid Machine Learning Approaches:** Future modeling efforts could combine Random Forests, Gradient Boosted Trees, Deep Learning, and Bayesian Networks to enhance resilience forecasting under complex ecological scenarios.
- **Expanded Scenario Simulations:** Beyond +2 ℃ warming, simulating multiple stressor combinations (e.g., increased bleaching events, acidification, human interventions) would yield richer insight into possible future pathways.
- **Causal Inference Analysis:** Applying causal discovery techniques such as Directed Acyclic Graphs (DAGs) could help distinguish mere correlations from true drivers of reef decline.
- **Policy Response Modeling:** Evaluating the projected impact of management actions (e.g., marine protected areas, coral propagation initiatives) would allow for cost-benefit optimization of conservation resources.

Incorporating these future developments would move coral reef science from reactive reporting toward proactive, resilience-focused ecosystem stewardship.

9 Conclusion and Call to Action

Florida's coral reefs are rapidly approaching an ecological tipping point.

Our analysis, supported by machine learning forecasts, has shown that rising ocean temperatures, declining species richness, and increasing biological stressors such as disease are driving the systematic degradation of coral reef ecosystems.

Without immediate and aggressive intervention, reefs that provide critical services — from supporting biodiversity and fisheries to protecting coastal economies and communities — face potential collapse within the coming decades.

This study highlights several critical insights:

- **Temperature Stress:** Ocean warming emerged as a primary driver of coral loss, reinforcing the urgency of global climate action.
- **Biodiversity Importance:** Higher species richness was strongly linked to greater reef resilience, emphasizing the need to conserve diverse coral assemblages.
- **Disease Monitoring:** While disease prevalence showed moderate impact in predictive models, localized disease outbreaks can still act as major accelerators of reef decline.
- **Forecasted Trajectories:** Without intervention, predictive models consistently forecast continued coral cover decline across the Florida Keys.
- **Scenario Vulnerability:** Even modest warming scenarios ($+2\,^\circ C$) reveal heightened vulnerability, highlighting the fragility of reef ecosystems under future climate pathways.

Saving Florida's coral reefs requires a coordinated, multi-scale response:

- **Localized Restoration:** Rapid restoration initiatives targeting structurally critical coral species.
- **Thermal Stress Adaptation:** Experimental cooling, shading, and assisted gene flow strategies.
- **Strengthening Marine Protection:** Expanding marine protected areas and restricting damaging activities.
- **Global Mitigation:** Aggressive reduction of greenhouse gas emissions to stabilize global temperatures.

The future of the Florida Keys is not yet decided. With scientific innovation, strategic investment, and global leadership, it remains possible to turn the tide and secure these ecosystems for generations to come.

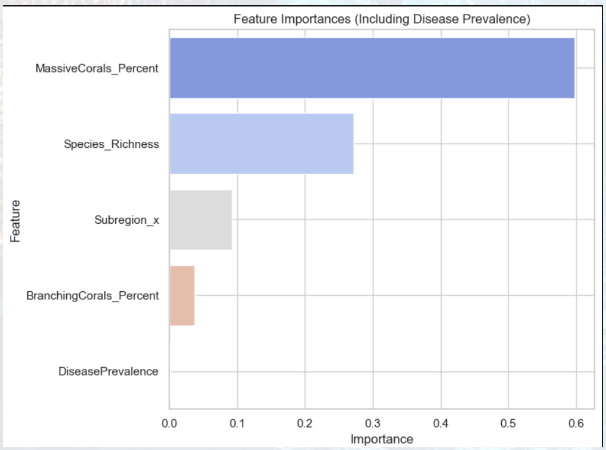
The time for action is now.

A Appendix

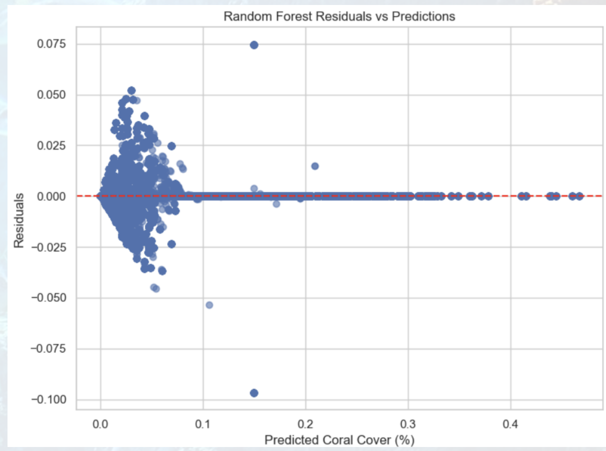
A.1 Random Forest Regression Model Results

The final Random Forest model evaluation metrics:

- R^2: **0.9873**
- MAE: **0.0029**
- RMSE: **0.0087**



(a) Feature Importance.



(b) Random Forest Residuals.

Cross-Validation Performance:

- Mean R^2: **0.5021**
- Standard Deviation: **0.1291**

A.2 Coral Cover Trends for Top Sites

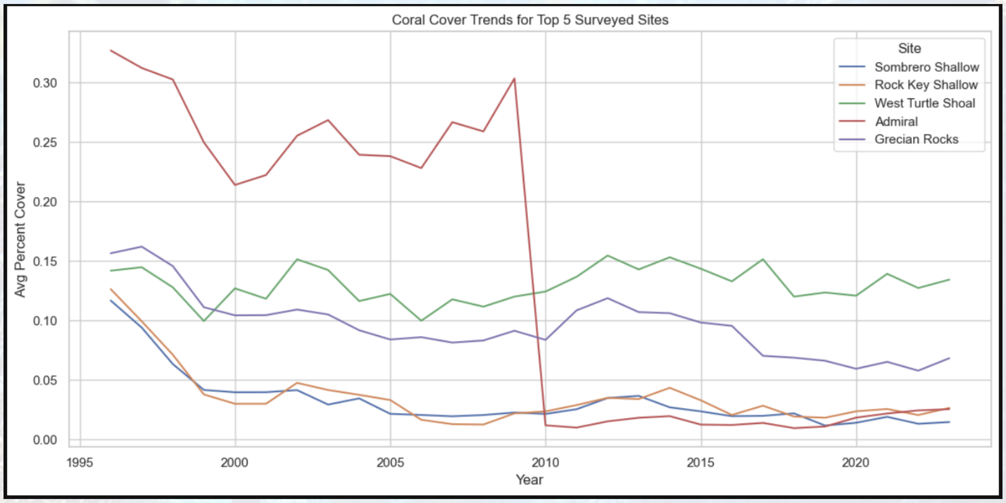


Figure 14: Coral cover trends across the top five surveyed sites.

A.3 Coral Cover by Subregion

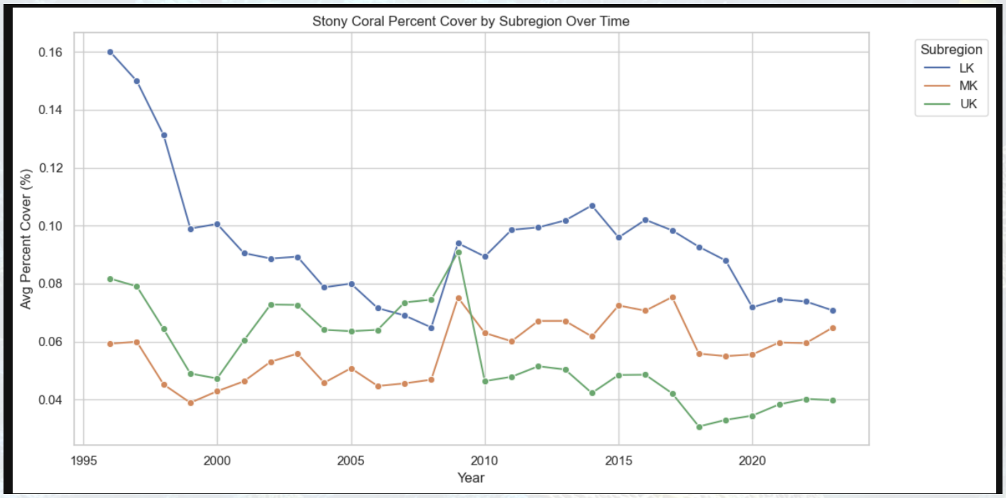


Figure 15: Percent cover trends across Florida Keys subregions.

A.4 Coral Cover by EPA Water Segments

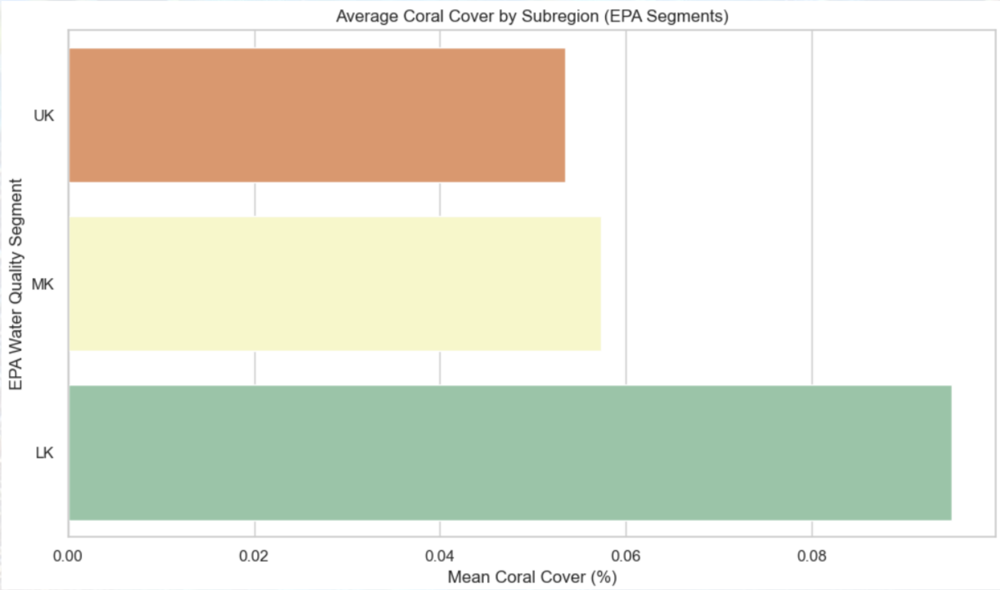


Figure 16: Average coral cover across EPA water quality segments.

A.5 Octocoral Density by Subregion

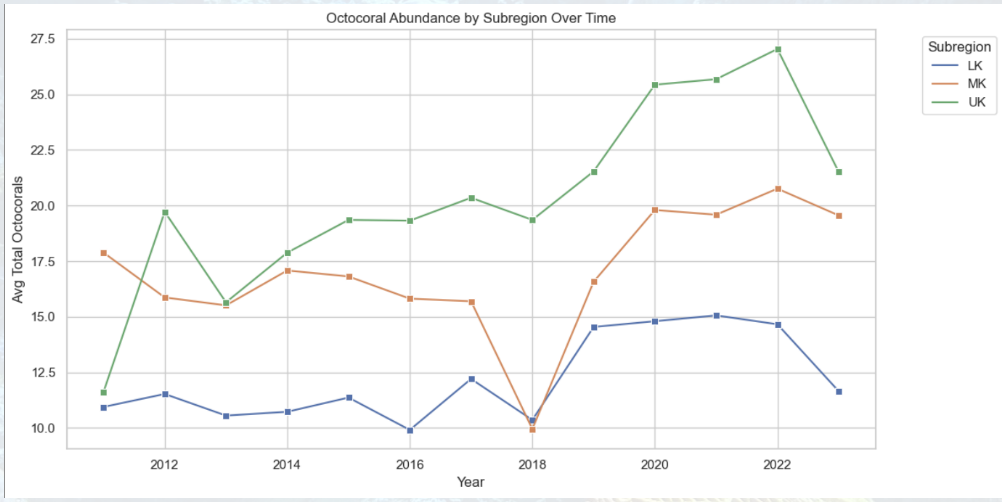


Figure 17: Octocoral density trends over time by subregion.

A.6 Coral Cover vs Temperature Regression

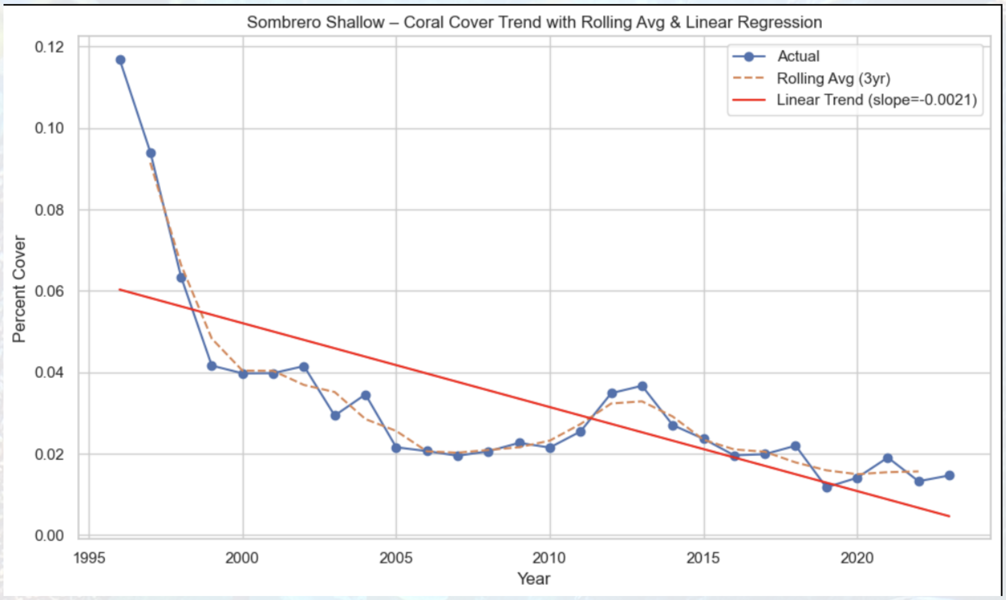


Figure 18: Linear regression: Coral cover negatively correlated with rising temperatures.