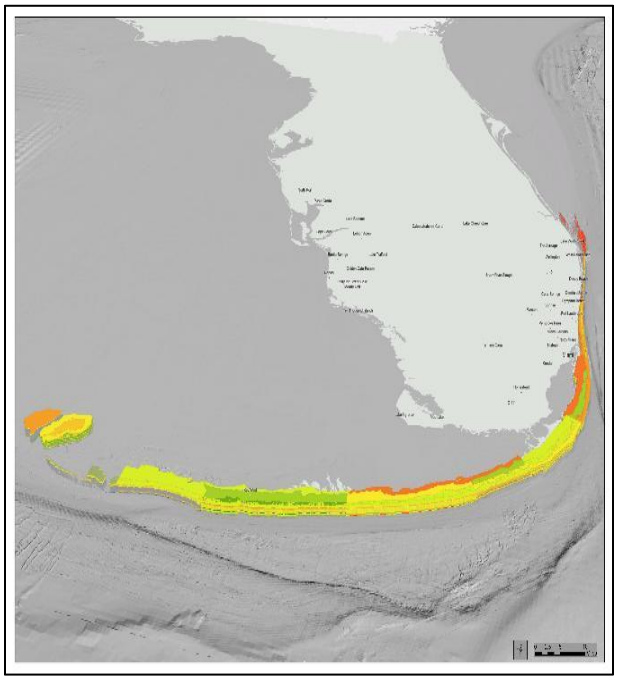
Calibration of the Biological Condition Gradient (BCG) for Florida's Coral Reef: Phase 2

Final Report



Florida Department of Environmental Protection
Coral Protection and Restoration Program

Calibration of the Biological Condition Gradient (BCG) for Florida's Coral Reef: Phase 2

Final Report

Prepared By:

Maya Becker[1], Ben Jessup[2], Patricia Bradley[2], and Brian K. Walker[1]

[1]Nova Southeastern University, Halmos College of Arts and Sciences, 8000 N. Ocean Drive, Dania Beach, FL 33004-3078
[2]Tetra Tech, Inc, Complex World, Clear Solutions, 73 Main Street, #38, Montpelier VT 05602

June 15, 2026

Completed in Partial Fulfillment of PO C5C9DD for

Florida Department of Environmental Protection
Coral Protection and Restoration Program
8000 N Ocean Dr.
Dania Beach, FL 33004

This report should be cited as follows:
Becker M., Jessup B., Bradley P., and Walker B.K. 2026. Calibration of the Biological Condition Gradient (BCG) for Florida's Coral Reef: Phase 2 Final Report. Florida DEP. Miami, FL. 108p.

This report was prepared for the Florida Department of Environmental Protection, Coral Protection and Restoration Program by Nova Southeastern University. Funding was provided by the Florida Department of Environmental Protection Award No. C5C9DD. The views, statements, findings, conclusions, and recommendations expressed herein are those of the authors and do not necessarily reflect the views of the State of Florida or any of its sub-agencies.

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List of Acronyms

BCG	Biological Condition Gradient
CREMP	Coral Reef Evaluation and Monitoring Project
DEP CPR	Florida Department of Environmental Protection's Coral Protection and Restoration Program
DRM	Disturbance Response Monitoring
EPA	United States Environmental Protection Agency
FCR	Florida's Coral Reef
FRRP	Florida Reef Resiliency Program DRM Disturbance Response Monitoring
FWC	Florida Fish and Wildlife Conservation Commission
GIS	Geographic Information System
KJCAP	Kristin Jacobs Coral Aquatic Preserve
NCRMP	National Coral Reef Monitoring Program
NPS	National Parks Service
NOAA	National Oceanic and Atmospheric Administration
NSU	Nova Southeastern University
SCTLD	stony coral tissue loss disease
SECREMP	Southeast Coral Reef Evaluation and Monitoring Project
SFCN	South Florida and Caribbean Network

Acknowledgements

Thank you to the Florida Department of Environmental Protection's Coral Protection and Restoration Program (DEP CPR) for supporting these efforts and funding the initial BCG model build to TetraTech, award No. WQ168. Funding for the second round of BCG updates and spatial analyses was provided to NSU by Florida's DEP CPR through award No. C5C9DD. Special Acknowledgments to Nicholas Jones for assisting in the second phase of the BCG.

Management Summary (300 words or less)

This project updated the Florida Biological Condition Gradient (BCG) model with recent data, held virtual training sessions for managers and stakeholders, investigated BCG differences between monitoring programs, and conducted a spatiotemporal analysis of the BCG to investigate broader patterns of reef condition. Three training webinars were held for reef managers and assessment practitioners to facilitate application of the BCG model for new samples. The webinars provided an overview of the BCG, explained data management and preparation, and demonstrated data input into the BCG model calculation tool.

NCRMP, DRM, and CREMP reef data collected since the BCG calibration project were compiled, formatted, and aggregated with existing BCG model data. Combining all monitoring program data into one analysis created artifacts due to differences in site selection, survey locations, methodology, unequal sampling effort, sampling different times of year, and differences in metrics collected. When programs were analyzed separately, spatiotemporal patterns emerged in multiple datasets.

Differences between strata scores were evident in all programs indicating that the Mid Channel reefs and Offshore patch reef were in better condition than the forereef and inshore sites. The randomized surveys performed better at detecting temporal declines. CREMP BCG scores were stable over time but varied significantly by strata. DRM and NCRMP had noticeable increasing BCG scores between 2021-2024 across all strata coinciding with the SCTLD endemism and the 4th global bleaching event. The Dry Tortugas had the lowest historical scores of any region but, in the last few years BCG scores climbed significantly, indicating measurable reef condition decline. The declining BCG scores suggest that the frequency of stressors is outpacing the capacity of the reef to recover naturally. We provide a list of management recommendations including standardizing randomized monitoring surveys by adding benthic cover to DRM and conducting NCRMP annually to create the most robust holistic monitoring dataset that could be used by all. We provide several recommendations on maintaining and continued development of the BCG model.

Executive Summary

This project updated the Florida Biological Condition Gradient (BCG) model with recent data, held virtual training sessions for managers and stakeholders, investigated BCG differences between monitoring programs, and conducted a spatiotemporal analysis of the BCG to investigate broader patterns of reef condition. A presentation was given to the Disturbance Advisory Committee (DAC) on January 7, 2026, to describe project activities and announce that training webinars were being scheduled. In early February, emails for webinar participants of potential interest were drafted, and electronic invitations were sent. The participant invitation list was compiled from existing lists of experts, practitioners, and stakeholders involved in Florida reef monitoring and assessment activities, including the experts who were involved in calibration of the Florida reef BCG model, and regular attendees of the DAC. The webinars were held on March 2 (9 participants), April 8 (9 participants), and May 12 (5 participants). The webinars provided an overview of the BCG, explained data management and preparation, and demonstrated data input into the BCG model calculation tool.

NCRMP, DRM, and CREMP reef data collected since the BCG calibration project were compiled, formatted, and aggregated with existing BCG model data. Combining all monitoring program data into one analysis created artifacts due to differences in site selection, survey locations, methodology, unequal sampling effort, sampling different times of year, and differences in metrics collected. Differences in sampling effort across months within a sample year also varied significantly across programs. The CREMP program conducted over 66% of the surveys between May and the end of July and month had a significant effect on the BCG scores. Over 75% of DRM surveys were conducted after August 30. NCRMP sampling window peaked in August and September with over 50% of surveys conducted in those months, about 30% before August, and 20% after September.

Large differences in sample effort within and between programs has occurred over time creating uneven distribution of effort across space and time that can influence many aspects of data analyses and should be considered with caution. CREMP demographic collections started in 2011 at a limited number of sites but were very consistent between 2014 and 2024. DRM had extremely low sample counts of less than 100 sites in 2005, 2020, and 2021. In 2020, DRM effort doubled to around 400 samples and in 2023-2025 increased to about 600 samples. NCRMP is a biennial survey by region, but this was not always the case. In 2014, over 400 sites were sampled across the FCR. In 2015, 100 sites were sampled. In 2016 and 2018, about 300 sites were sampled, but in 2020 less than 100 were collected in the KJCAP and in 2021 about 150 were collected in the Keys. In 2022 about 350 samples were collected and in 2024 over 500. Combining program data produced a striping artifact in the analyses due to the unequal sampling size, particularly with NCRMP biennial sampling. Mean BCG scores were significantly different between programs; therefore, spatiotemporal patterns were analyzed within each program separately.

Differences between strata BCG scores were evident in all programs indicating that some subregion habitats were in better condition than others. This was very noticeable with the

Mid Channel reefs and Offshore patch reef having lower scores than the forereef and inshore sites.

DRM had the longest historical time series and showed a noticeable rise in the probability of a BCG 5 across all strata since 2019. This rise coincided with an increase in sample effort but also with SCTLD and the 4^{th} global bleaching event. The DRM Space Time Cube and Emerging Hot Spot analyses showed sporadic and diminishing hot spots in the Upper Keys and Biscayne National Park subregions and the Palm Beach subregions had consecutive cold spots. Both cluster patterns indicate a declining reef condition due to the presence of high surrounding BCG scores through time. Biscayne's diminishing hot spots indicated that reef condition declined for at least 19 out of the 21 sample years based on BCG scores and the amount of declined reef sites is steadily decreasing over time. These declines coincide with increasing urbanization and development of the nearby city and port of Miami that produces large amounts of groundwater runoff, pollution, increases sedimentation loads, and more.

DRM BCG scores showed the Dry Tortugas coral communities had historically been in the best condition relative to the rest of the FCR, however, BCG scores climbed significantly in the last few years, indicating measurable reef condition decline. This change coincided with the emergence of SCTLD in 2021 and the recent impacts of the 4^{th} global bleaching event, notably in 2023. BCG scores indicate that the severity and abundance of marine stressors to this region may have hit a tipping point.

NCRMP BCG scores averaged higher than any other program, but showed consistent spatiotemporal patterns. NCRMP showed most consistent declines in reef condition since 2016 than DRM with higher probabilities of a BCG 5 until 2026 where the probability of being a BCG 6 became very high. This may be due to the inclusion of macroalgae in the surveys as stony coral cover has been consistently declining in every region with corresponding increases in macroalgae cover. NCRMP BCG scores also showed in the Dry Tortugas and Martin County corroborating the DRM results. The increasing presence of hot spots around the Dry Tortugas suggests a significant declining condition in the region.

CREMP BCG scores were mostly stable over time but varied significantly by strata, especially in the inshore and forereef zones which were generally higher than most other subregion-zones based on the random forest model. Lower Keys offshore reef sites tend to possess lowered water clarity than its neighboring zones, suggesting water quality may be a contributing factor to declining reef conditions and in turn higher BCG trends experienced in the inshore and forereef zones of the Lower Keys.

The declining BCG scores suggest that the frequency of stressors is outpacing the capacity of the reef to recover naturally. The randomized surveys performed better at detecting temporal declines. CREMP BCG scores were stable over time but varied significantly by strata. DRM and NCRMP had noticeable increasing BCG scores between 2021-2024 across all strata coinciding with the SCTLD endemism and the 4^{th} global bleaching event.

Our analyses showed that combining all monitoring program data into one analysis created artifacts due to the varying sampling effort, methodologies, and time of year. We recommend that the program managers and their senior scientists take a serious look at how to leverage each randomized program to create the most robust holistic monitoring dataset that could be used by all. Adding benthic cover to DRM and conducting fewer NCRMP sites annually would create the most robust holistic monitoring dataset that could be used by all.

We also recommend the following: Ensure the BCG decision rules work both ways, collect consistent juvenile data across programs, develop separate numeric rules for the KJCAP region, develop a reef fish BCG for Florida, maintain the current coral data on Florida's DSS, maintain the Florida reef story map (Florida Coral Reef BCG), investigate using BCG as biocriteria in FL's WQ program, develop narrative rules for BCG Levels 1 and 2, develop a generalized stressor axis (GSA) for Florida, possible use of flags, and utilize BCG scores to identify areas for restoration.

1. BACKGROUND

Florida's Coral Reef (FCR) is uniquely located in proximity to some of Florida's largest metropolitan cities: Ft. Lauderdale and Miami. Urbanization hot spots present a set of challenges to the marine scape as anthropogenic stressors from pollution runoff, increased nutrient loads, overfishing from commercial and recreational fisheries, and agricultural waste continues to mount against FCR urbanization progresses (Principe et al., 2011). Continuous multi-faceted anthropogenic threats to the marine ecosystem ultimately hinder the ecosystem's ability to function properly, leading to large-scale declines in ecosystem function and resiliency (Santavy et al., 2022a). Coral reefs are inherently valuable due to the many essential ecosystem services humans have come to rely on in the forms of coastal protection from storms and wave energy, food and job security supported through a large fishing industry, and tourism (Woodhead et al., 2019). It is estimated that Florida's corals have immense economic value as they contribute billions of dollars to economies while reaching over 500 million individuals globally at the national, regional, and local levels (Santavy et al., 2022b). Recent decades have brought some of the most disruptive threats to FCR with the outbreak of a highly lethal disease, stony coral tissue loss disease, in 2014 followed by some of the most intense bleaching events Florida has ever experienced in the following years of 2015-2017 (Robertson et al., 2023; Powell, 2024). The frequency and scale of anthropogenic stressors have slowly been increasing over time, making it inherently difficult to track and effectively manage, giving way for a tool that can manage and model rapid declines in reef health (Robertson et al., 2023).

The Biological Condition Gradient (BCG) is a gradient model of increasing anthropogenic stress to describe the state of the marine system (Bradley & Jessup, 2024). The BCG utilizes a unique tool of expert narrative approach which helps guide existing knowledge into a modeled framework for coral reefs that can assist monitoring and site-restoration activities (Moore et al., 2022). The use of expert elicitation has been a popular choice for various disciplines like the public health sector, engineering, and of course, natural resource management like water quality (Moore et al., 2022; Colson & Cooke, 2018). Large scale degradation among FCR is due to multifaceted issues declining the system at a rate faster than we can effectively study and research, thus a narrative based expert approach to the problem is ideal to help combat the issues of fast growth and lack of empirical data (Robertson et al., 2023; Moore et al., 2022). Utilizing expert advice in the marine space helps combat the biggest issues where uncertainty and data gaps are common, while synthesizing our current understanding of the state of the system (Robertson et al., 2023). Naturally, when discussions among experts in the field develop, so do natural ecological definitions and thresholds that help define the problem or state of the system in a more realistic fashion, especially for management purposes (Martin et al., 2009). The narrative approach method can better direct prioritization of monitoring programs or restoration areas and are best suited to understand and appropriately incorporate sources of uncertainty (Moore et al., 2022). Primarily, the expert consensus aids in reducing uncertainty through utilizing a medium based approach, which is ideal in this setting as the group of experts have high confidence and behave independently of others in their reasoning (Runge et al., 2011; Hora et al., 2013).

Employing an expert elicitation approach is still met with nuance as structural and analytical interpretive biases persist within this application (Moore et al., 2022). Even the most experienced groups of experts are met with variation amongst other experts (Runge et al., 2011). In calibration for the BCG in Florida, it was reported that common constraints for their process included lack of availability of both sample data and experts available relating to benthic assemblages (Bradley & Jessup, 2024). While steps were taken to mitigate variation amongst the group as much as possible, variability in reasoning behind selected BCG attributes and levels from experts was a big constraint for model development. (Bradley & Jessup, 2024). While it is impossible to remove all bias from the group consensus, expert elicitation can be very beneficial in helping to better prioritize restoration activities, translating technical data into user friendly narrative rules or classes, and are better equipped and knowledgeable about making decisions with uncertainty in the data (Moore et al., 2022).

Originally created for water quality systems, the BCG was adopted to help manage coral reef conservation in the Caribbean, and now Florida through assessing ecological integrity of four main components: resiliency, diversity, pristineness, and nativeness (Principe et al., 2011; Schallenberg et al., 2011). The BCG model was adapted to Florida through site-specific evaluations of quantitative data using species size-structured abundance, community structure, and benthic habitat composition to develop numeric decision rules that distinguish between the differing BCG levels (Bradley & Jessup, 2024). For the Florida BCG, the model utilizes long term monitoring program data, some which began back in 1996 spanning hundreds of sites across southeast Florida and the Dry Tortugas. The BCG model today is made up of 5 different biological monitoring programs: the Southeast Coral Reef Evaluation and Monitoring Project (SECREMP) that is monitored by the National Coral Reef Institute at Nova Southeastern University Oceanographic Center; the Coral Reef Evaluation and Monitoring Project (CREMP) that is managed by the Florida Fish and Wildlife Conservation Commission (FWC); the National Coral Reef Monitoring Program (NCRMP) who is managed by the National Oceanic and Atmospheric Administration; the Florida Reef Resiliency Program (FRRP) Disturbance Response Monitoring (DRM), which is managed also by the Florida Fish and Wildlife Conservation Commission (FWC); and the South Florida and Caribbean Network (SFCN) which is monitored by the National Parks Service (NPS).

The BCG scale is represented using a stressor-response curve with discrete intervals depicting stress, starting with level 1 being considered pristine conditions in the absence of measurable stressors, up through level 6 which signifies significant disturbance, changing structure and function of the original community (Figure 1) (Bradley & Jessup, 2024). The numeric decision rules originally created by the expert panel were used as an accuracy check that the model could be verified against. The BCG performed well during these test runs with up to an 83% model validation rate that was also able to predict all scores within 1 level of the expert consensus. (Bradley & Jessup, 2024).

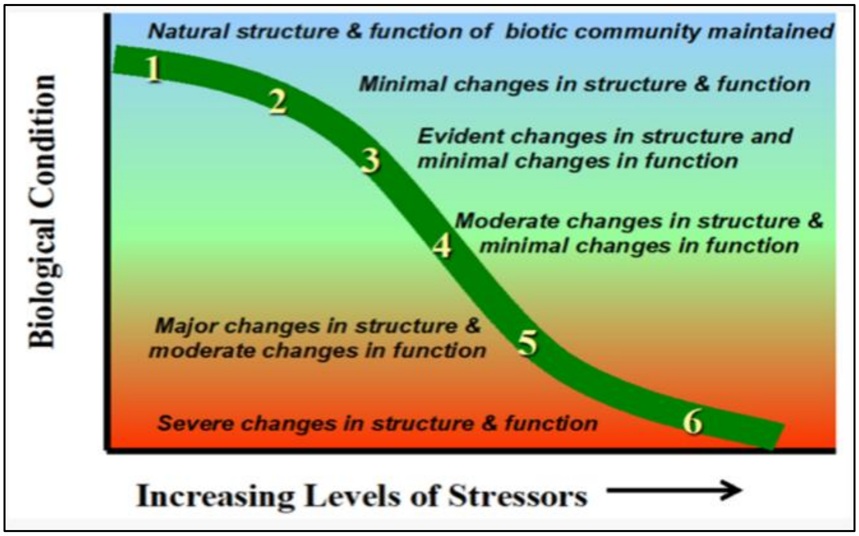

Figure 1. The BCG Gradient Scale represented in a graph of incremental levels of change experienced on a system from anthropogenic stressors (from: Bradley & Jessup, 2024).

Level 1 depicts pristine or pre-industrial conditions which mimic as close to the original, untouched ecosystem as possible. Level 2 portrays some minimal changes in the structure of the biotic community with little change in ecosystem functioning; this level is supposed to represent the earliest significant changes in densities, species composition, and biomass. Level 3 is the lowest site grade that exists in the BCG dataset so far and suggests changes in structure have occurred due to the loss or shifts of relative abundance of highly sensitive taxa. Level 4 describes marine environments that have had moderate changes in structure due to replacement of most but not all of the intermediate sensitive taxa to more tolerant taxa. Ecosystem function at level 4 is also largely maintained through this level. Level 5 possesses major changes to the structure of the biotic community such as most sensitive taxa are greatly diminished or missing along with organism stress and have moderate changes in ecosystem function which can include functional loss of sensitive taxa and keystone species. Lastly, level 6 describes a level of extreme environmental stress which is reflected in extreme changes in biotic structure such as wholesale changes in taxonomic composition and major loss of ecosystem function as they are severely depleted from stressors (Bradley & Jessup, 2024).

The FL BCG model includes all sites in existing monitoring programs between the 1990s up until 2021. These resulting scores have yet to be analyzed in a broader context of spatiotemporal impacts on Florida's coral reefs. Identifying spatial patterns can identify areas of concern, whereas identifying historical trends can help determine the trajectory of conditions over time. This information can be used to improve local conditions for corals and identify locations to focus restoration efforts.

The goals of this project were to update the BCG model, train managers and stakeholders on its use, and evaluate the BCG as a useful metric in quantifying changes in reef condition across Florida.

2. METHODOLOGY

2.1. **Training Workshops**

Three video conference training sessions, or webinars, were conducted for local managers and stakeholders to utilize the BCG model. Training sessions were held on data management and preparation, inputting data into the BCG model calculation tool, and assistance in interpretation of the results. Trainees received materials prior to the training calls, including agendas; presentations for background, procedures, and interpretations; handouts for data formatting; links to on-line automated BCG calculation tools; and reports or other documentation for interpretation of results.

2.2. **Data Compilation and QA/QC**

BCG assessment results existed for thousands of sites from the five main monitoring programs in Florida between 2005 and 2021. To update this database, 2022 – 2024 NCRMP, DRM, and CRMP reef data were compiled and formatted, including coral and benthic cover statistics, site information, and sample metadata. These data were aggregated with existing BCG model data, and BCG scores were calculated for all new sample sites.

Importing data into the BCG calculation tool (BCGcalc) requires a specific format. Tetra Tech's experience in creating and developing the model provided the ability to recognize and solve potential errors in the data and formatting that cause incorrect BCG model calculations.

The QA review resulted in minor corrections in field naming conventions in addition to two important QA corrections. The designation of juvenile coral colonies was a big problem between datasets. According to field survey protocols, the "Juvenile" designation was assigned to coral colonies less than 4 cm in diameter. For all colonies reported as "Juvenile" without dimensions, default dimensions were added so that coral tissue area could be calculated (as required for several model metrics). The default dimensions were 3 cm maximum diameter, 2 cm perpendicular diameter, and 1 cm height.

Another important correction was for transect length associated with each sample because this metric is used for density calculations. Transect lengths were initially assumed to be standard as described in field survey protocols. However, the actual transect length was available in the sample metadata. The actual length was used instead of the initially entered standard/prescribed length. It was also important to ensure that transect lengths were consistent for all entries within a sample. In other words, no variation in transect length is possible for a sample.

2.3. **Updating BCG Scores**

There is a two-step approach to updating the BCG model with new scores. The first step entails filling out the data fields and obtaining the coral taxon identifications (Taxa ID) for each entry of the raw datasets before computing new scores with the model. The model may flag the dataset as not ready due to missing core input fields. Each dataset must have the following data fields: Sample ID, Taxa ID, Total Transect Length, Juvenile Coral Designation, Maximum Diameter, Perpendicular Diameter, Height, and Total Percent Mortality. Once all parameters have been validated by the model, a corresponding taxa translator file is produced that becomes the source dataset for the actual BCG calculations following. This is an iterative part of the first step as the model will continue to check the field names and coral Taxa IDs and flag the dataset as not ready until each flagged Taxa ID is addressed for their issues, namely misspellings, and re-ran within the model.

The second step entails updating the BCG scores using the newly QA/QC'd taxa translator file from step one which assesses each site and scores them based upon the narrative rules set in the BCG model. The output file for the score calculation includes the resulting BCG scores, original input data, and reference files.

Updated BCG scores were completed for all monitoring programs: CREMP KEYS, SECREMP, CREMP DRY TORTUGAS, NCRMP, and FRRP-DRM (DRM) (Table 1). The CREMP and NCRMP programs' scores were updated to include 2024 data. DRM was updated to include 2025 data.

Table 1. List of all monitoring programs used to update the BCG scores with the latest monitoring data and their temporal extents.

SECREMP	2013-2024
CREMP KEYS	2011-2024
CREMP DRY TORTUGAS	2011-2024
NCRMP	2014-2024
DRM	2005-2025

2.4. **Designation of Spatial Strata**

Due to the abundance of levels within each categorical predictor, a random forest model was selected as an ideal test to run in order to help determine the most optimal spatial designations for the BCG scores. To analyze the BCG scores, associating coral habitat zone strata provided by DRM was associated to each monitoring program's BCG scores. Data were procured by privately contacting the data coordinator for DRM's data portal and using their zone strata datasets, characterizing reef areas for site selection based on features that are classified based off cross shelf positions, distances from shore, and depth (Harrell et al., 2022). The DRM strata have four spatial designations that can be used to stratify the BCG scores: regions, subregions, zones, and subregion-zone (zone strata split by subregions longitudinally).

Random Forests are a type of supervised machine learning algorithm that are best suited to handle large amounts of data dominated by categorical factors like the BCG dataset (Fernandez, 2021). A classification style random forest model was used to account for the categorical nature of the BCG scores and the large scale of the dataset. A random forest classification style is a decision tree prediction process that breaks the dataset down into smaller subsets based on the predictor variables and votes the most popular variable response as the significant factor (Boehmke & Greenwell, 2020). The results of the random forest model provide an error index known as the mean decrease in accuracy that identifies the importance of a predictor, known as the variable importance metric, based on the impurity of the decision tree splits across the entire model (Benard et al., 2022). The higher the mean decrease in accuracy value, indicated that a certain predictor had a more "pure" split in the decision tree prediction process than other factors leading to that predictor being designated as the most significant contributor to the response outcomes (Breiman, 2001; Benard et al., 2022).

The random forest model was adjusted to run BCG scores on a binned version of the BCG score levels as model results for the 13 original BCG levels were too weak to distinguish within the model resulting in extremely high-class error rates over 90% for 10 out of the 13 classes (

Table 2). The model was adjusted down to just four unique bins classed as BCG levels 3, 4, 5, and 6 for the remaining model runs. The random forest classification model was run on all monitoring program data combined and then again for each program of DRM, CREMP, and NCRMP were split out individually for individual predictor variable significance assessments. Once the model was run, an optimal spatial and temporal strata was designated for all the monitoring programs' BCG scores based on the mean decrease in accuracy metric in anticipation for spatial and temporal analyses along FCR.

A Chi Square Test of Independence was conducted on the BCG scores sampling months and sampling years to determine their significance to BCG score distribution and how strong or weak that association is with a Cramer's V statistical test (McHugh, 2013). The Chi-square statistical test helps to identify group differences for nominal responses and not normally distributed data such as the BCG scores (McHugh, 2013). While the Chi-square test reports significance between two categorical variables, it cannot determine the strength or weakness of this association therefore, needs an associated statistical test to identify the strength and direction of the relationship between groups (Singh, 2023; McHugh, 2013; Shishkina et al., 2018).

A quartile coefficient of dispersion (QCD) statistical test was used in conjunction with a traditional box plot to determine the spread and relative variability of the BCG scores within each subregion zone of each sample year. Using a coefficient of dispersion test is most ideal for a dataset structure such as this where there are several categorical predictors and responses as well as being resistant to outliers and non-normally distributed in the data (Botta-Duka, 2023).

Table 2. Random Forest Model Class Error for the raw BCG scores.

BCG Class Level	Class Error
3	0.56
3.25	1.00
3.5	1.00
3.75	0.94
4	0.94
4.25	0.99
4.5	0.99
4.75	0.94
5.0	0.16
5.25	0.99
5.50	1.00
5.75	0.95
6.0	0.51

2.5. **Spatiotemporal analyses**

To assess significant trends through space and time, a hotspot cluster analysis was performed using space time cube data at appropriate time intervals to elicit spatial clustering of high and low BCG scores. Spatial clusters of data at various time intervals identified through the Random Forest models were compared to isolate consistent temporal patterns. BCG scores were then used to evaluate temporal differences between habitat strata used in allocating the random points for NCRMP and DRM or one most appropriate. Strata were categorized by the resulting trend analysis results into biological condition gradient status through time (e.g improving, stasis, degrading).

A Space Time Cube is a geoprocessing tool in ArcGIS Pro that visualizes data in a 3D scene both over space and time by stacking 2D map layers as the spatial data vertically on top of each other to represent the temporal component of the data, allowing for identification of spatiotemporal trends, hotspots, and other patterns permeating through the dataset (Esri, 2026a). The time-series component to the Space Time Cube is distinguished by 1-year intervals beginning on the first calendar day of the year. The master BCG score dataset has a vast temporal and spatial constraint reaching all of southeast Florida for approximately the last 20 years. This robust tool was most ideal to help guide the initial analyses of major statistical hot spot and cold spot trends and identify data gaps through time to further investigate. The Space Time Cube tool in ArcPro offers an excellent mode into viewing DRM and CREMP datasets through time however, minimum temporal parameters restrict the usage of this tool to be employed on the NCRMP dataset as there is a required ten unique time periods, in this case sample years, needed to run the tool. The Space Time Cube associates the BCG scores to a spatial strata polygon summarizing statistics for each unique strata for each time-period. A Space Time Cube for DRM program scores was created using the spatial strata designation of subregion-zone split by one year time slices reporting the mean BCG scores, standard deviation, and sample counts for every subregion-zone at every sample year. A Space Time Cube for CREMP was created only at the site level for each station and split by the one year time slices and reporting the same metrics as the DRM cube of mean, standard deviation, and sample count.

Emerging Hot Spots and Optimized Hot Spots are similar in that they both identify statistically significant clusters of high values and low values but emerging hot spots go one step further and take clustering detected in the optimized hot spot and identify more specific trends within these hot or cold spots of new, intensifying, diminishing, or sporadic clusters (Esri, 2026b). The optimized hot spot tool is very robust as it automatically interrogates the dataset and will automatically adjust data by aggregating incident data, identifying and adjusting to appropriate scales, and correcting for both spatial dependence and multiple testing using the Getis-Ord_Gi statistic (Esri, 2026a). An Emerging Hot Spot is similar in that it builds from the work done within the Optimized Hot Spot tool and will identify various types of trends calculated from the hot spot and cold spot regions such as new hot spots, intensifying hot spots, oscillating hot spots, consecutive cold spots, and new cold spots. This is an abbreviated list of the trending hot and cold spots computed by the Emerging Hot Spot tool, an exhaustive list of the emerging hot spot definitions can be viewed in ***Appendix E***. Once these new hot and cold spot areas have been further identified by the tool, each bin (bins refer to 1 time splice at 1 point or strata polygon in time) receives a z-score and a p-value that gets computed by the Mann-Kendall trend test (Esri, 2026a). The Mann-Kendall is a rank correlation analysis for sample size and its time sequence (Esri, 2026a). Its ranking indicates statistically how strong the trend in hot or cold spots are for an area overall through time (Karmeshu, 2012).

3. RESULTS

3.1. BCG model manager and stakeholder training (Task 4)

A presentation was given to the Disturbance Advisory Committee (DAC) on January 7, 2026, to describe project activities and announce that training webinars were being scheduled. In early February, emails for webinar participants of potential interest were drafted, and electronic invitations were sent. The participant invitation list was compiled from existing lists of experts, practitioners, and stakeholders involved in Florida reef monitoring and assessment activities, including the experts who were involved in calibration of the Florida reef BCG model, and regular attendees of the Florida reef Disturbance Advisory Committee (DAC). These lists were expanded as potential participants became aware of the opportunity and passed the invitation forward. The broad invitation was extended to 60 or more people (Appendix A).

The webinars were held on March 2 (9 participants), April 8 (9 participants), and May 12 (5 participants). Reminders were given at DAC meetings leading up to the webinars. Recordings were made of the webinars, which are available on request. They were not widely distributed due to the large size of the video file.

Meeting agendas were identical for the three BCG training webinars. The agendas were distributed to those invitees who responded that they would attend one of the webinars.

The agendas for the 3-hour webinars were as follows:

- **Introductions** (10 minutes)
  - Settling in, presenters and acknowledgements, starting recording, agenda, and logistics
- **BCG Background** (30 minutes)
  - BCG Framework
  - Handouts for BCG Background
  - BCG calculation tool basics
  - Handouts for Exercises
- **Orientation to the BCG Calculation Tool** (20 minutes)
  - Links, outline of functions and resources, and process flowchart
- **Running the BCG Calculation Tool** (60 minutes)
  - Walk-through with participants using the input handouts
- **Wrap-up** (20 minutes)

Protocol documents narrating the steps of how to QA/QC the datasets, format model input files, run the model, and interpret results were prepared for the workshop to train individuals on updating BCG scores in the future. Presentation materials for the workshop were drafted to orient the workshop participants to the BCG model and current project objectives. Materials prepared for the training webinars and as additional reference documentation included:

- **Training and Demonstration Presentation:**
  - FCR_BCGcalc_Webinar_Introduction_Demonstration.pptx
- **The Florida Reef BCG Calculation Tool (BCGcalc):**
  - tetratech-wtr-wne.shinyapps.io/FLCoralBCGCalc/
- **BCG Factsheet**: A Practitioner's Guide to the Biological Condition Gradient: A Framework to Describe Incremental Change in Aquatic Ecosystems
- **Florida BCG StoryMap**: https://storymaps.arcgis.com/stories/a8722829a8ee48a1b1a28f66b8ebae28
- **Florida BCG Report**: ShinyAppDocuments/FLCoral_BCGCalc/Reports/Florida_Coral_BCG_Report.zip at main · Blocktt/ShinyAppDocuments · GitHub
- **BCGcalc User's Manual** – File: FCR_BCG_UsersGuide.docx
- **Demonstration Data Sets**
  - Excel workbook with required fields completed for 3 samples (Tt_BCG_FileBuilder_Input_20260330.csv)
  - Excel workbook with errors to be resolved (Tt_BCG_FileBuilder_Input_20260512_Mismatch.csv)
- **BCG Taxa Translator and Attribute Files** (download both files FLCoral_BCG_Attributes_20240320.csv and FLCoral_BCG_Taxa_Translator_20240320.csv): https://github.com/leppott/BioMonTools_SupportFiles/tree/main/data/taxa_official

3.2. **Update existing BCG results with latest data (Task 2)**

3.2.1. Sampling Effort Across Time

Sampling effort for each major monitoring program, CREMP, DRM, and NCRMP varied within a sampling year and across sampling years (Figure 2 &3). Most of the sample effort for CREMP was completed before September, whereas NCRMP and DRM have significant sampling effort in September and October. When combined, all programs had the majority of sampling completed after July. DRM sampling effort had high variability, an increase in sampling effort through time as observed with unusually low sampling effort (<100 sites surveyed) in 2005, 2013, and 2017. Although CREMP began in 1996 with presence/absence and cover data, they started collecting coral demographic data at limited number of locations in 2011. Since 2014, coral demographic data was collected at almost all sites. This is the most consistent sampling effort through time by returning to the same sites annually (Table 4). NCRMP benthic surveys began collecting coral demographic and benthic cover data in 2014 with typically near or over 300 samples per sample year. NCRMP sampling was considerably low in 2015, 2020, and 2021 with less than half the average sample size for these three sample years. Recently, combined regional effort has increased substantially with over 500 NCRMP samples and over 600 DRM samples collected in 2024. In 2020, DRM effort doubled to around 400 samples and in 2023-2025 increased to about 600 samples.

Chi-square comparisons showed that BCG scores across all sample years and sample months for every program were statistically significant (p-values < 0.05, Table 3) except for CREMP BCG scores across sample years (p-value = 0.4531). The Cramer's V statistical test noted that association strength to BCG scores was quite low across the board for all programs.

Table 3. Results of the Chi-Square test of Independence and Cramer's V statistical result for each monitoring program.

PROGRAM	X-SQUARE	DF	P-VALUE	Cramer's V	Response Variable
ALL	812.3	240	<0.0001	0.09	Sample Year
CREMP	157.42	156	0.45	0.13	Sample Year
NCRMP	355.62	84	<0.0001	0.15	Sample Year
DRM	503.8	240	<0.0001	0.09	Sample Year
ALL	278.59	108	<0.0001	0.06	Sample Month
CREMP	268.96	96	<0.0001	0.20	Sample Month
NCRMP	293.19	108	<0.0001	0.12	Sample Month
DRM	88.922	60	0.009	0.06	Sample Month

Table 4. Percentage of sampling effort by Subregion-Zone across all years for each program. The highest and lowest sampling percentages are bolded for each monitoring program.

Subregion-Zone	DRM	NCRMP	CREMP
Biscayne > Forereef	4.62%	3.63%	2.62%
Biscayne > Inshore	0.80%	0.45%	1.43%
Biscayne > Mid Channel	4.43%	1.48%	
Biscayne > Offshore Patch Reef	1.02%	0.45%	
Broward-Miami > Inner Reef	4.59%	3.04%	2.62%
Broward-Miami > Inshore	9.14%	3.40%	3.93%
Broward-Miami > Middle Reef	3.77%	6.49%	3.93%
Broward-Miami > Outer Reef	2.34%	3.22%	2.62%
Deerfield > Inshore	**0.14%**	0.22%	
Deerfield > Middle Reef	0.38%	0.76%	1.31%
Deerfield > Outer Reef	0.33%	1.48%	1.31%
Lower Keys > Forereef	8.59%	8.82%	**13.11%**
Lower Keys > Inshore	1.97%	1.52%	4.53%
Lower Keys > Mid Channel	4.97%	2.42%	7.27%
Lower Keys > Offshore Patch Reef	2.54%	0.81%	
Marquesas > Forereef	1.59%	0.63%	
Marquesas > Mid Channel	1.38%	0.40%	
Marquesas-Tortugas Transition > Forereef	0.64%	0.27%	
Marquesas-Tortugas Transition > Offshore Patch Reef	0.42%	0.36%	
Martin > Inshore	1.73%	0.40%	2.38%
Martin > Reef Ridge Complex	0.26%	0.49%	
Middle Keys > Forereef	5.69%	3.94%	5.13%
Middle Keys > Inshore	0.71%	**0.04%**	
Middle Keys > Mid Channel	1.99%	0.67%	3.93%
Middle Keys > Offshore Patch Reef	0.59%	0.22%	**0.12%**
Mid-Upper Keys Transition > Forereef	3.13%	3.36%	5.24%
Mid-Upper Keys Transition > Inshore	1.30%	0.36%	
Mid-Upper Keys Transition > Mid Channel	0.80%	1.61%	
Mid-Upper Keys Transition > Offshore Patch Reef	0.31%	0.22%	
North Palm Beach > Inshore	0.21%	0.45%	
North Palm Beach > Reef Ridge Complex	0.68%	2.91%	
South Palm Beach > Inshore	0.48%	0.22%	1.31%
South Palm Beach > Outer Reef	3.38%	2.15%	5.24%
Tortugas > Bank Reefs	0.55%	11.32%	1.67%
Tortugas National Park > Forereef	**9.97%**	**16.92%**	10.61%
Tortugas National Park > Lagoon	2.79%	3.58%	3.93%
Upper Keys > Forereef	5.52%	7.65%	6.91%
Upper Keys > Mid Channel	3.25%	1.16%	3.93%
Upper Keys > Offshore Patch Reef	2.99%	2.46%	3.34%

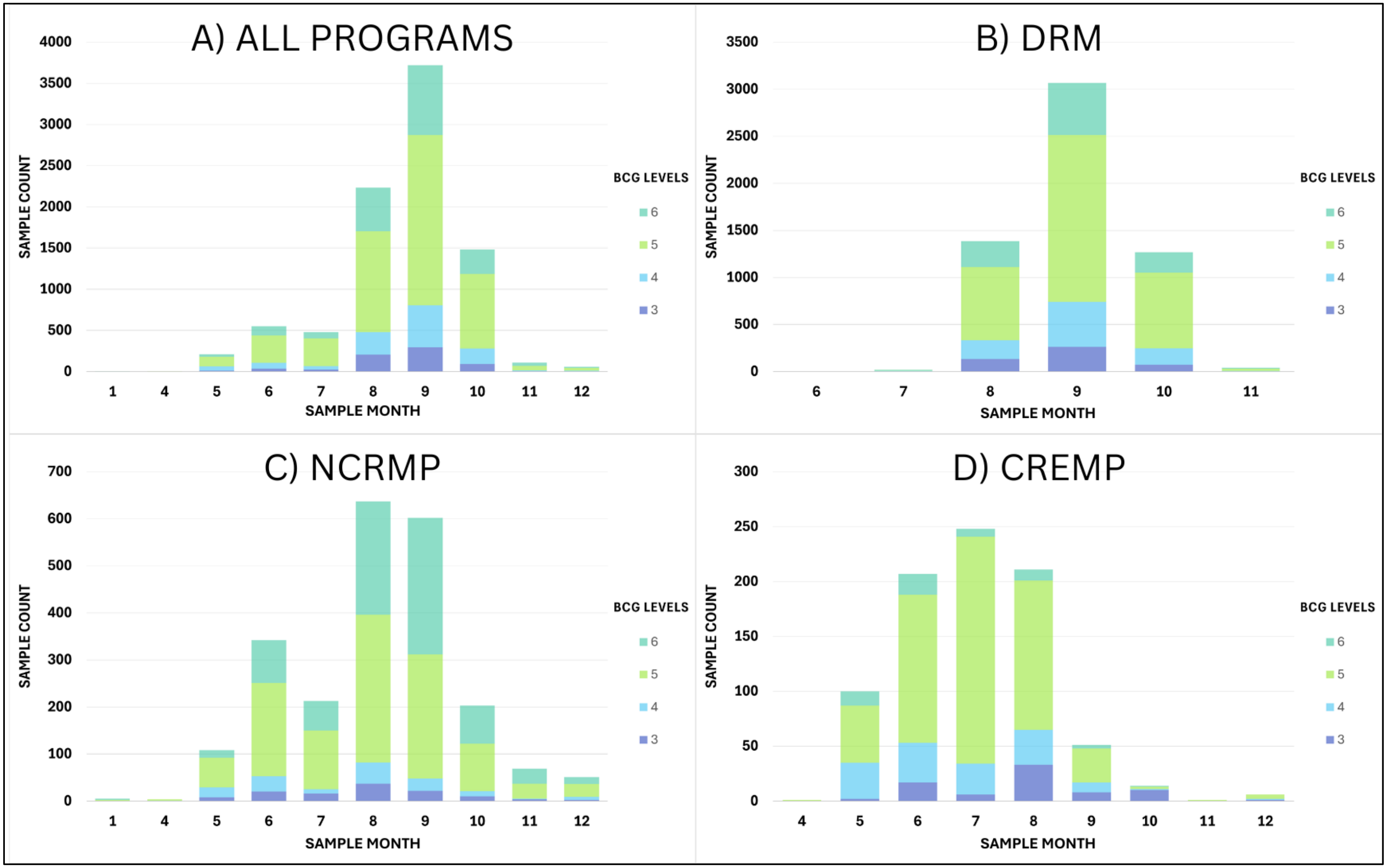

Figure 2. Sample month distribution of BCG scores for all programs combined and individually separated. A) is all programs combined, B) is DRM, C) is NCRMP, and D) is CREMP.

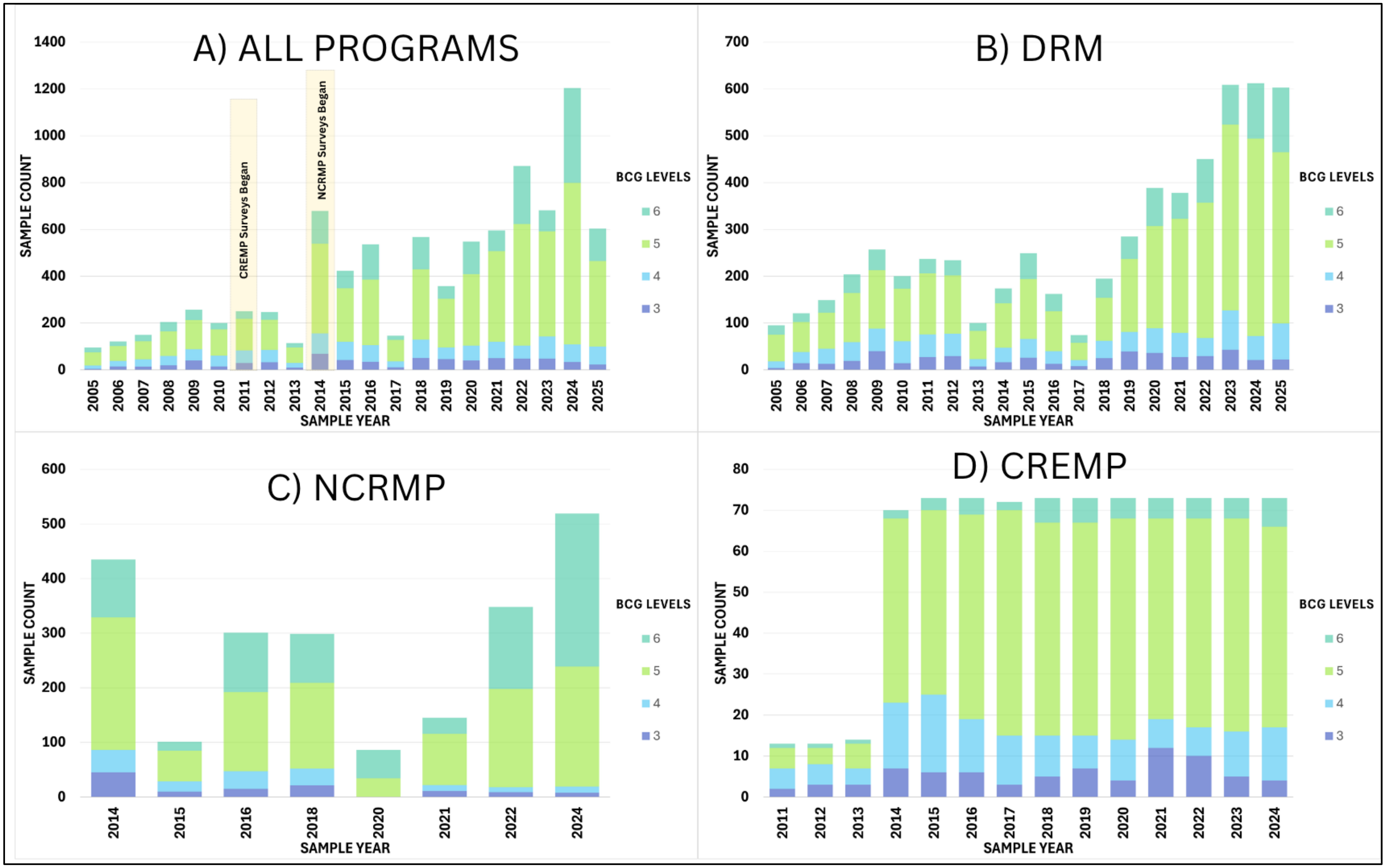

Figure 3. Sampling distribution of BCG scores across years by program. A) is all programs combined, B) is DRM, C) is NCRMP, and D) is CREMP. Yellow highlighted bars on the top left plot indicate the years when NCRMP (2014) began and CREMP (2011) started collecting coral demographic data at limited sites.

3.2.2. Sampling Effort Across Subregion Zones

The distribution of sampling effort across space was a highly variable factor between programs and within programs over time. The subregion-zone strata are made up of 39 unique areas where the reef zones are defined by cross shelf position, depth, shore distance, and the subregions are distinguished latitudinally (Figure 4& Harrell et al., 2024). The CREMP program was the most consistent in sampling the same strata over time, however there was uneven sampling effort across strata and many strata were not included (**Error! Reference source not found.**, Figure 5). For example, 23.7% of the sampling effort was conducted in two strata, Tortugas National Park Forereef and the Lower Keys Forereef, whereas 17 other strata had less than 5% effort (Table 4). Middle Keys offshore patch reef, South Palm Beach inshore, Deerfield outer and middle reef, and Biscayne inshore all had consistently very low sampling conducted for CREMP sites (Table 4).

NCRMP and DRM sampled all the strata, but at varying levels of effort reflective of their stratified random approach (**Error! Reference source not found.**, Figure 6, Figure 7), however both programs focused heavy effort in two strata: Tortugas National Park Forereef and the Lower Keys Forereef. NCRMP strata with high variability in sampling effort throughout the years were the Broward-Miami Middle Reef, Tortugas National Park Forereef, Tortugas Bank Reefs, Lower Keys Forereef, and Upper Keys Forereef. In the DRM program, the Broward Miami inshore and Tortugas National Park forereef strata exhibited the highest sampling effort in the last three sample years than any other region at 9.1% and 9.97%, respectively. NCRMP's sampling effort was most sparse in Martin County, the Marquesas, and the Middle Keys (Table 4). This was mostly due to sporadic sampling in these areas over time. The Marquesas is one of the least sampled subregions with surveys only conducted in 2014 and 2016. The Kristin Jacobs Coral Aquatic Preserve (KJCAP) was not sampled in 2014 or 2015 for NCRMP. And the Keys were not sampled in 2020 and 2021 for NCRMP either. DRM had most spatial coverage across strata out of all monitoring programs with addition of the Marquesas and Marquesas-Tortugas Transition areas in 2019 (Figure 7).

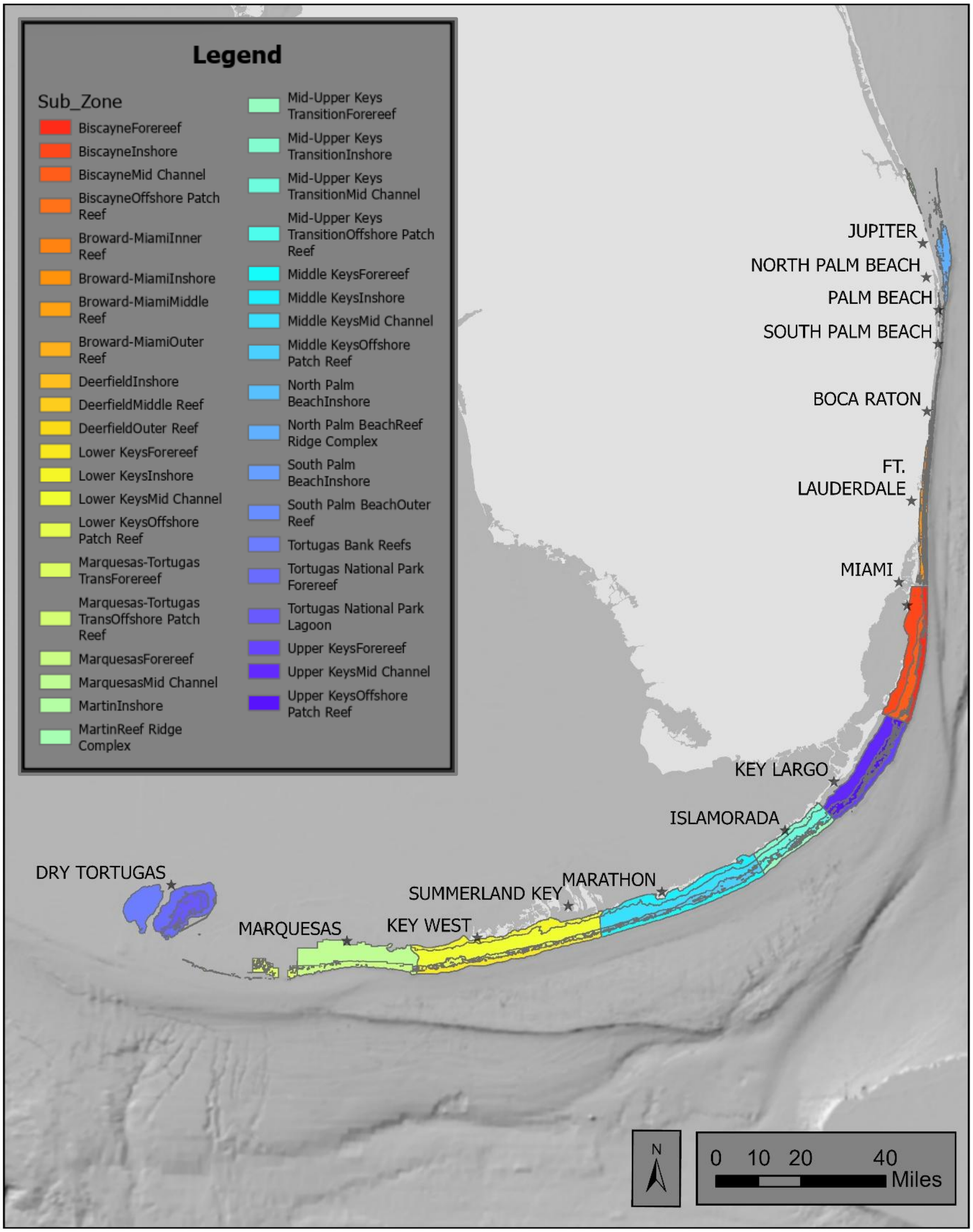

Figure 4. A map of the DRM stratification used herein defined by the subregion-zone complex.

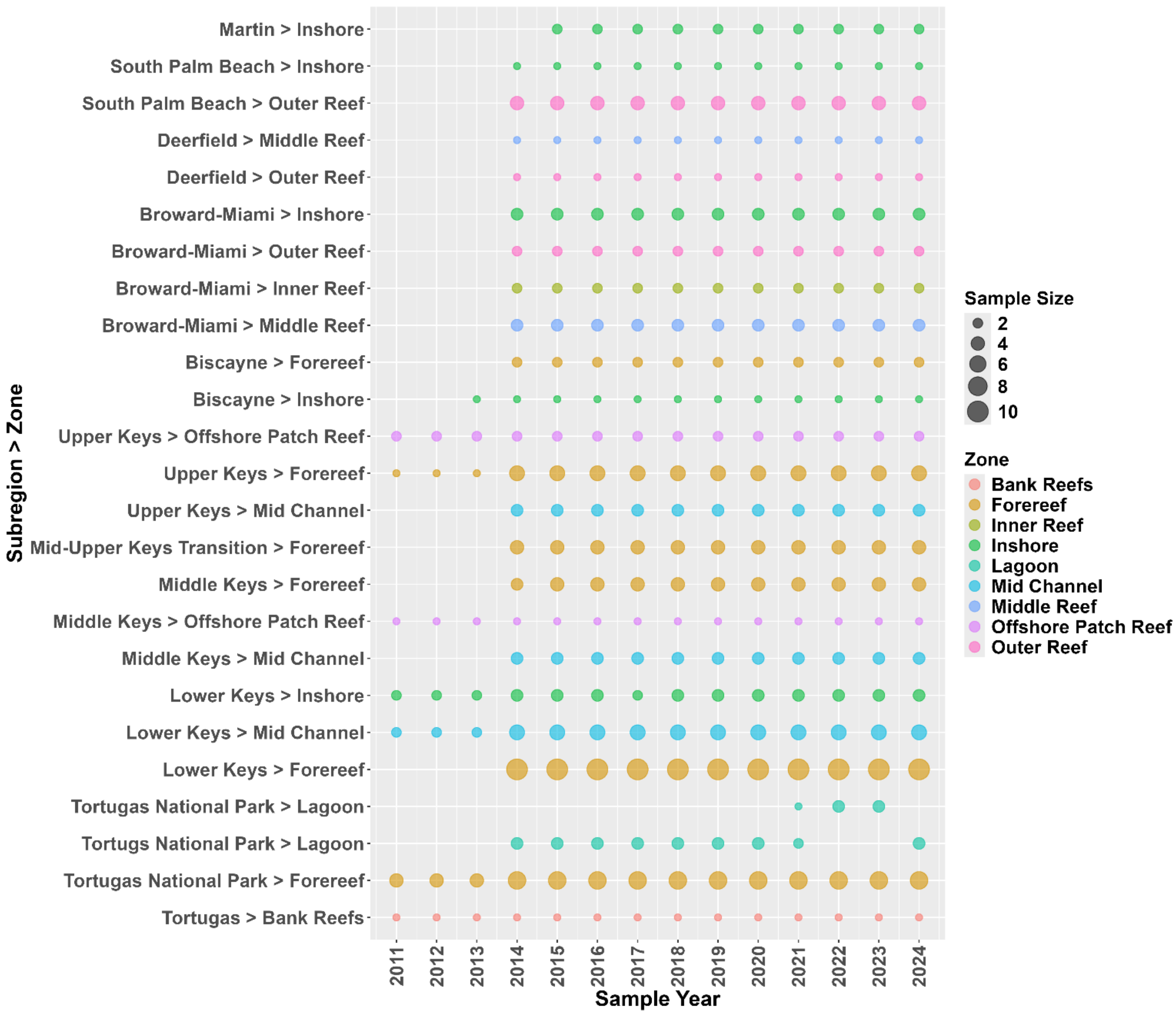

Figure 5. CREMP monitoring program raw sample count of spatial sampling effort for each subregion-zone per each sample year.

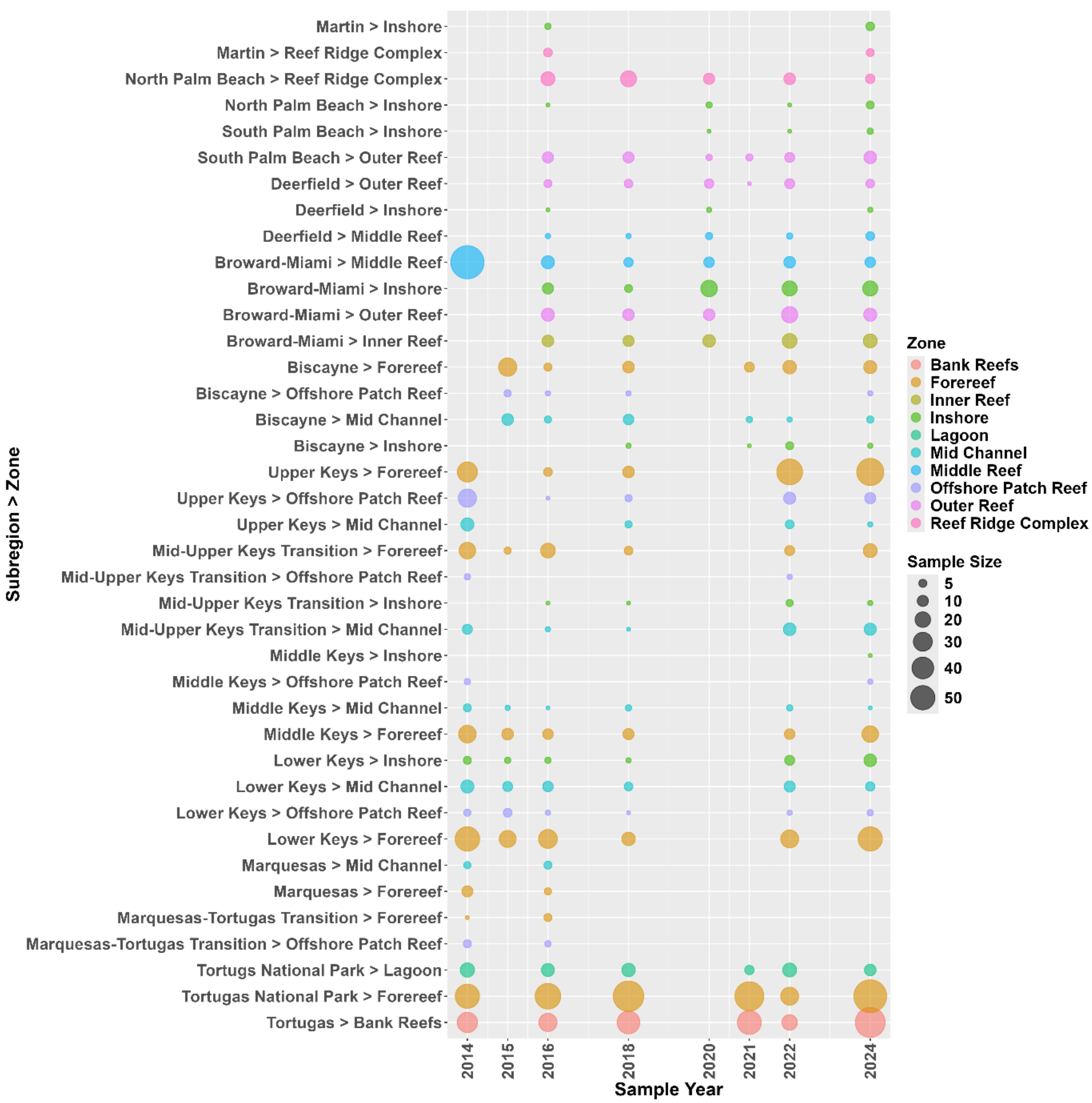

Figure 6. NCRMP monitoring program raw sample count of spatial sampling effort of each subregion-zone through time.

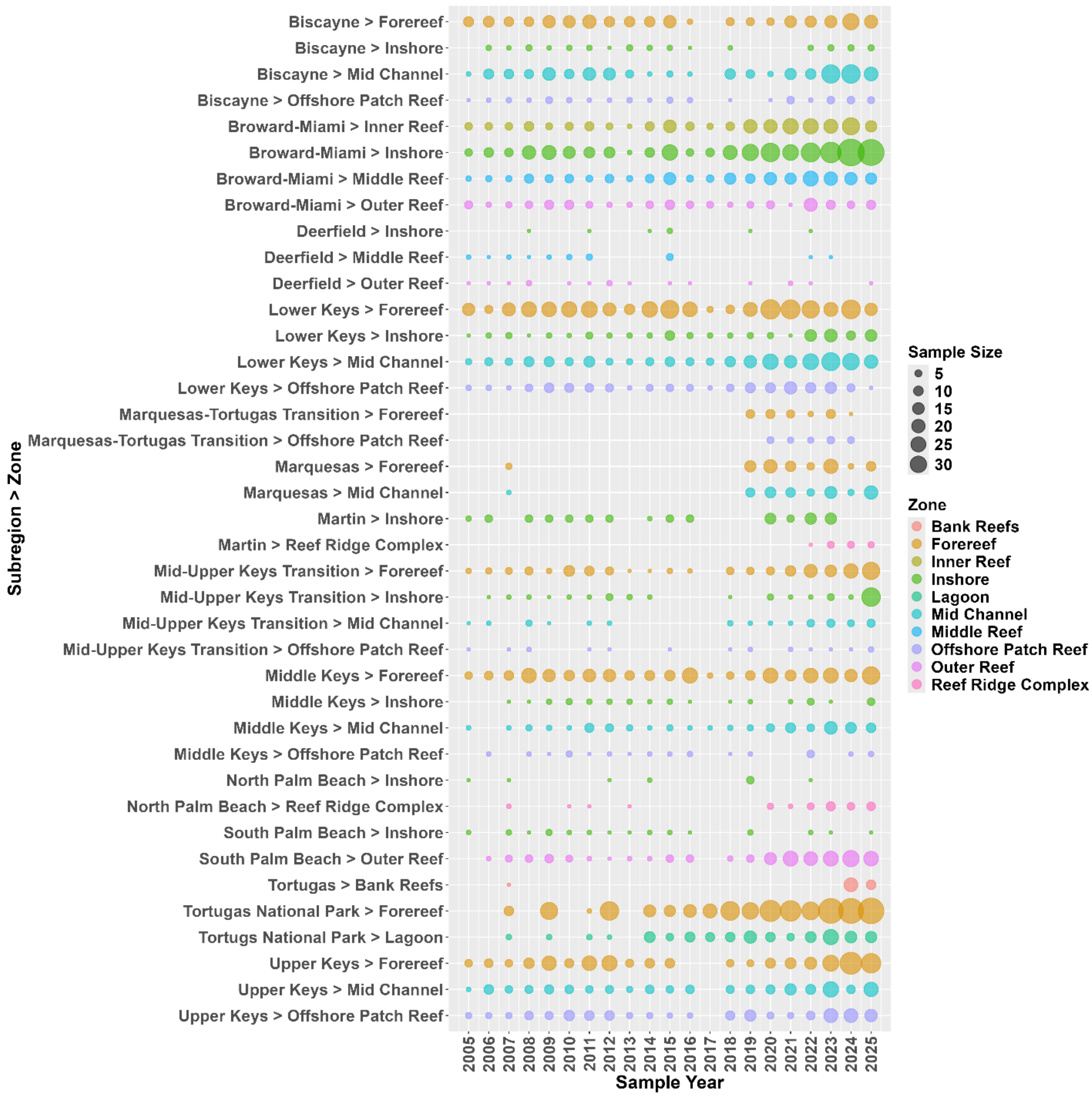

Figure 7. DRM monitoring program raw sample count of spatial sampling effort of each subregion-zone through time.

3.1. *BCG scores by program and strata*

3.1.1. CREMP

The mean BCG scores across all years by strata for each program give an indication of the strata in the best condition (Figures 8-13). In the CREMP monitoring program, the Tortugas Bank Reefs had the lowest mean BCG score of 3.1 (Table 5). The Lower Keys Mid Channel (3.9) and Middle Keys Offshore Patch Reef (3.9) had mean BCG scores less than 4. And Tortugas National Park Forereef and Middle Keys Inshore had a mean BCG of 4. The Lower Keys Inshore (5.4), Mid-Upper Keys Transition Inshore (5.6), and Martin Inshore (5.7) had the highest mean BCG scores. In the CREMP monitoring program, the Dry Tortugas National Park lagoon, Dry Tortugas National Park forereef, and the Lower Keys Mid Channel experienced the highest variation in spread of BCG scores (Figure 9). Apart from the Broward-Miami inshore, the remaining inshore subregion zones tended to have very stable high BCG scores (worst condition) overall of predominantly 5 and 6 (Figures 8 and 9).

Temporal patterns in BCG scores were evident over time in strata (Figures 8 and 9). Martin inshore, South Palm Beach inshore, and Broward Miami inshore all showed increasing scores in the last ten years. Conversely, the Upper Keys middle reef has shown decreasing BCG scores since 2021.

3.1.2. DRM

In the DRM monitoring program, the Lower Keys Mid Channel, Middle Key Mid Channel, and Mid-Upper Keys Transition Mid Channel strata had the lowest mean BCG score of 4.1 (Table 5). The mean scores were lowest in the Dry Tortugas region and mid channel zones while the highest was in North Palm Beach and Martin County (**Error! Reference source not found.** and 11). Specifically, the Broward-Miami inner and outer reef, Deerfield inshore, middle, and outer reef, Martin inshore and reef ridge complex, South Palm Beach inshore and outer reef, and North Palm Beach inshore and reef ridge complex contained the highest mean BCG scores through time compared to the remaining subregions. Martin reef ridge complex, and the Deerfield inshore subregion zones received mean BCG scores of 6.0 for all sample years combined (Table 5).

The DRM monitoring program had high variability across several subregion zone strata. The Lower Keys forereef, inshore, mid channel, offshore patch reef, Mid Upper Keys Transition mid channel, all subregions of the mid channel, and both the lagoon and forereef of the Dry Tortugas National Park experience high variability. The QCD was highest for the Mid-Upper Keys Transition Mid Channel with a QCD value of 0.3.

Temporal patterns in BCG scores and their variability were evident over time in strata with historical lower scores. The Dry Tortugas National Park forereef, Dry Tortugas National Park lagoon, Lower Keys mid channel, Lower Keys offshore patch, and Middle Keys mid channel, all showed shifts to higher scores over time (**Error! Reference source not found.**). Conversely, the Mid Upper Keys Transition inshore has shown decreasing BCG scores in 2022-2024.

3.1.3. NCRMP

In the NCRMP monitoring program, the mean scores were generally lowest in the Dry Tortugas and Keys and highest in North Palm Beach and Martin County, with some exceptions. The Mid-Upper Keys Transition Mid Channel (4), Lower Keys Mid Channel

(4.2), Middle Keys Mid Channel (4.3), and Lower Keys Offshore Patch Reef (4.4) strata had the lowest mean BCG scores (Table 5). The Middle Keys Inshore, Martin Inshore, Martin Reef Ridge Complex, North Palm Beach Inshore, South Palm Beach Inshore, and Deerfield Inshore had mean BCG scores of 6. The NCRMP monitoring program had low variability across most subregion zone strata (QCD < 0.1), except for the Mid-Upper Keys Transition Mid Channel in 2022 and 2024 (0.3).

Temporal patterns in BCG scores and their variability were evident over time in certain strata. The Biscayne mid channel, Upper Keys mid channel, Mid Upper Keys Transition mid channel, the Middle Keys mid channel, the Lower Keys mid channel, and the Marquesas mid channel experienced the highest variability consistently out of all the subregion zones (Figures 12 and 13). Conversely, subregion zones of Martin inshore, Martin reef ridge complex, North Palm Beach reef ridge complex and inshore, South Palm Beach inshore, and Deerfield inshore that lie within the norther regions of the study area were the most stable through time (Figures 12 and 13).

Table 5. Mean BCG scores for each monitoring program and each subregion-zone for all sample years combined. Highest and lowest mean scores per program are bolded.

Subregion-Zone	CREMP	DRM	NCRMP
Martin > Inshore	**5.7**	5.9	**6.0**
Martin > Reef Ridge Complex	5.0	**6.0**	**6.0**
North Palm Beach > Inshore		6.0	**6.0**
North Palm Beach > Reef Ridge Complex		5.7	5.9
South Palm Beach > Inshore		5.9	**6.0**
South Palm Beach > Outer Reef	4.8	5.2	5.7
Deerfield > Inshore		**6.0**	**6.0**
Deerfield > Middle Reef	5.0	5.0	5.5
Deerfield > Outer Reef	5.1	5.0	5.6
Broward-Miami > Inner Reef	4.5	5.0	5.4
Broward-Miami > Inshore	4.8	5.4	5.7
Broward-Miami > Middle Reef	4.9	5.2	5.4
Broward-Miami > Outer Reef	5.0	5.1	5.6
Biscayne > Forereef	4.8	4.9	5.2
Biscayne > Inshore	4.9	5.1	5.9
Biscayne > Mid Channel		4.3	4.7
Biscayne > Offshore Patch Reef		4.8	5.0
Upper Keys > Forereef	5.0	4.9	5.3
Upper Keys > Mid Channel	4.9	4.4	4.6
Upper Keys > Offshore Patch Reef	4.5	4.7	5.0
Mid-Upper Keys Transition > Forereef	5.0	4.9	5.0
Mid-Upper Keys Transition > Inshore	5.6	5.5	5.6
Mid-Upper Keys Transition > Mid Channel		4.1	**4.0**
Mid-Upper Keys Transition > Offshore Patch Reef		4.9	4.8
Middle Keys > Forereef		4.8	5.0
Middle Keys > Inshore	4.0	5.0	**6.0**
Middle Keys > Mid Channel		4.1	4.3
Middle Keys > Offshore Patch Reef	3.9	4.5	4.5
Lower Keys > Forereef	4.9	4.8	5.2
Lower Keys > Inshore	5.4	4.4	5.2
Lower Keys > Mid Channel	3.9	**4.1**	4.2
Lower Keys > Offshore Patch Reef		4.4	4.4
Marquesas > Forereef		4.8	4.7
Marquesas > Mid Channel		4.6	4.6
Marquesas-Tortugas Transition > Forereef		4.4	4.6
Marquesas-Tortugas Transition > Offshore Patch Reef		4.3	4.6
Tortugas > Bank Reefs	**3.1**	5.0	5.0
Tortugas National Park > Forereef	4.0	4.5	5.0
Tortugas National Park > Lagoon	4.5	4.4	4.9
Mean (SD)	**4.7 ±0.6**	**4.9 ±0.5**	**5.2 ±0.6**

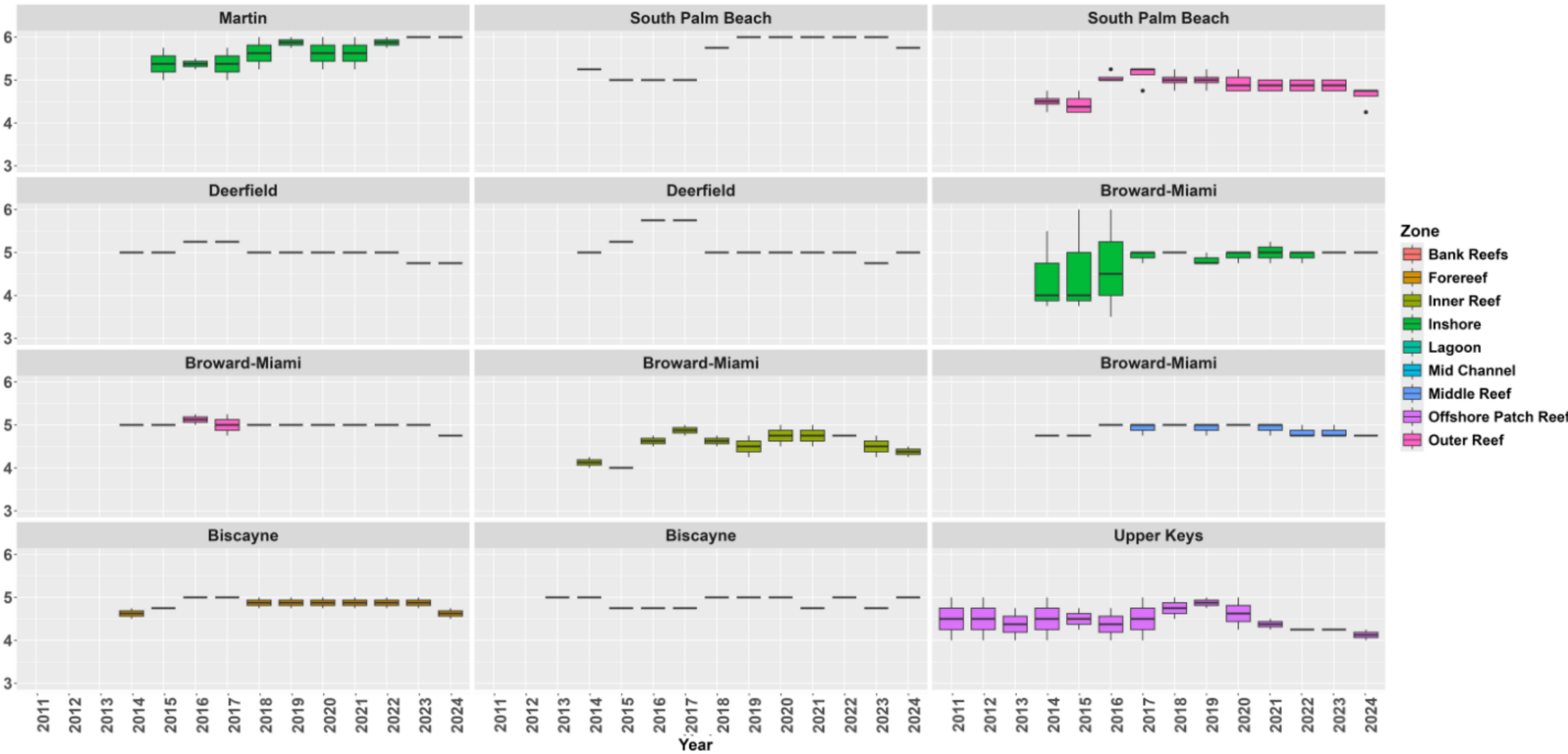

Figure 8. CREMP BCG score distributions by subregion zone the KJCAP region, Biscayne National Park and the Upper Keys.

Figure 9. CREMP BCG score distributions by subregion zone the Florida Keys and Dry Tortugas regions.

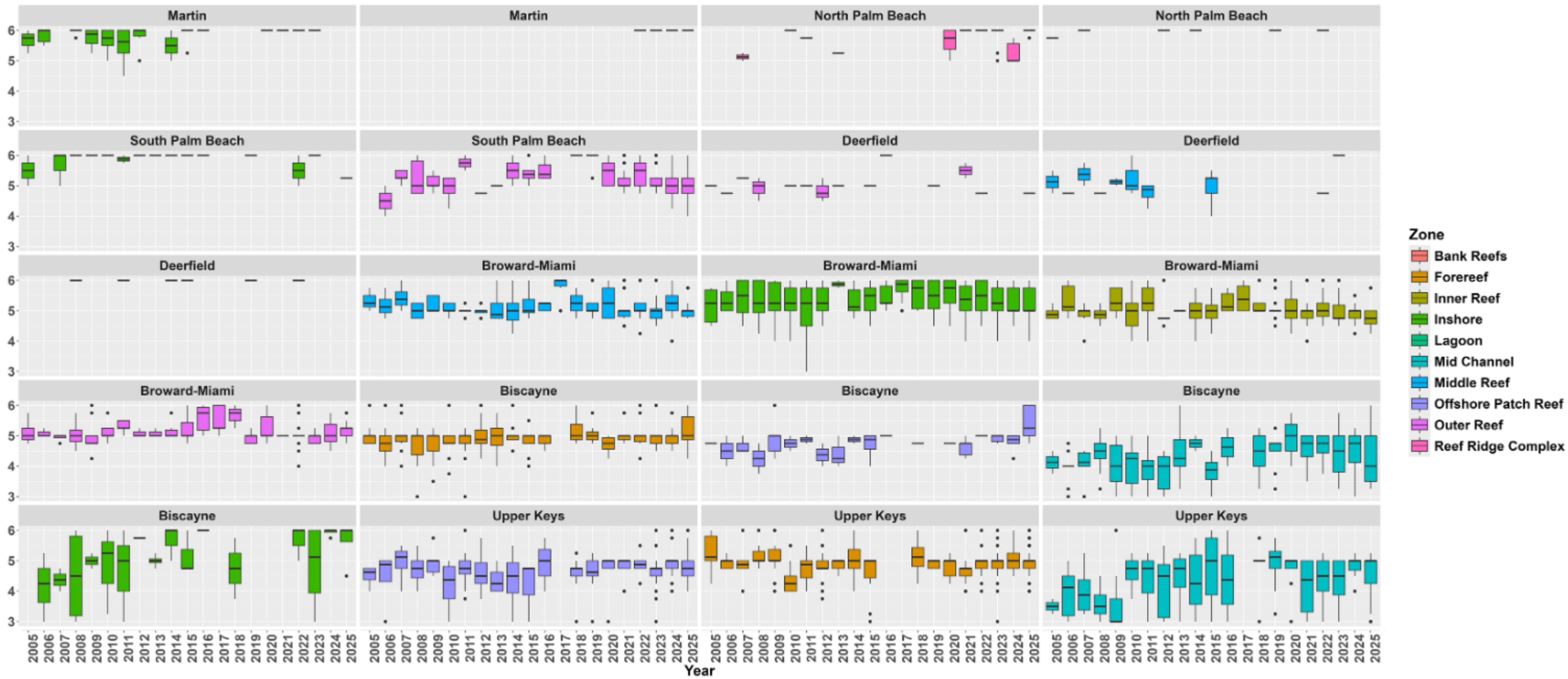

Figure 10. DRM BCG score distributions by subregion zone the KJCAP region, Biscayne National Park and the Upper Keys.

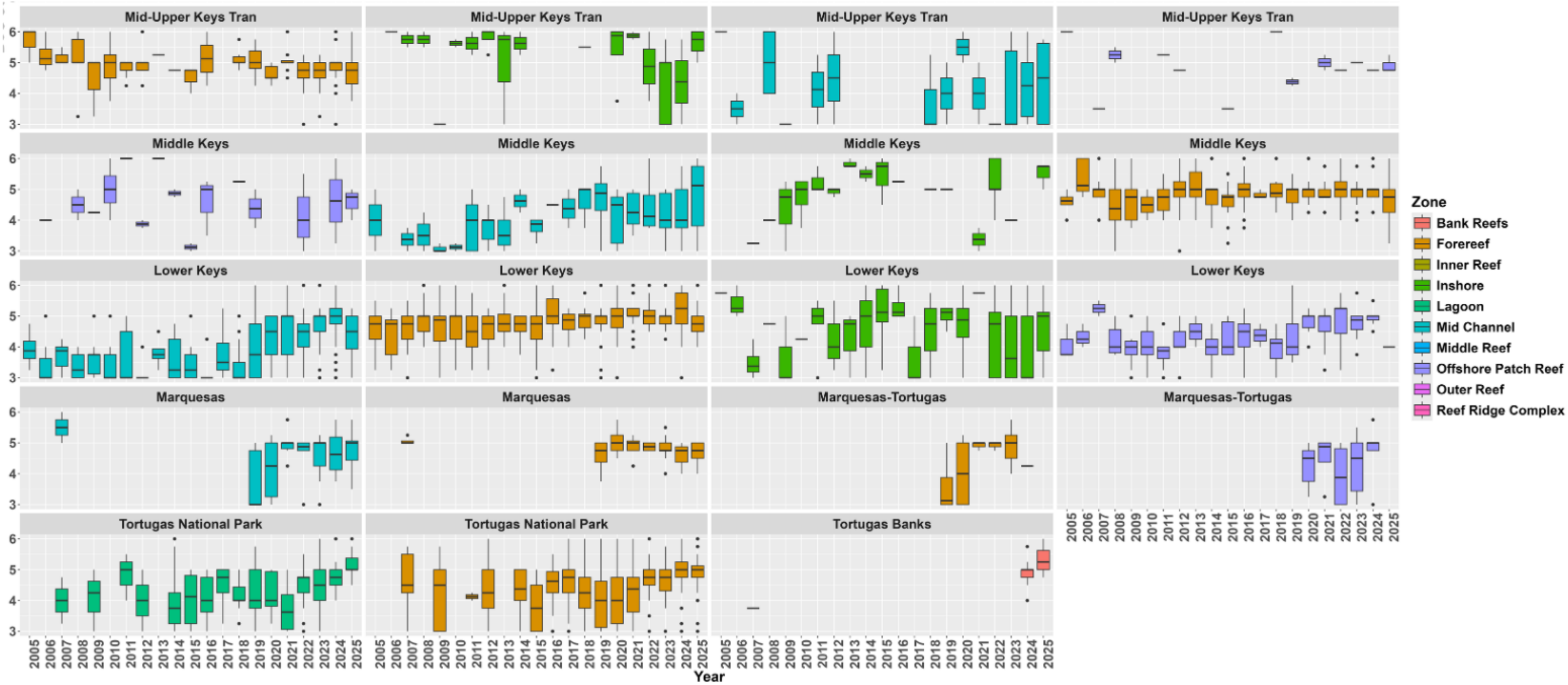

Figure 11. DRM BCG score distributions by subregion zone the Florida Keys and Dry Tortugas regions.

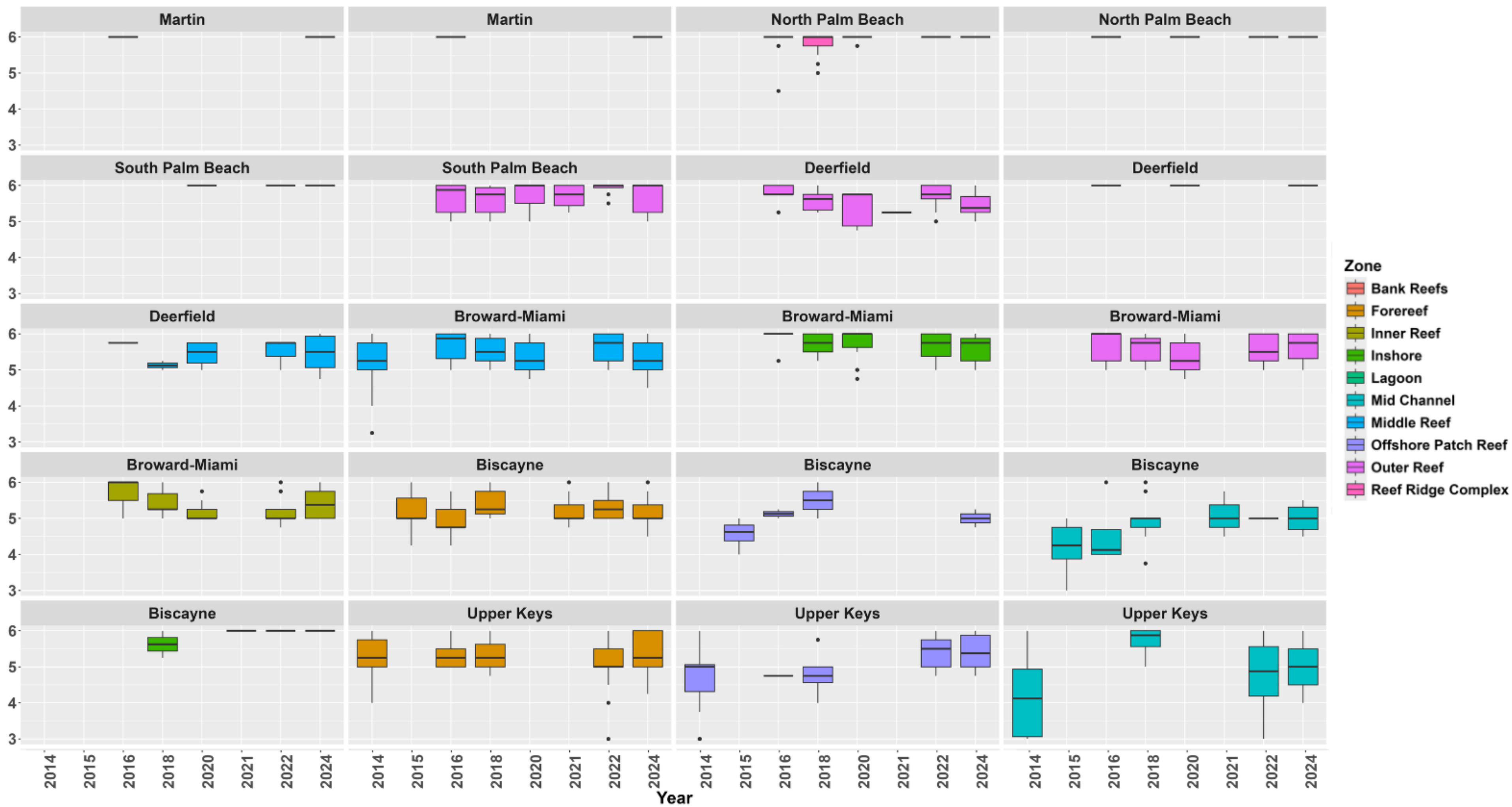

Figure 12. NCRMP BCG score distributions by subregion zone the KJCAP region, Biscayne National Park and the Upper Keys.

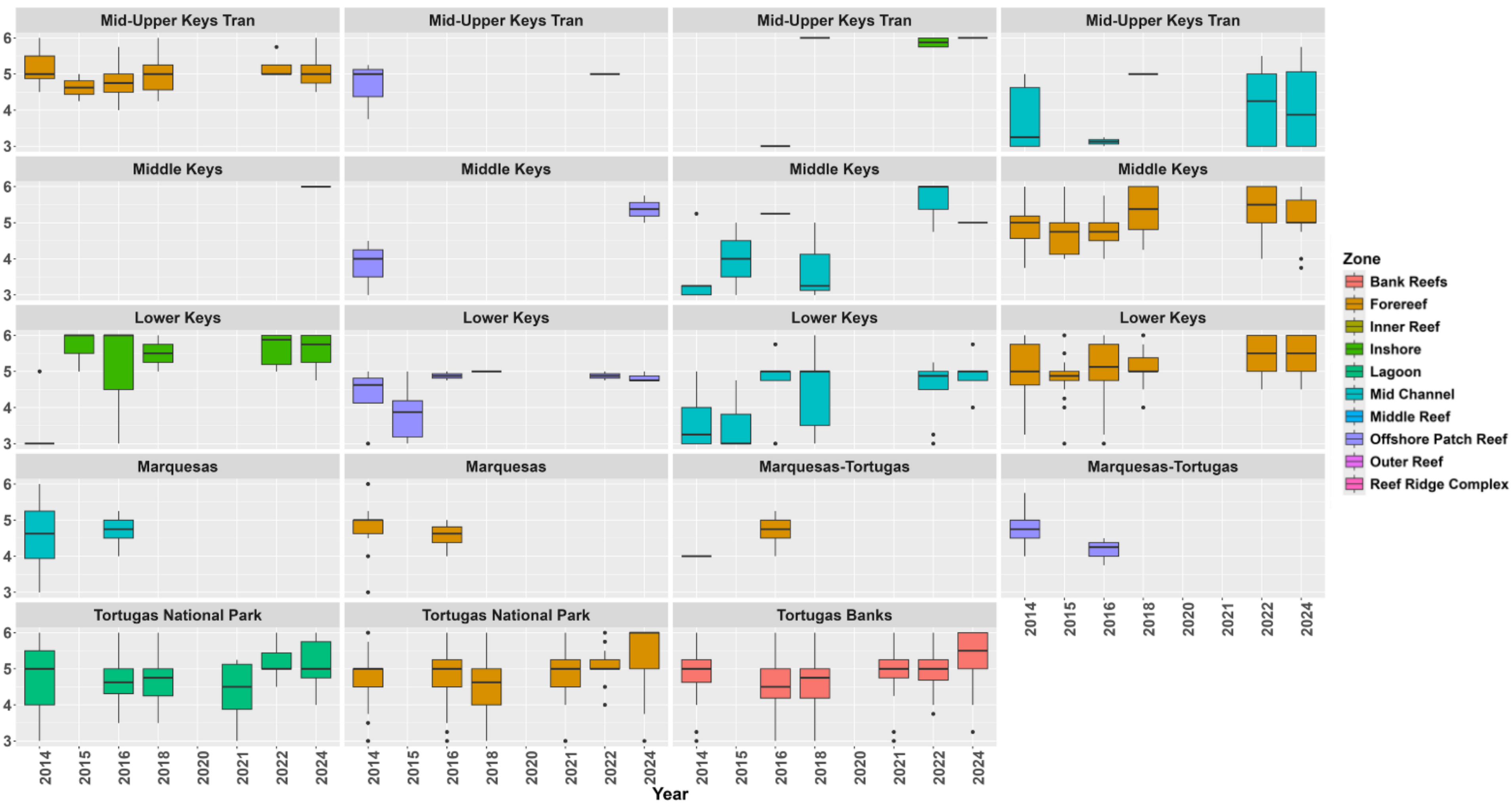

Figure 13. NCRMP BCG score distributions by subregion zone the Florida Keys and Dry Tortugas regions.

3.1.4. Random Forest Models

A random forest classification type decision model was employed on the binned BCG score dataset for all programs combined to determine which factors are most significant to predicting BCG model scores for a spatial temporal analysis. The CREMP model had the lowest error rate of 24.53%, whereas NCRMP and DRM error rates were higher (39.48% and 38.88% respectively) (Table 6). The class-specific error rate for all programs was the lowest at class level 5 and much weaker (high error rates) for the remaining BCG levels like the other programs split out (Table 6). The model was the least accurate in predicted BCG scores for class level 4 across all programs as CREMP had a level 4 error rate of 61.05%, NCRMP (92.72%), DRM (85.27%), and all combined (83%) (Table 6). The random forest model indicated that for 2 out of 3 of the monitoring programs, subregion-zone and sample year were the most significant factors for BCG model scores within the NCRMP and DRM program. The CREMP program stood out for its most significant spatial temporal factors to be sample month and subregion-zone (Table 7). Lastly, the all programs random forest model run noted significant factors of sample year, zone, and program as the most significant influence (Table 7). Having monitoring programs as the most significant factor for the all program model is expected as there are many differences that drive the survey design within each program, capturing a different effect of the reef with each survey.

Table 6. Random forest model error results for each monitoring program.

Program	Input Factors	Significant Factors	Out-Of-Box Error Rate	Class Lvl 3 Error	Class Lvl 4 Error	Class Lvl 5 Error	Class Lvl 6 Error
CREMP	Year, Month, Region, Subregion, Zone, Sub-Zone	Sample Month, Sub-Zone	24.53%	50.00%	61.05%	9.52%	53.84%
NCRMP	Year, Month, Region, Subregion, Zone, Sub-Zone	Sample Year, Sub-Zone	39.48%	67.07%	92.72%	25.31%	45.30%
DRM	Year, Month, Region, Subregion, Zone, Sub-Zone	Sample Year, Sub-Zone	38.88%	79.10%	85.27%	12.26%	70.59%
ALL	Program, Year, Month, Region, Subregion, Zone, Sub-Zone	Program, Sample Year, Zone	38%	77%	83%	12%	63%

Table 7. Variable important results of significant predictor impacts to BCG score predictions in the random forest model. The Mean Decrease in Accuracy identifies how strong a factor was at predicting pure model results. The higher the mean decrease in accuracy, the more significant the factor is at predicting BCG scores correctly.

Program	Factor	Mean Decrease Accuracy
CREMP	Sample Year	-9.03
CREMP	Sample Month	27.23
CREMP	Region	18.68
CREMP	Subregion	40.5
CREMP	Zone	44.52
CREMP	Sub Zone	63.29
NCRMP	Sample Year	96.4
NCRMP	Sample Month	52.09
NCRMP	Region	26.66
NCRMP	Subregion	43.29
NCRMP	Zone	63
NCRMP	Sub Zone	65.61
DRM	Sample Year	85.09
DRM	Sample Month	57.72
DRM	Region	26.82
DRM	Subregion	55.13
DRM	Zone	76.12
DRM	Sub Zone	78.97

3.1.5. Multi-dependence heat maps

Multi-dependence heatmaps show the relationship between the two most significant predictors tested during the random forest models and the predicted BCG score levels. CREMP BCG scores were modeled using sample month and subregion zone and had the most stable expected heat map, with a majority of the sites at BCG level 5 (Figure 14). CREMP sites within offshore patch reef, mid channel reef zones, and the Dry Tortugas National Park zones had lower BCG scores than any other predicted subregion-zone. Class prediction probability power was strongest for BCG score 5 as most subregion zones and most sample months contained approximately 60-80% probability (Figure 15). The northern subregion-zones of FCR and the mid to lower Florida Keys subregion-zones exhibited the highest probability of a class prediction as level 5 at approximately 80% across the two areas of interest. There were also annual variations in the probability of predicting scores which showed as distinct vertical striping in the plots.

The expected BCG scores modeled for DRM showed differences in both subregion-zones and sample years (Figure 16). Annual patterns of increasing scores were evident by the vertical striping of warmer colors from left to right with a distinct transition occurring for sampling post 2020 (Figure 16). Forereef subregion-zones also had noticeably higher predicted BCG scores across time. The DRM monitoring program exhibited approximately 50-70% probability for BCG 5 in all subregion-zones (Figure 18). BCG 5 score prediction probabilities were especially high for many of Broward-Miami subregion-zones, Deerfield subregion zones, and Upper Keys subregion zones (Figure 18). The BCG level 4 prediction probabilities of subregion-zones noticeably decrease after 2019 (Figure 17).

The expected NCRMP BCG scores from the random forest model show a gradual shift to higher BCG scores over time as the shading darkens predominantly by the last two sample years, leaving the most recent sample year as having the highest expected BCG scores throughout the subregion-zones (Figure 19). The NCRMP random forest model exhibits a much different result than either DRM or CREMP as there is a higher probability of predicted class levels for BCG level 5 and 6 within NCRMP BCG scores (Figures 20 & 21). By the most recent sampling year, 2024, reveals the highest class probability now exists at class level 6, the highest possible BCG score, unlike the DRM and CREMP programs (Figure 21).

The NCRMP model exemplified the increasing probability of a worse BCG score throughout time (Figure 20 and 21). The likelihood of a class 3 to 4 predictor gradually decreased through time (Figure 20). Similar to the other programs, BCG class level 5 was the highest predicted class level with approximately 50-60% probabilities, but it also uniquely showed higher probabilities for BCG 6 in 2024.

All monitoring programs were then combined in a random forest model to evaluate what the effects from combining different programs with differing levels of effort over time had on the analysis (Figure 22). Similar to the other monitoring programs, class predicted probabilities were the highest for class level 5 and decrease dramatically in probability for any other BCG class level (Figures 23 and 24). The predicted probability for class level 6 showcases more intense striping effect caused by the dramatic increase in sampling effort through time as NCRMP surveys began in 2014 (Figure 24). The expected BCG scores also show more intense oscillation effect due to unevenly weighted sampling effort across space and time, masking true reef patterns that are more prevalent within each program when isolated (Figure 24). Year 2024 had a distinct higher expected BCG score from other years carried over specifically from the NCRMP monitoring (Figure 19).

Figure 14. CREMP random forest heatmap showing expected BCG scores for every subregion zone (y-axis) for every sample month (x-axis). BCG level 3 and 4 scores are green to yellow while levels 5 and 6 are orange to red in color.

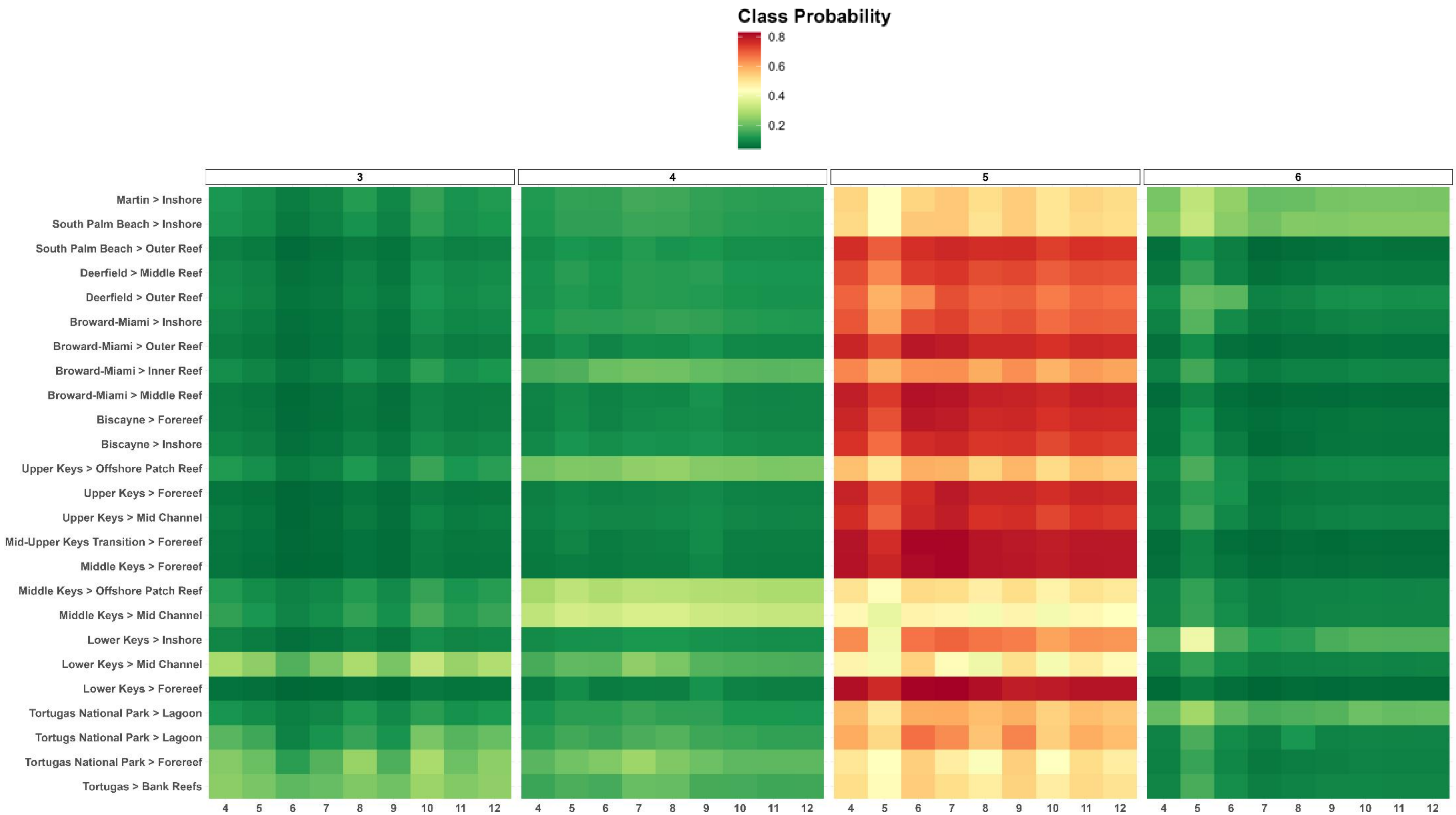

Figure 15. CREMP random forest heatmap showing predicted class probabilities of BCG scores for every subregion zone for every sample year. Each plot shows predicted probabilities for each BCG level starting from left to right the first plot is BCG class level 3, class level 4, class level 5, and the last plot on the right-hand side is class level 6.. Lower class probabilities are green to yellow while higher probabilities are orange to red.

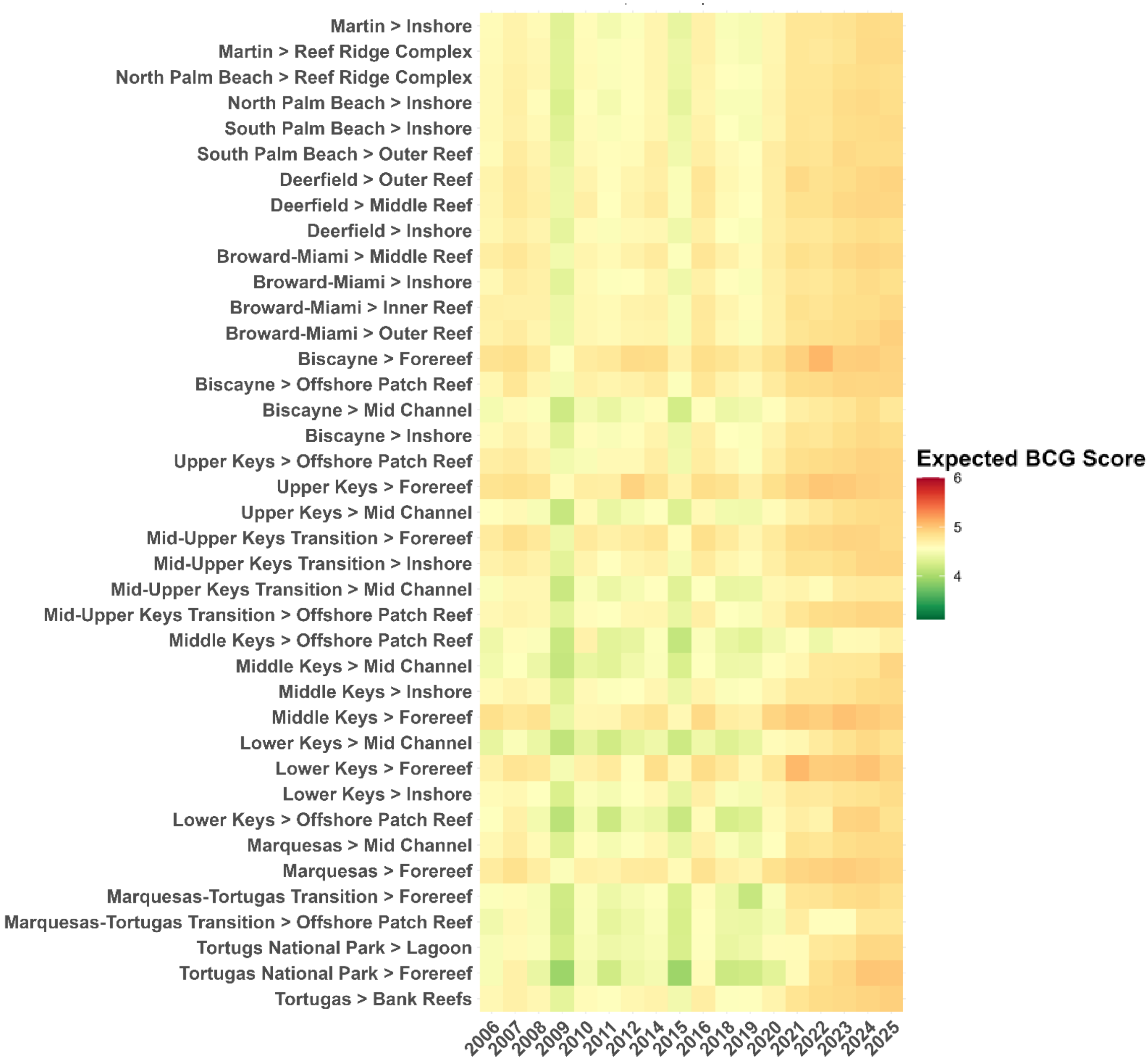

Figure 16. DRM random forest heatmap showing expected BCG scores for every subregion zone for every sample year. BCG level 3 and 4 scores are green to yellow while levels 5 and 6 are orange to red in color.

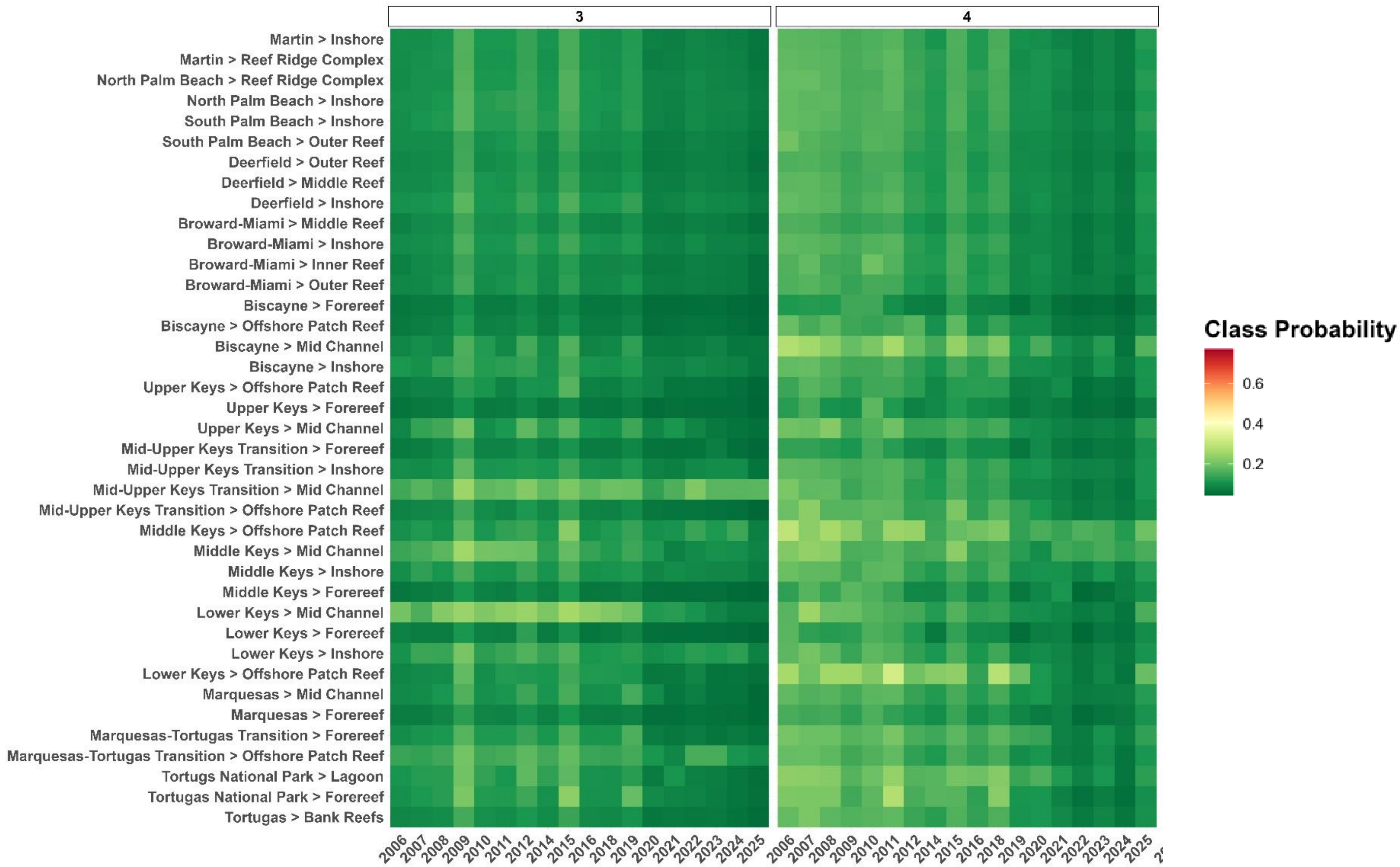

Figure 17. DRM random forest heatmap showing predicted class probabilities of BCG scores for every subregion zone (y-axis) for every sample year (x-axis). Each plot shows predicted probabilities for each BCG 3 and 4. Lower class probabilities are green to yellow while higher probabilities are orange to red.

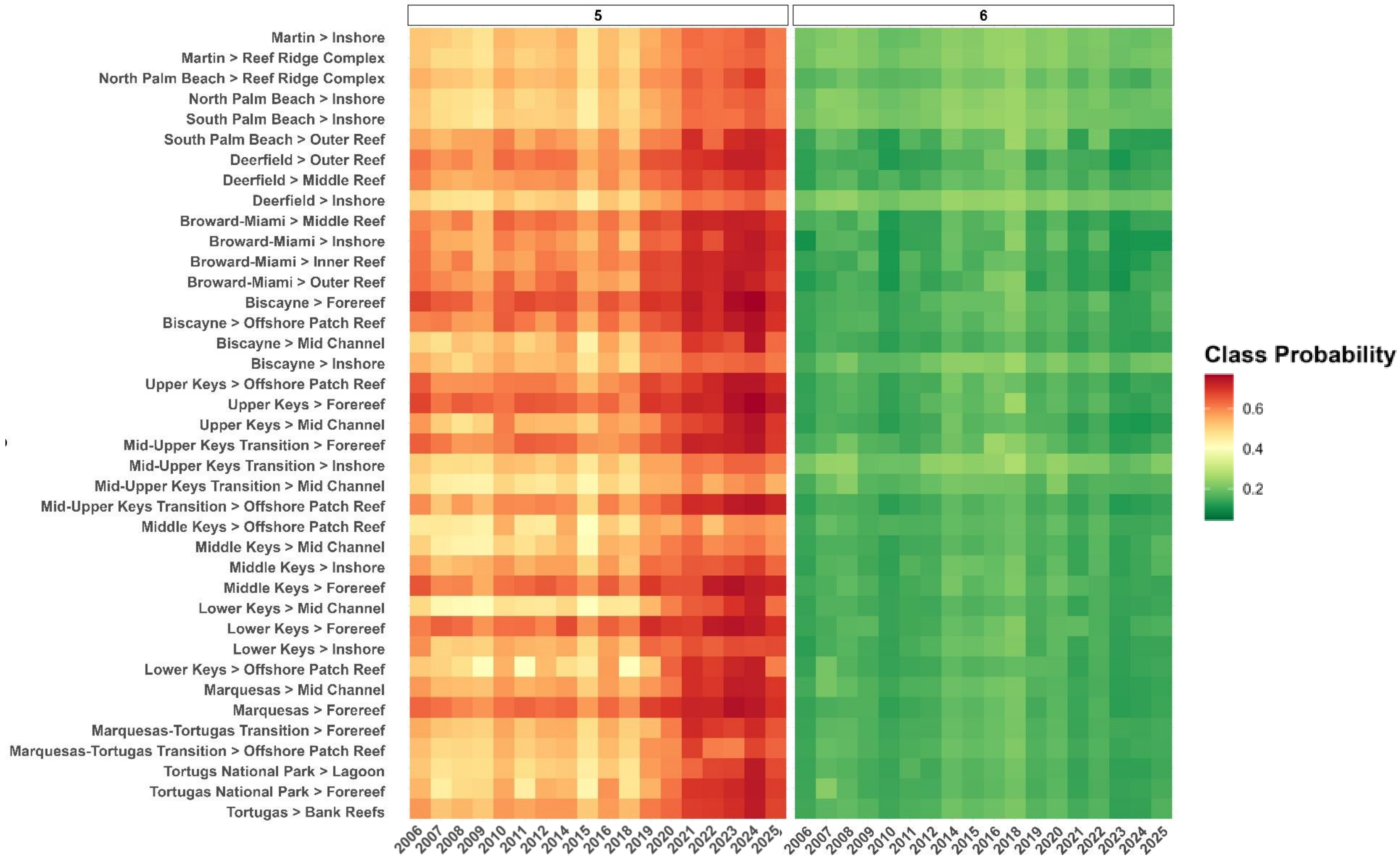

Figure 18. A continuation of the DRM random forest heatmap showing predicted class probabilities of BCG scores for every subregion zone (y-axis) for every sample year (x-axis). Each plot shows predicted probabilities for each BCG 5 and 6. Lower class probabilities are green to yellow while higher probabilities are orange to red.

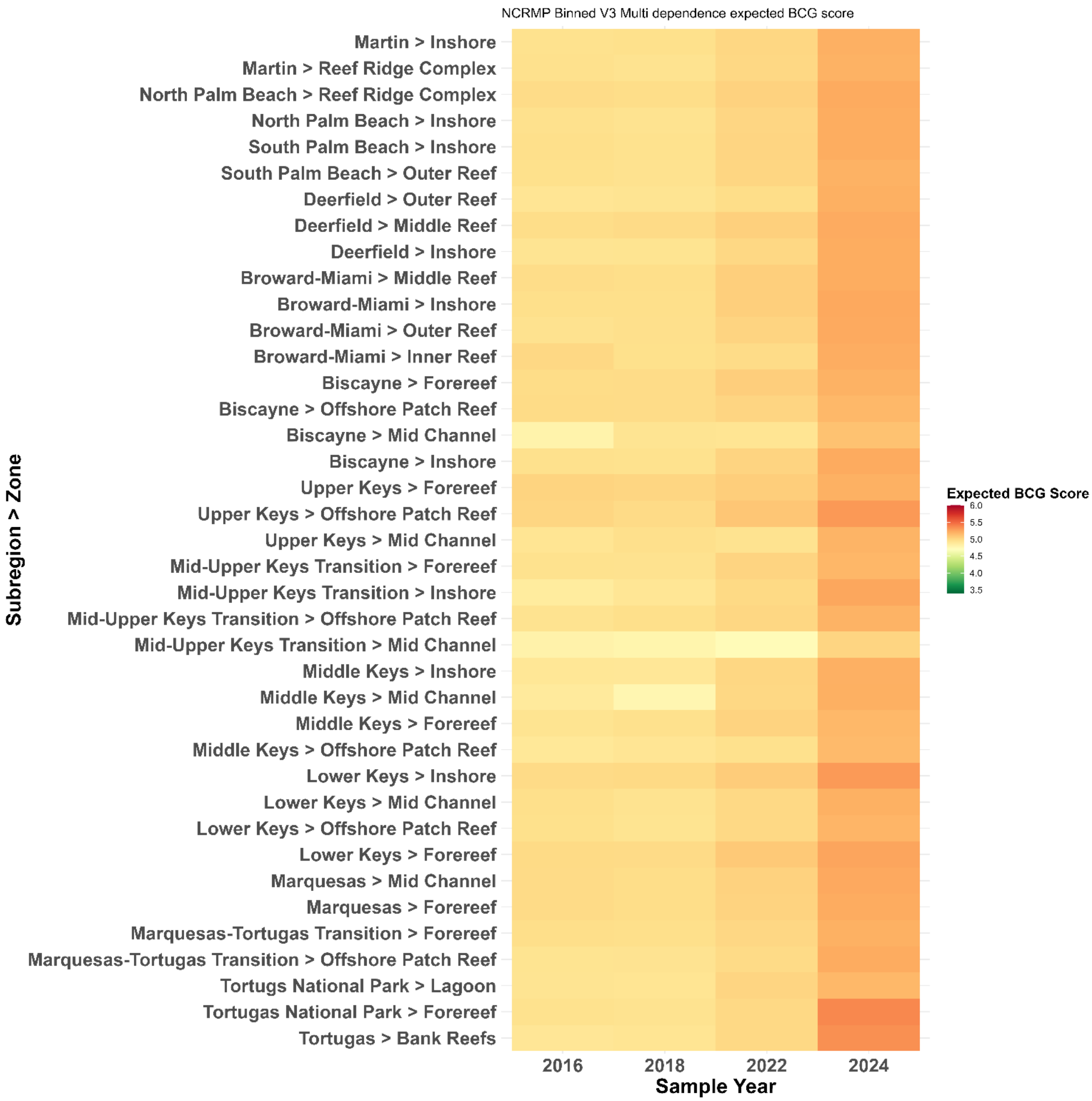

Figure 19. NCRMP random forest heatmap showing expected BCG scores for every subregion zone for every sample year. BCG level 3 and 4 scores are green to yellow while levels 5 and 6 are orange to red in color.

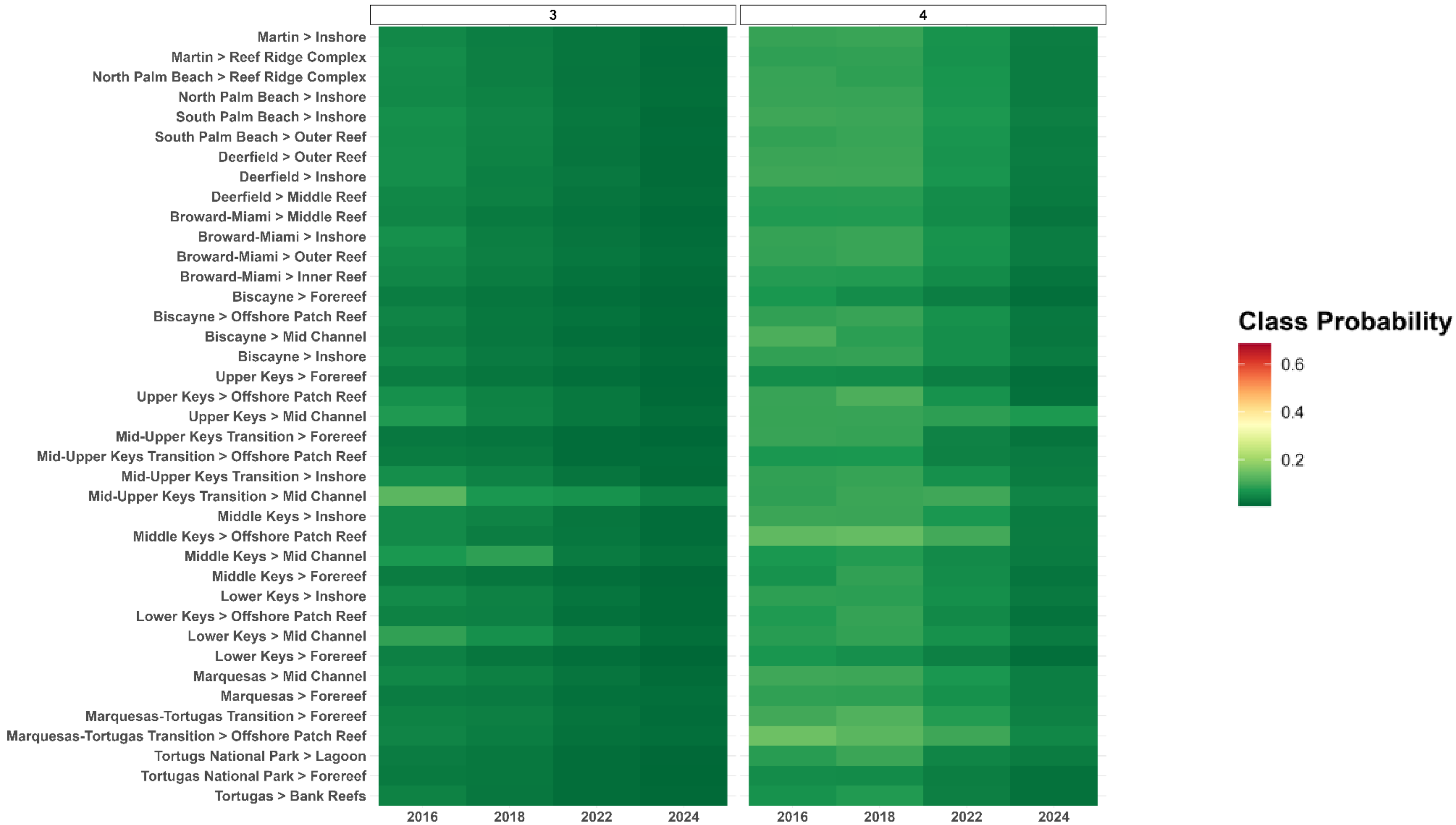

Figure 20. NCRMP random forest heatmap showing predicted class probabilities of BCG scores for every subregion zone (y-axis) for every sample year (x-axis). Each plot shows predicted probabilities for each BCG level 3 and 4. Lower class probabilities are green to yellow while higher probabilities are orange to red.

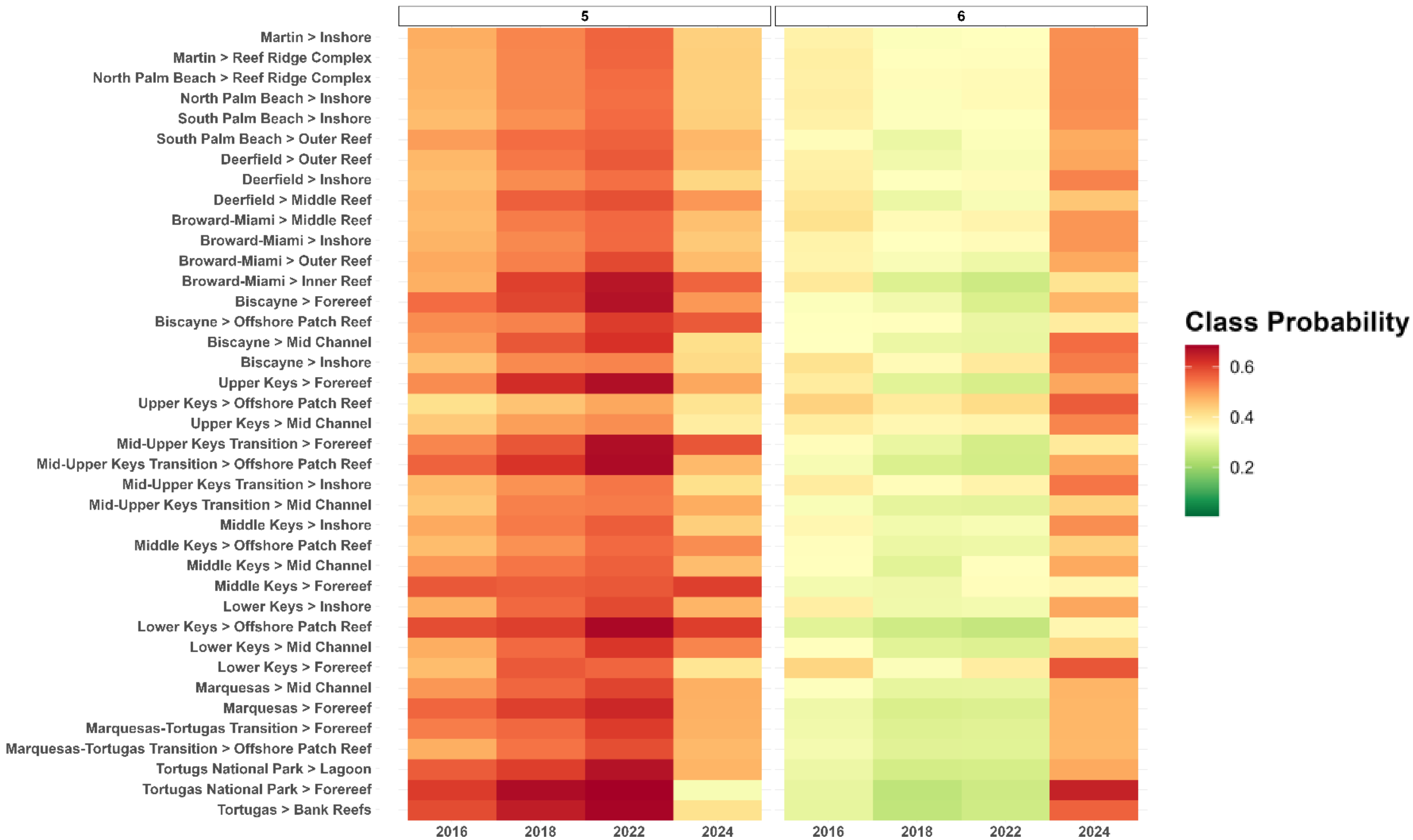

Figure 21. A continuation of the NCRMP random forest heatmap showing predicted class probabilities of BCG scores for every subregion zone (y-axis) for every sample year (x-axis). Each plot shows predicted probabilities for each BCG level 5 and 6. Lower class probabilities are green to yellow while higher probabilities are orange to red.

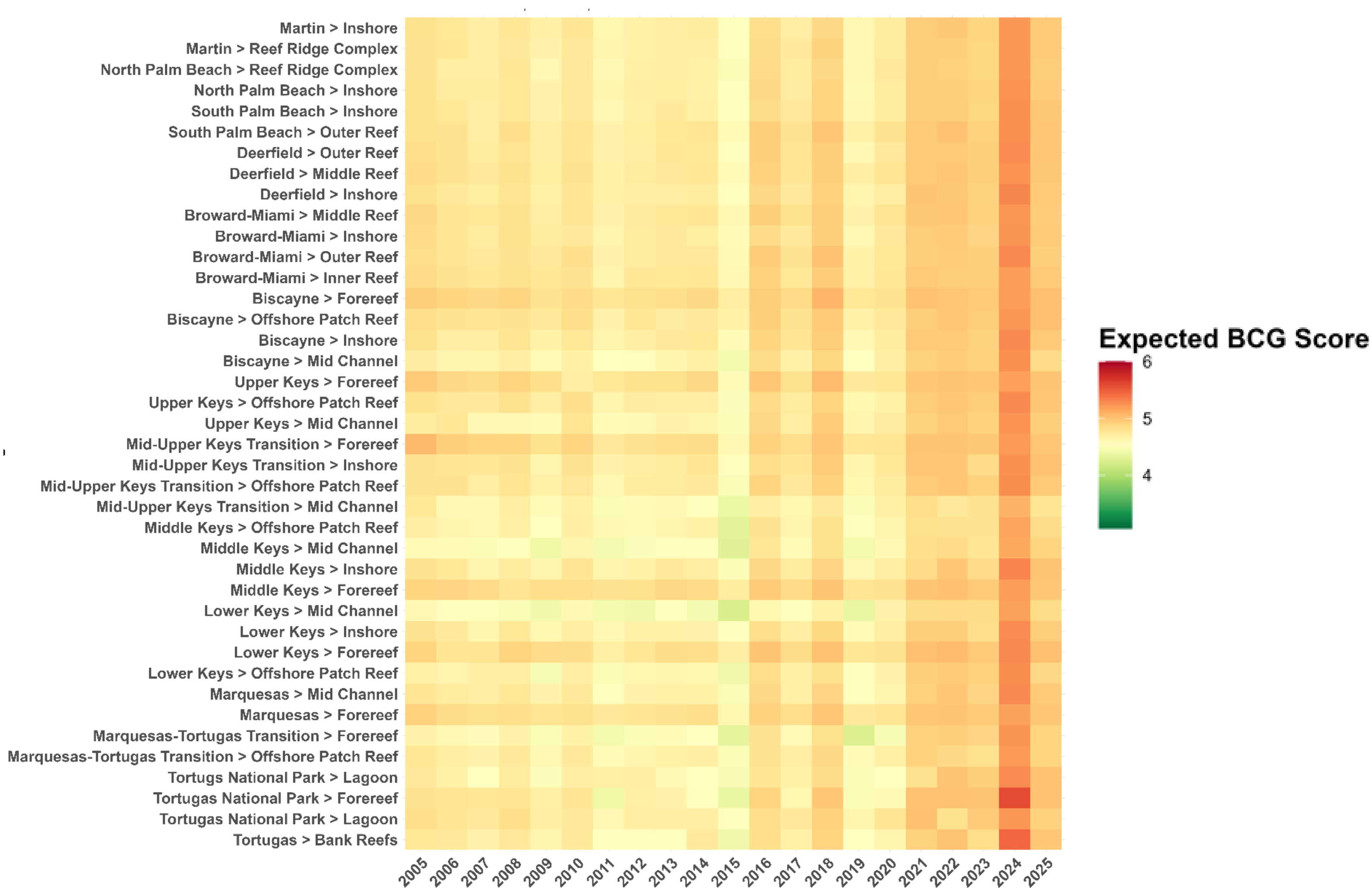

Figure 22. All monitoring programs DRM, NCRMP, and CREMP combined in the random forest heatmap showing expected BCG scores for every subregion zone (y-axis) for every sample year (x-axis). BCG level 3 and 4 scores are green to yellow while levels 5 and 6 are orange to red in color.

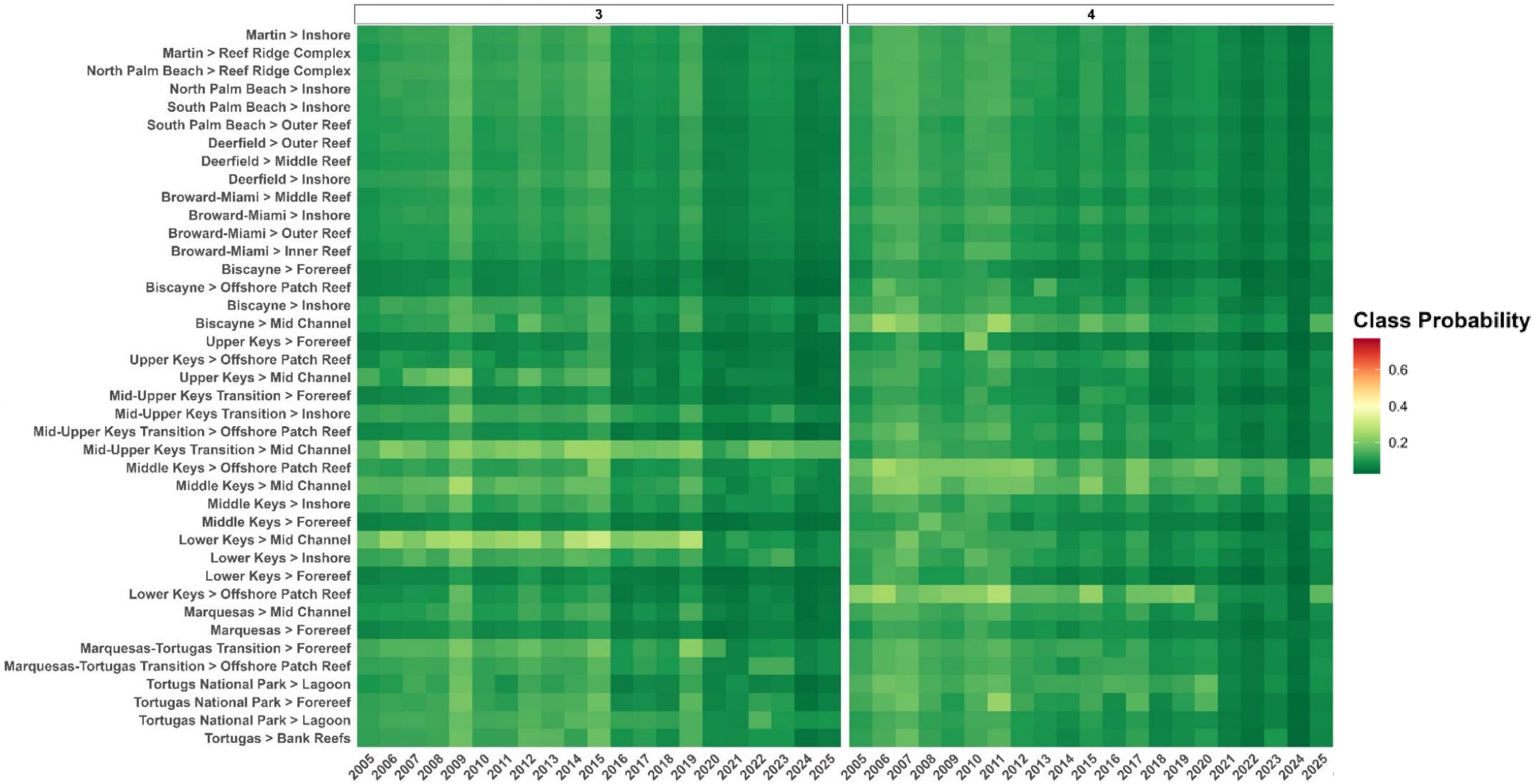

Figure 23. A monitoring programs, DRM, NCRMP, and CREMP combined in the random forest heatmap showing predicted class probabilities of BCG scores for every subregion zone (y-axis) for every sample year (x-axis). Each plot shows predicted probabilities for each BCG level 3 and 4. Lower class probabilities are green to yellow while higher probabilities are orange to red.

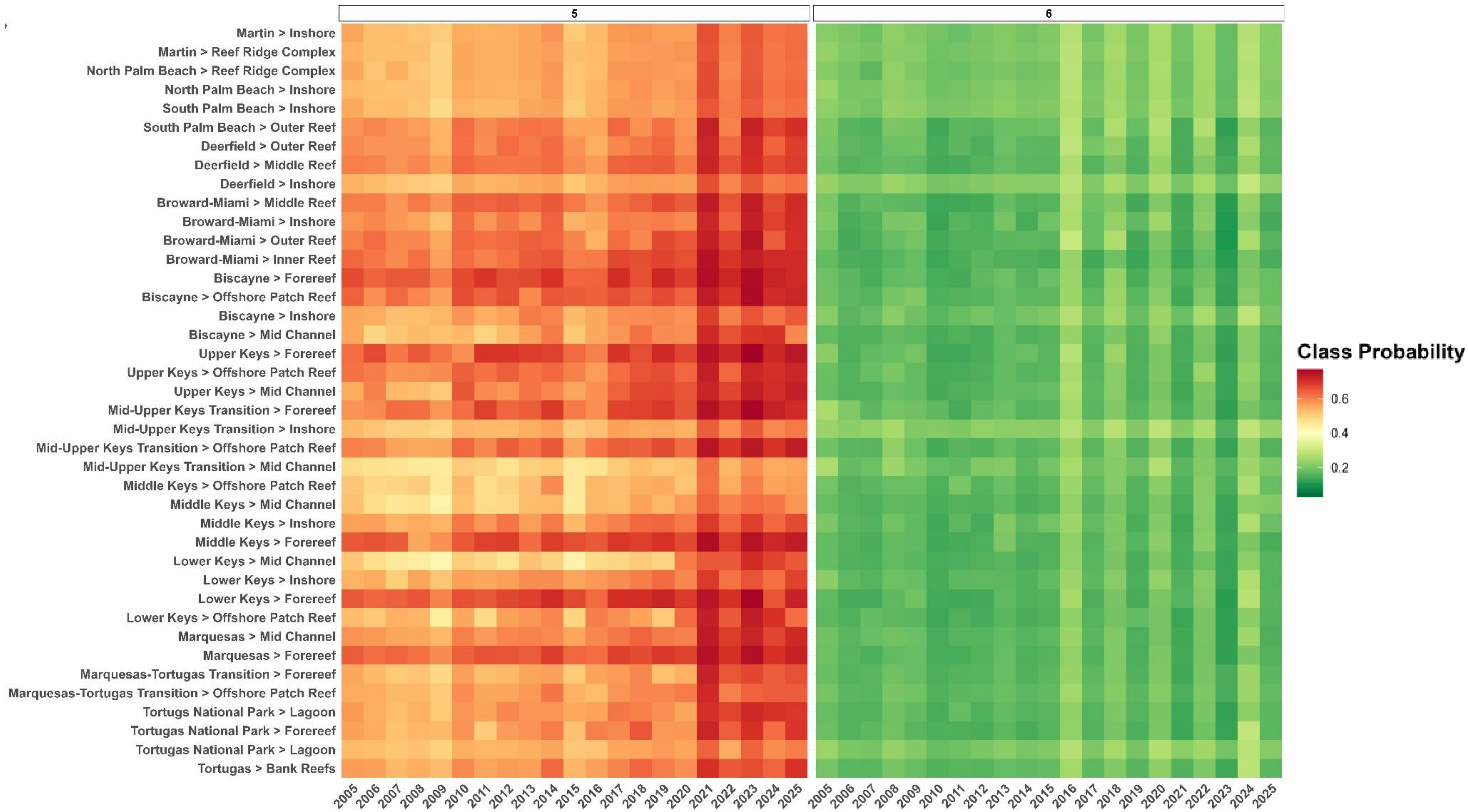

Figure 24. All monitoring programs, DRM, NCRMP, and CREMP combined in the random forest heatmap showing predicted class probabilities of BCG scores for every subregion zone (y-axis) for every sample year (x-axis). Each plot shows predicted probabilities for each BCG level 5 and 6. Lower class probabilities are green to yellow while higher probabilities are orange to red.

3.1. **Spatiotemporal BCG score analyses (Task 3)**

3.1.1. Emerging Hot Spot Space Time Cubes

The long term consistent annual data collections qualified the DRM and CREMP monitoring programs to be used in a robust spatiotemporal analysis called the Space Time Cube. The spatial designation was different for the two programs based on their sampling methodology. DRM's stratified random site sampling provided spatial coverage across all subregion-zone strata providing a more comprehensive analysis of change in habitat condition over time. CREMP's repeated sampling at the same sites over time limited the spatial strata coverage and therefore was only assessed at the site level to analyze community changes over time.

3.1.1.1. DRM

illustrates an overview of DRM's space time cube 3D visualization of mean BCG scores across all subregion zones for every sample year starting from the bottom polygon with the earliest sample in 2005 to the top polygon of mean scores from 2025. Hot Spot results were calculated using the Getis-Ord-Gi score for every sample year available in every subregion-zone or site. Significant cold spots (low scores relative to surrounding strata) occurred in the Dry Tortugas and Marquesas Tortugas Transition areas from 2006 through 2019, but no significant change in those strata since (**Error! Reference source not found.**).

There was a lack of significant pattern change in BCG scores over time within most of the subregions of the Florida Keys (**Error! Reference source not found.**). All associating z-scores and p-values within all subregion-zones of the Middle Keys and Lowers Keys, with the exception of 2021 in the Lower Keys (p-value = 0.02, z-score = 2.25) and 2011 in the Middle Keys (p-value = 0.03, z-score = 2.16 for all subregion zones), were insignificant.

All subregion zones in Biscayne National Park (BNP) were a statistically significant hot spot (high scores relative to surrounding strata) for every sample year with the exception of 2022 and 2023 (**Error! Reference source not found.**). The most notable BNP hot spots occurred consistently between 2008 and 2012 (2008 mean BCG score = 4.5; 2012 mean BCG score = 5.75). The Broward-Miami subregion had few significant BCG score trends with consistent hot spots from 2008 to 2012 (mean BCG score = 5.3). In the Broward-Miami subregion, from 2018 to 2025 there were no statistically significant BCG trends through time (**Error! Reference source not found.**).

A significant cold spot (low scores relative to surrounding strata) occurred in the northernmost regions of the KJCAP between 2018 and 2025 (**Error! Reference source not found.**). All of the most recent time points for South Palm Beach outer reef and inshore, North Palm Beach reef ridge complex and inshore, and Martin reef ridge complex, and inshore showed a significant clustering of scores (Table 8).

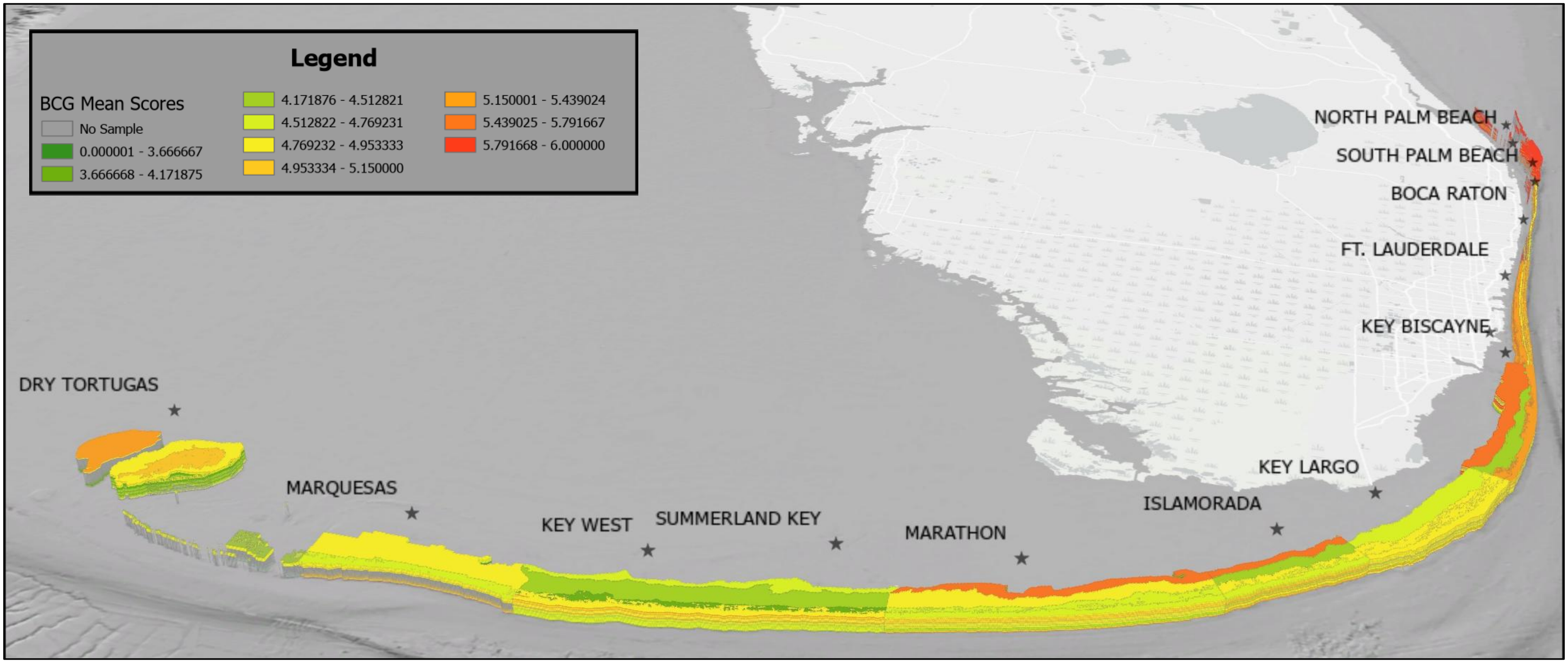

Figure 25. DRM's space time cube 3D visualization of mean BCG scores across all subregion zones for every sample year starting from the bottom polygon with the earliest sample in 2005 to the top polygon of mean scores from 2025.

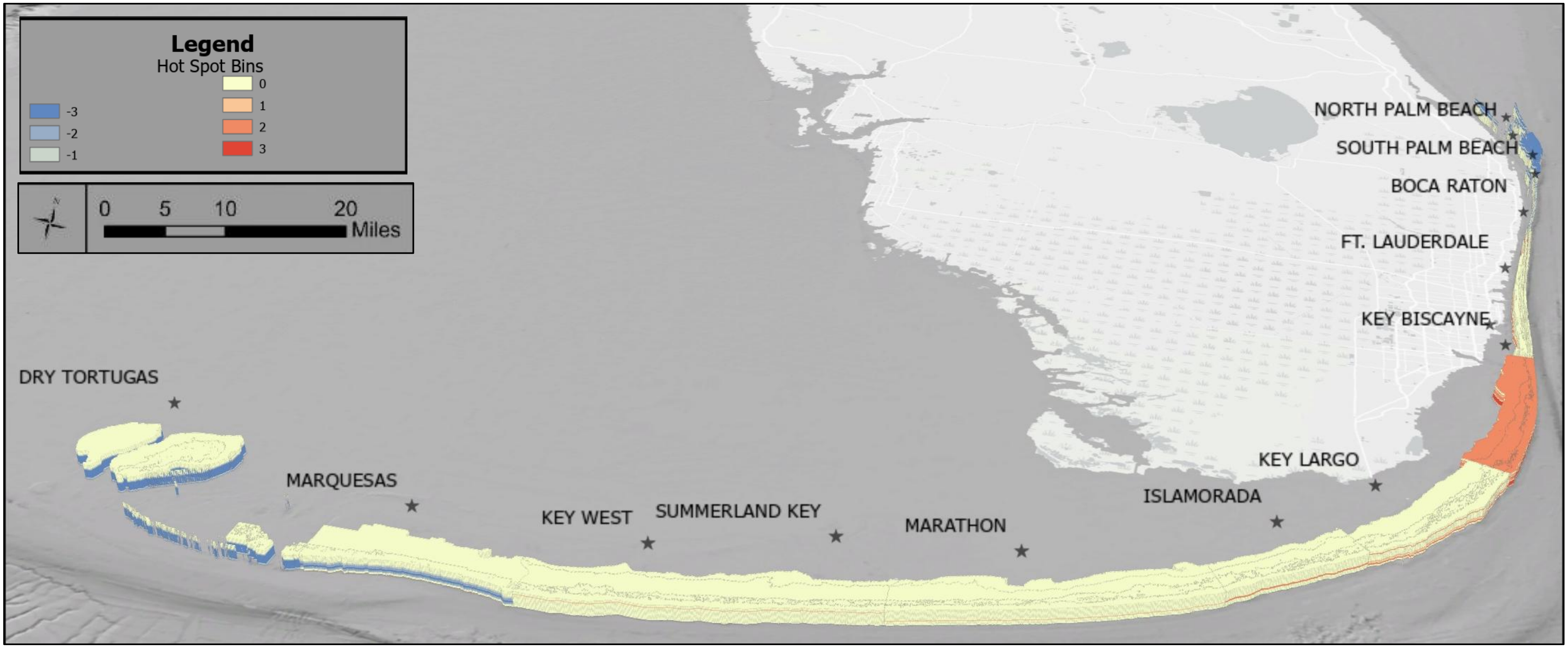

Figure 26. DRM's space time cube 3D visualization hot spot bin scores across all subregion zones for every sample year starting from the bottom polygon with the earliest sample in 2005 to the top polygon of 2025 . Bin levels are tied to confidence levels of 99% (bin 3), 95% (bin 2), and 90% confidence (bin 1). Bins are shaded blue for cold spots and red for hot spots while the cream-colored bins represent no statistically significant pattern occurred (bin 0).

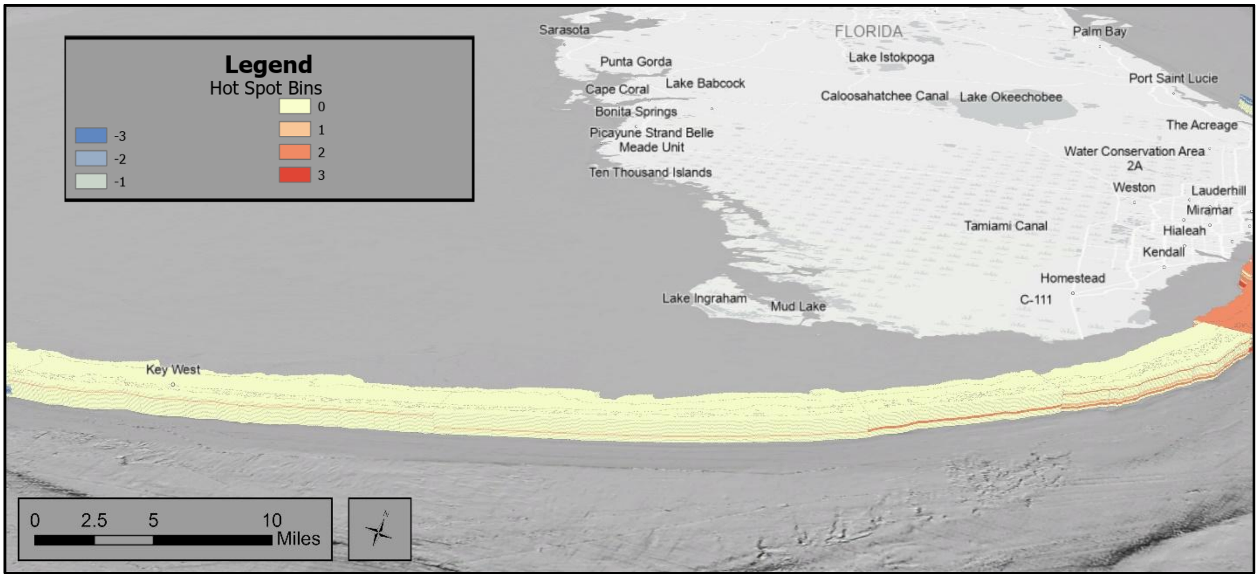

Figure 27. DRM Space Time Cube visualization of Hot Spot trend per each sample year in the subregion zones of the Florida Keys region.

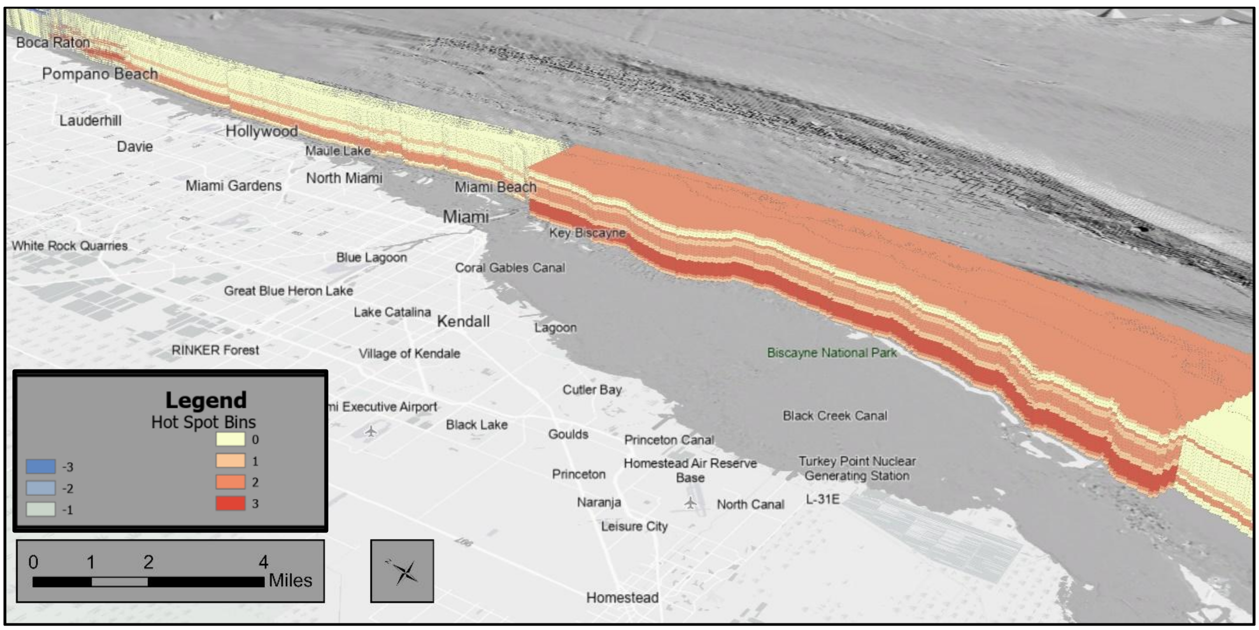

Figure 28. DRM space time cube visualization of hot spot trend per each sample year in the subregion zones of Biscayne National Park (right) and Broward-Miami (left).

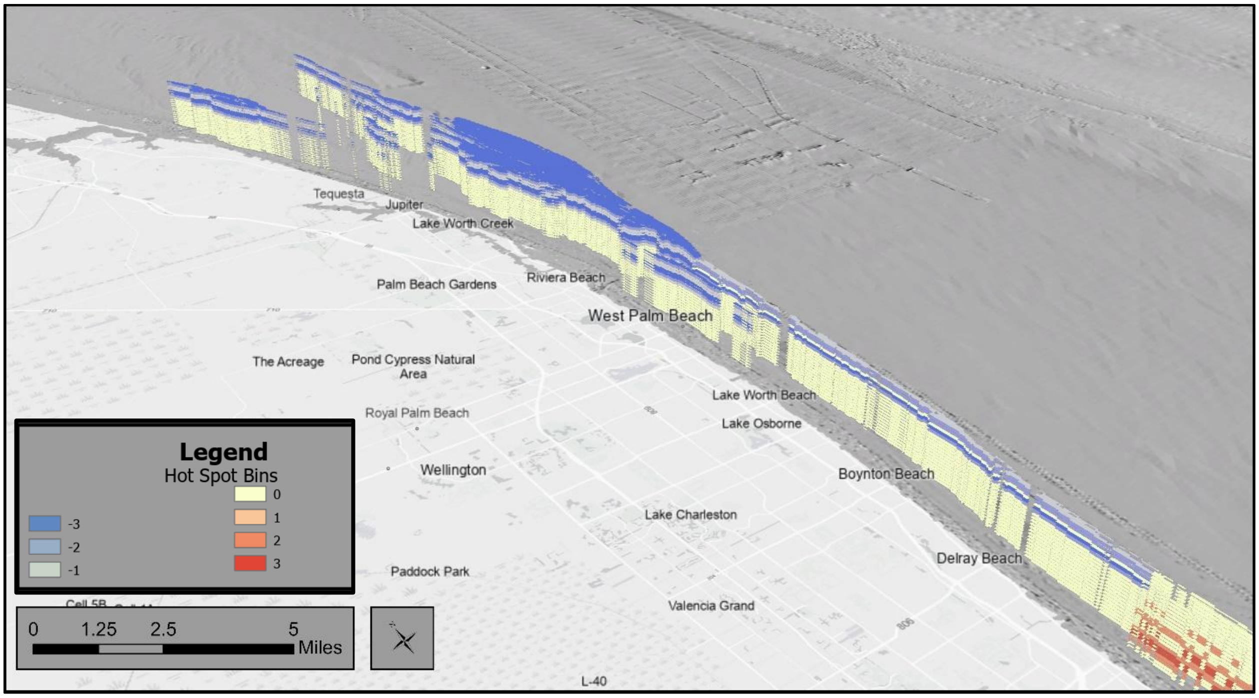

Figure 29. DRM Space Time Cube visualization of Hot Spot trend per each sample year in the subregion zones of South Palm Beach outer reef, South Palm Beach inshore, North Palm Beach reef ridge complex, North Palm Beach inshore, Martin reef ridge complex, and Martin inshore.

The Emerging Hot Spot analysis showed few significant hot or cold spots throughout the entire monitoring period (**Error! Reference source not found.**). The analysis classified the Mid Upper Keys subregion zones as a sporadic hot spot and the BNP subregion zones as diminishing hot spots (Figure 30). Deerfield middle and outer reef subregion zones classified as significant oscillating cold spots (Figure 30). South Palm Beach outer reef and inshore, North Palm Beach reef ridge complex and inshore, and Martin reef ridge complex, and inshore were all classified as a consecutive cold spot (Table 8).

Table 8. Results of the cold spot analysis on the DRM space time cube for the northern most subregion-zones of the study region.

Location	SAMPLE COUNT	Z-SCORE	P-VALUE
Martin Inshore	11	-3.43	0.00
Martin Inshore	5	-4.79	0.00
Martin Inshore	14	-2.17	0.03
Martin Inshore	13	-2.28	0.02
Martin Reef Ridge Complex	1	-2.17	0.03
Martin Reef Ridge Complex	5	-2.28	0.02
Martin Reef Ridge Complex	5	-3.00	0.00
Martin Reef Ridge Complex	1	-3.37	0.00
North Palm Beach Inshore	5	-2.71	0.01
North Palm Beach Inshore	1	-2.17	0.03
North Palm Beach Reef Ridge Complex	4	-3.43	0.00
North Palm Beach Reef Ridge Complex	2	-4.79	0.00
North Palm Beach Reef Ridge Complex	5	-2.17	0.03
North Palm Beach Reef Ridge Complex	6	-2.28	0.02
North Palm Beach Reef Ridge Complex	6	-3.00	0.00
North Palm Beach Reef Ridge Complex	7	-3.37	0.00
South Palm Bech Inshore	3	-2.71	0.01
South Palm Bech Inshore	2	-2.17	0.03
South Palm Bech Inshore	1	-2.28	0.02
South Palm Beach Outer Reef	16	-2.68	0.01
South Palm Beach Outer Reef	23	-4.05	0.00
South Palm Beach Outer Reef	23	-2.63	0.01
South Palm Beach Outer Reef	25	-2.73	0.01
South Palm Beach Outer Reef	16	-2.43	0.02

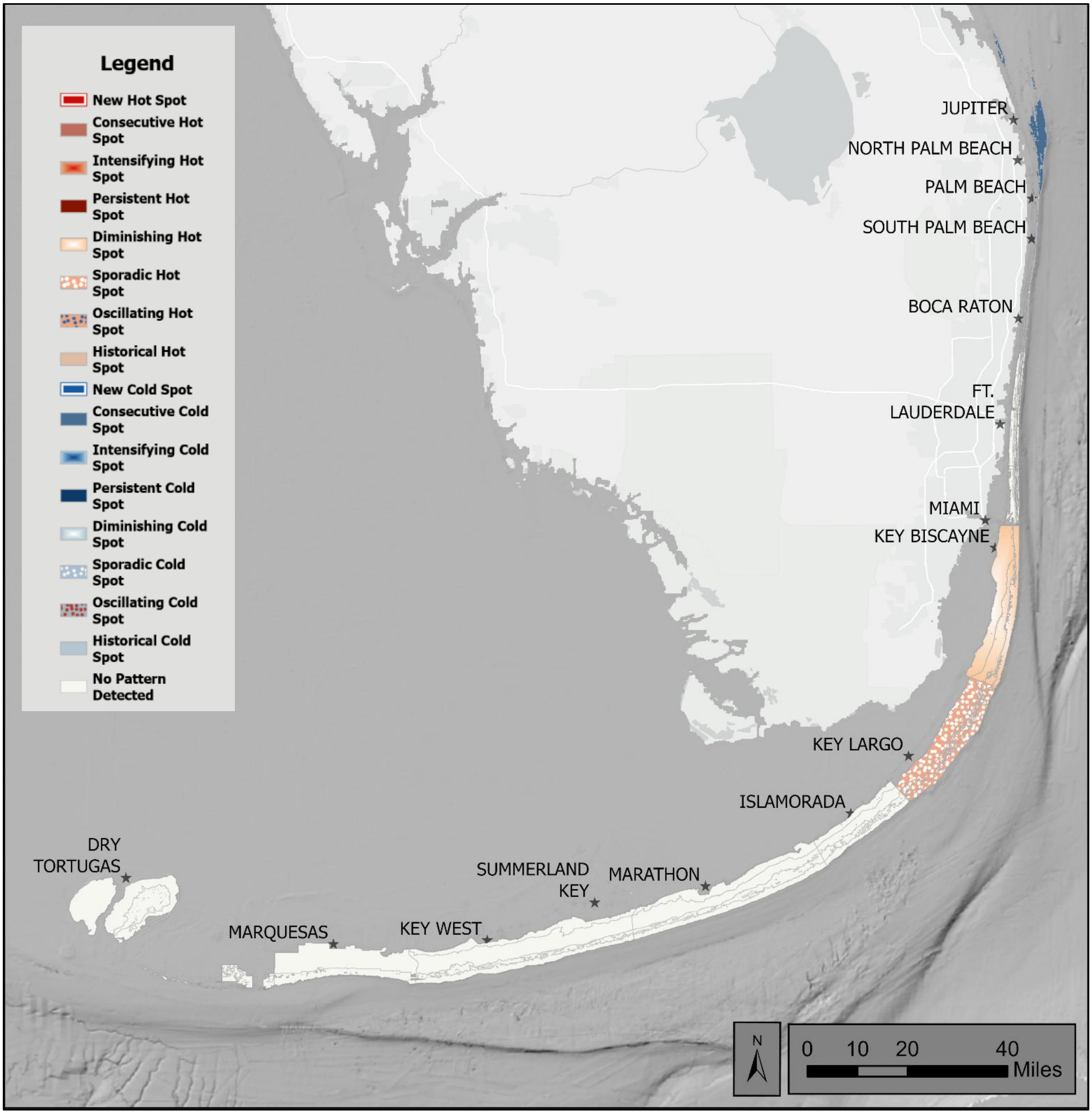

Figure 30. DRM emerging hot spot results based off the space time cube results.

3.1.1.1. CREMP

Error! Reference source not found. illustrates an overview of CREMP's space time cube 3D visualization of mean BCG scores across all subregion zones for every sample year at each CREMP site starting from the bottom polygon with the earliest sample in 2011 to the top polygon of mean scores from 2024. Mean BCG scores overall for CREMP sites significantly increased (p-value = 0.001) through time from 2011 through 2024 for all sites combined (Figure 31). Statistically significant clustering of cold spots persisted throughout all CREMP Dry Tortugas sites from 2019 to 2024 (**Error! Reference source not found.** & 33; Table 9).

Other areas with consistent scores through time were four CREMP sites in the Lower Keys region residing in the inshore, mid channel and forereef strata had a cold spot for every space time cube with the exception of the first two sample years of 2011 and 2012 (Figure 34). Five out of the seven CREMP sites in the Middle Keys also experience stable cold spot trends between 2014 and 2024 (Figure 34).

Conversely, the Martin inshore subregion-zone had statistically significant hot spot trend between 2017 and 2024 (mean BCG score = 6.0). These two CREMP sites were classified as statistically significant cold spot sites from 2013 through 2016 (mean BCG score = 5.25) (Figure 35).

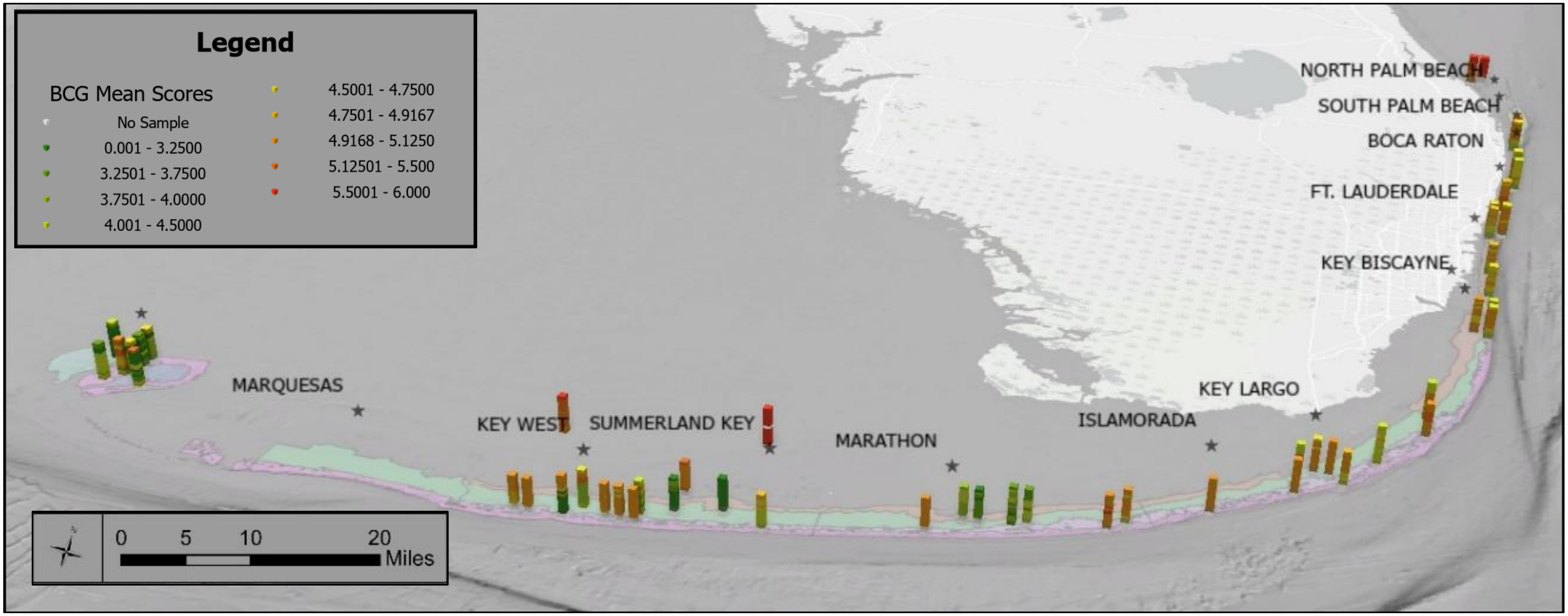

Figure 31. Calculated mean BCG scores for each CREMP site at each sample year along the entire FCR with.

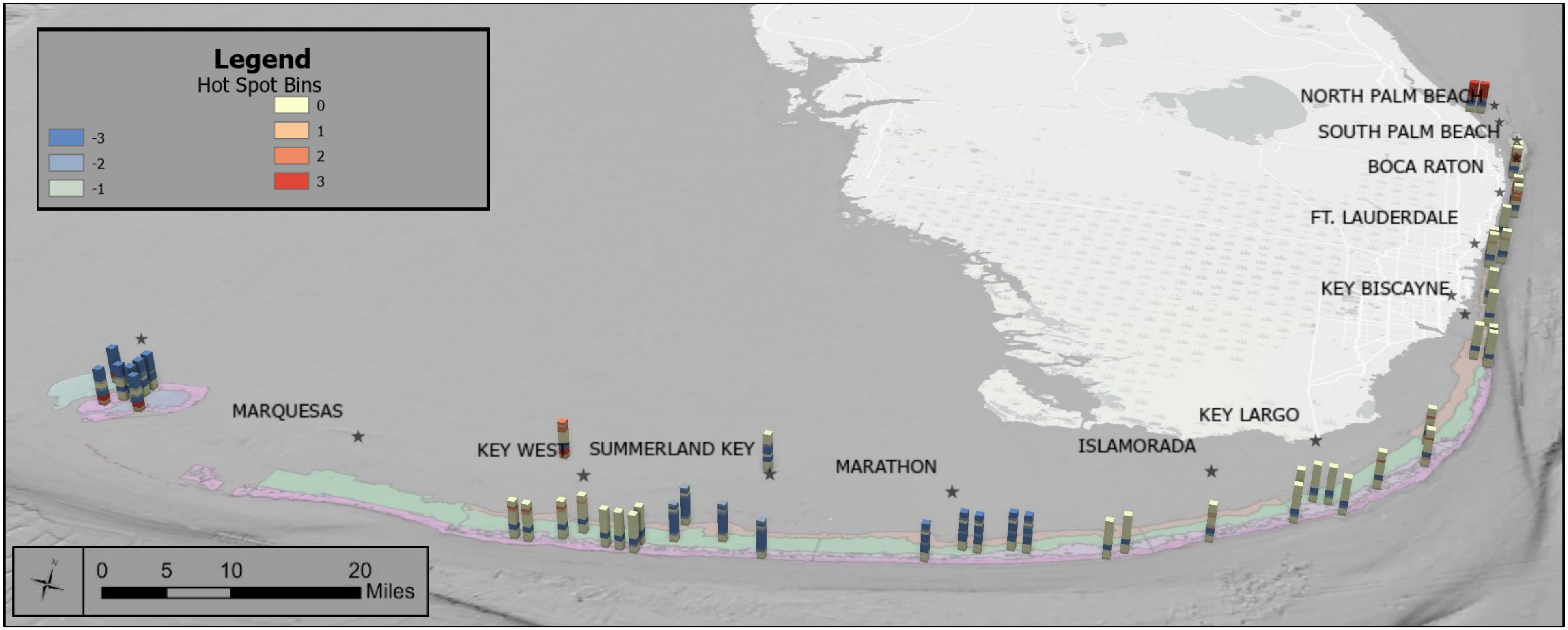

Figure 32. CREMP's space time cube 3D visualization hot spot bin scores across all subregion zones for every sample year starting from the bottom polygon with the earliest sample in 2011 to the top polygon of 2024.

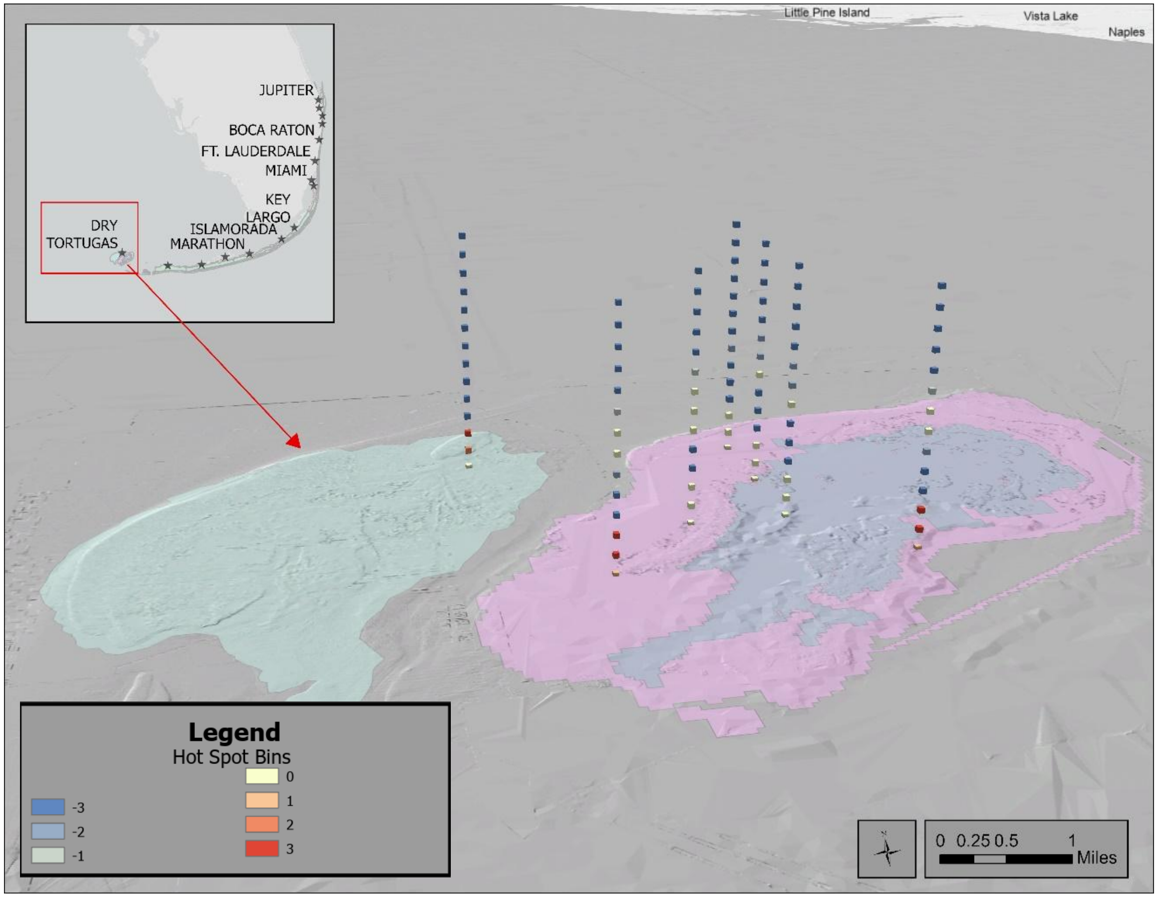

Figure 33. CRMP hot spot results in the Dry Tortugas region based on the space time cube analysis for sample years 2011-2024.

Table 9. Example list of CREMP hot spot results for Dry Tortugas sites in 2024. Full list of significant results can be found in the appendix.

CREMP Space Time Bin Site ID	Hot Spot p-value	z- score	Mean BCG Value
420	<0.001	-3.70	4.75
406	<0.001	-4.80	4.25
462	<0.001	-3.55	3.75
532	<0.001	-4.76	3.50
518	<0.001	-3.55	4.75
546	<0.001	-4.76	5.25
504	<0.001	-4.10	5.00

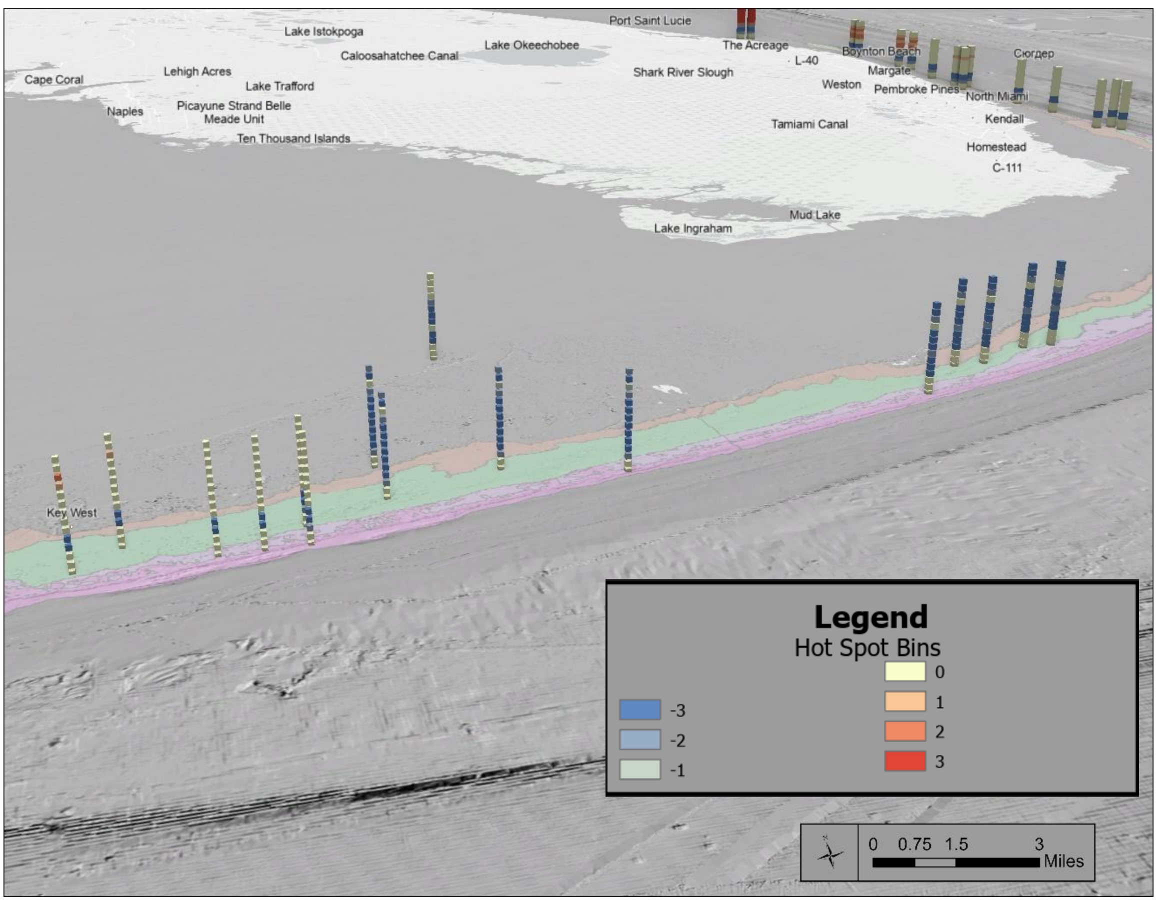

Figure 34. CREMP sites displayed as hot spot binned scores in the Lower Keys subregions of Florida's Coral Reef.

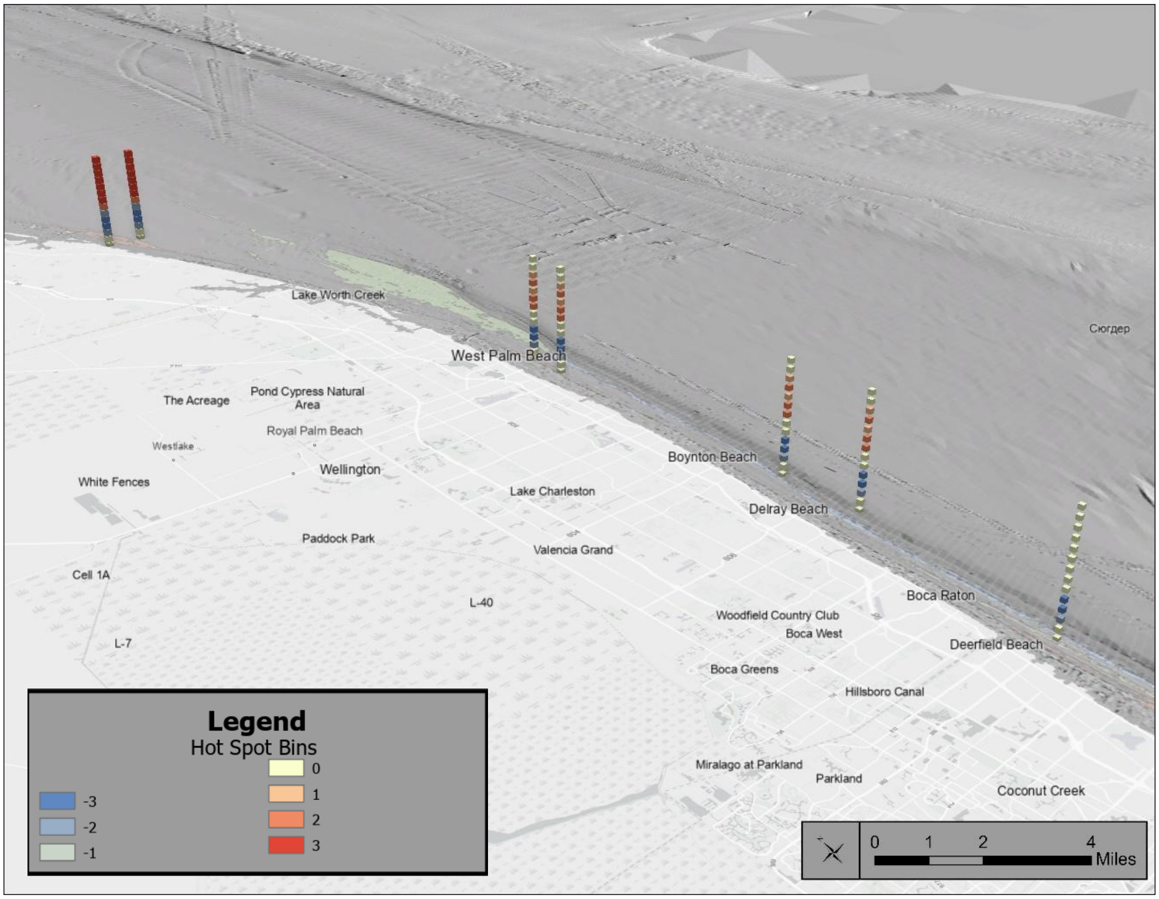

Figure 35. CREMP hot spot space time cube results within the northern subregion zones of the KJCAP area.

The Emerging Hot Spot analysis was computed using the Mann-Kendall trend test on CREMP BCG sites as a way to assess temporal significance of the hot spots created by the Space Time Cube. Overall, there was significant clustering predominantly seen within the Dry Tortugas, Lower Keys, Middle Keys, and Martin subregions (Figure 36). The Dry Tortugas National Park forereef and lagoon sites along the western side of the region experienced overall sporadic cold spots and one consecutive cold spot (percent significant cold spot = 57.14 %, 71.43%, 71.43% for the sporadic sites and 78.57% for the consecutive cold spot site; Figure 36). The Lower Keys forereef and mid-channel strata classified as consecutive cold spots (percent cold spot = 85.71%). The five sample stations in the Middle Keys classified as sporadic cold spots with a moderate amount of significance in scores trending down through time (percent significant cold spot = 71.42%). The Maritn inshore sites classified as oscillating hot spots (percent significant hot spot = 57.14%).

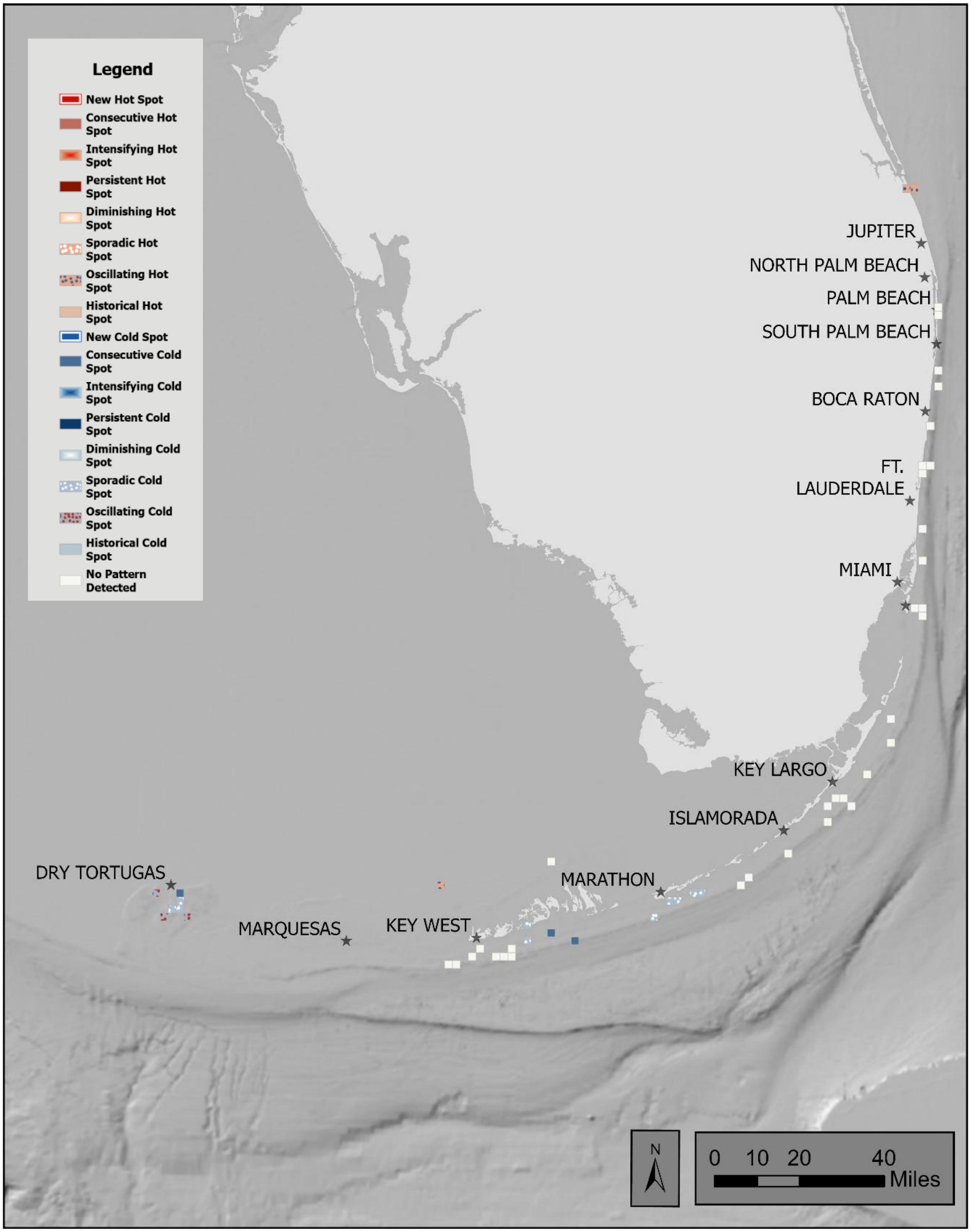

Figure 36. CREMP emerging hot spot results based on the space time cube analysis.

3.1.2. Optimized Hot Spots

3.1.2.1. NCRMP

The NCRMP dataset was limited by its temporal extent and therefore the Emerging Hot Spot Space Time Cube analysis could not be used. Instead, an Optimized Hot Spot analysis was a choice fit. The analysis was run for all samples for each sampling year (2016, 2018, 2022, and 2024) as individual programs and all combined (Figures 37 & 38). This provided a relative cluster analysis across the FCR with distinct spatiotemporal patterns.

In 2016 there was only one area of significant clustering which were cold spots in the southern area of the Biscayne National Park subregion (Figure 38). In 2018, hot spot clustering appeared in the northern region of the KJCAP around Jupiter as well as the southern edge of the Dry Tortugas Bank Reefs while maintaining the single cold spot cluster off Biscayne National Park. By 2022, hot spot clustering increased to more sites around Jupiter while the Biscayne National Park cold spot cluster disappeared and a new cold spot cluster emerged in the Mid Upper Keys subregions. In 2024, there was an emergence of significant hot spot clustering within the Dry Tortugas, Deerfield, and Martin subregions. Cold spot clusters were still present and expanded slightly within Biscayne National Park.

An emerging hot spot analysis combining both monitoring programs of DRM and NCRMP together revealed the masked and predominant oscillation effect of combining programs together (Figure 39). It was evident compared to the other hot spots (Figures 30, 36, and 37) that the combined program emerging hot spot revealed drastically different sporadic and oscillating hot spots for almost the entire FCR.

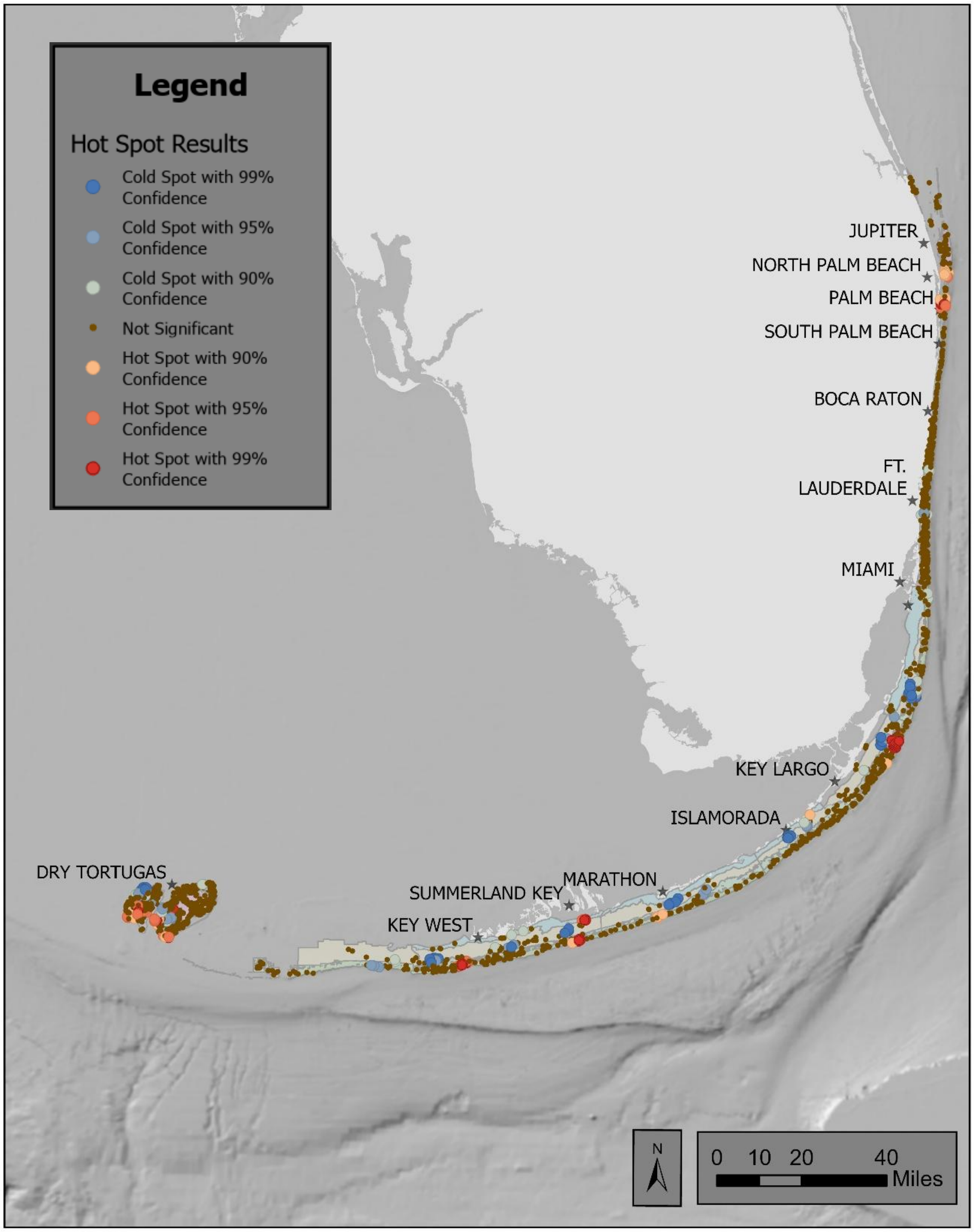

Figure 37. NCRMP Optimized Hot Spot analysis for all monitoring programs and all sample years of 2016, 2018, 2022, and 2024 combined.

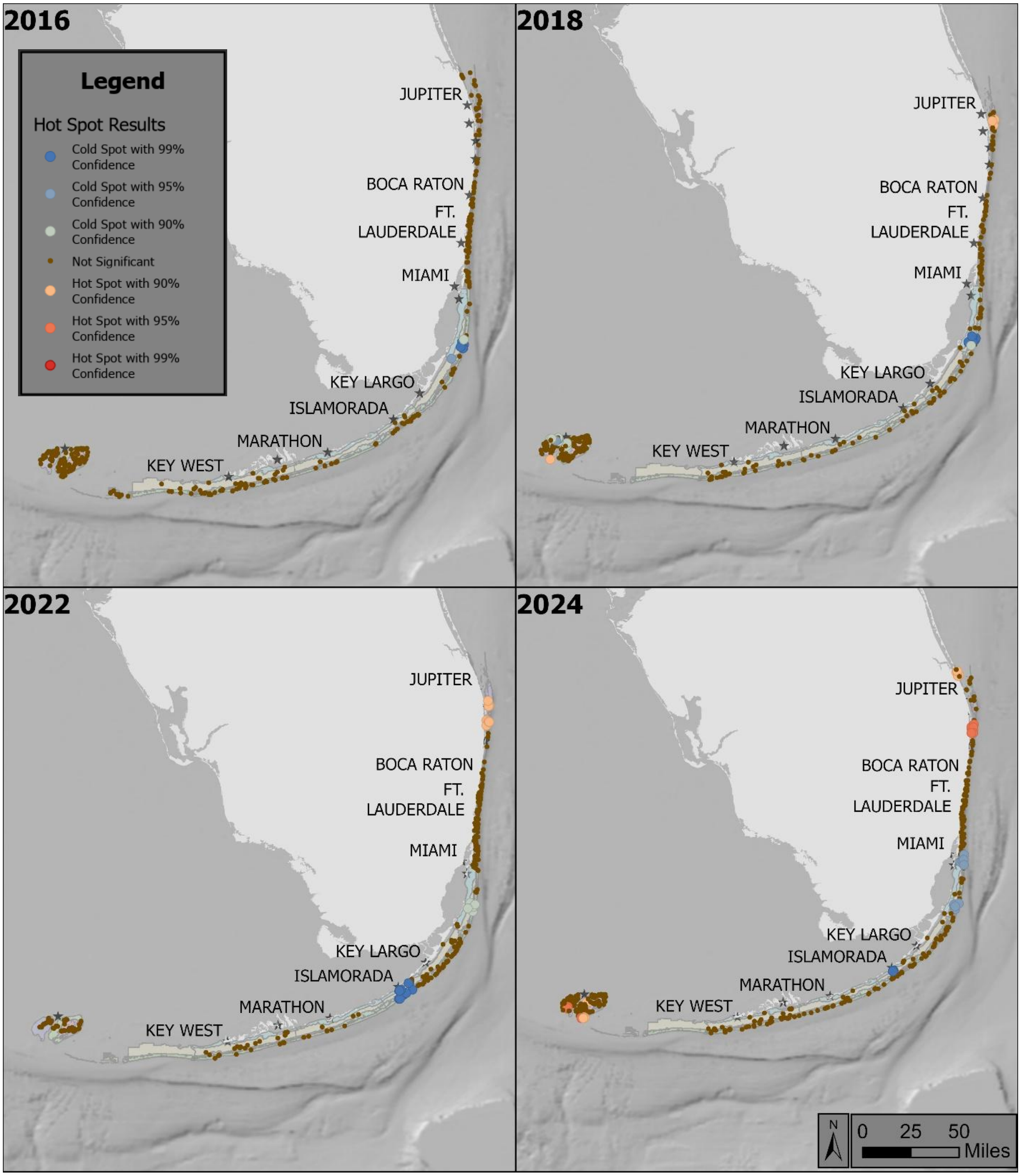

Figure 38. NCRMP Optimized hot spot analysis time series for every NCRMP sample year. Sample years are bolded below each map image.

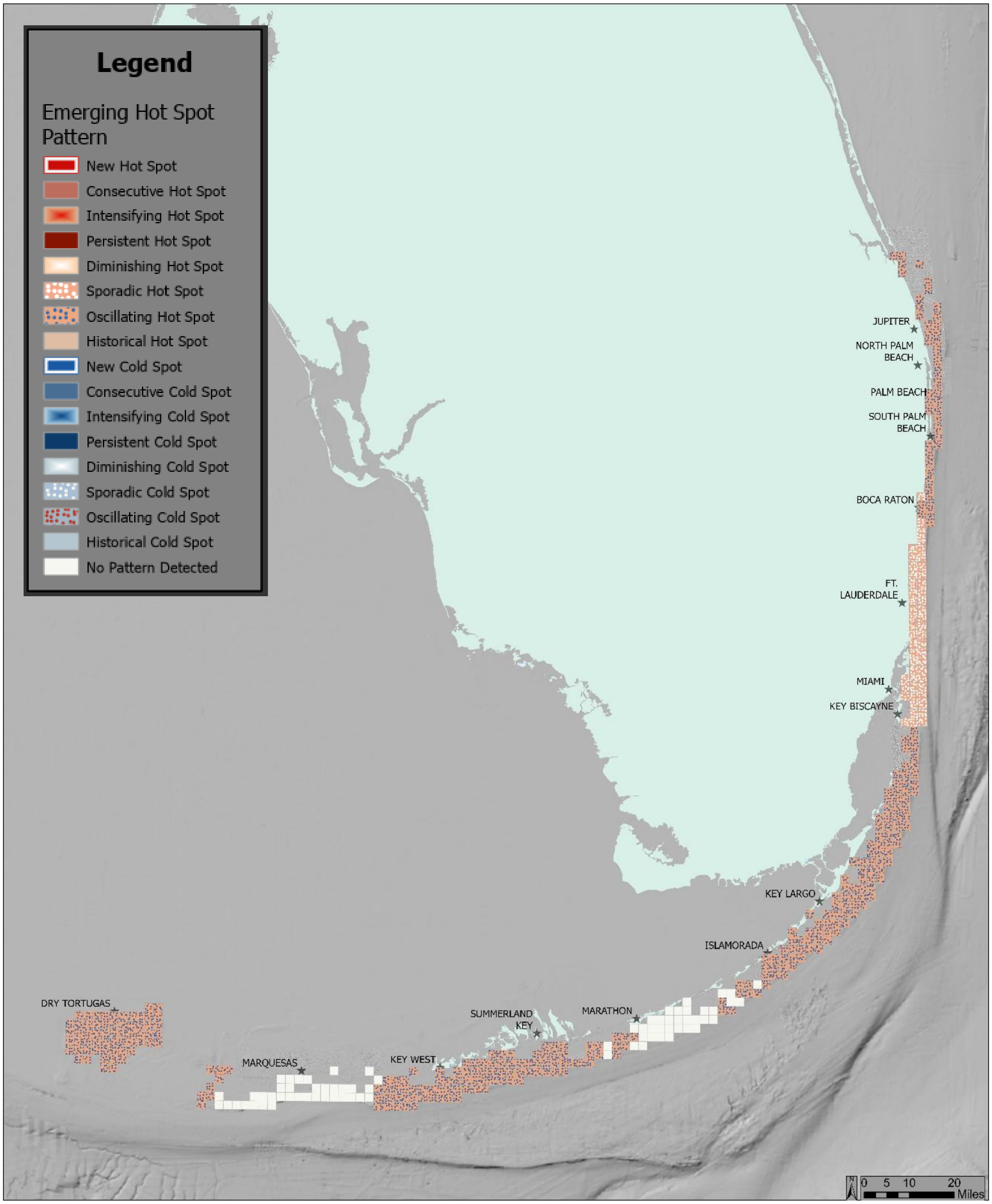

Figure 39. Results of the Emerging Hot Spot Analysis combining the DRM and NCRMP monitoring programs for analysis that produced oscillating and sporadic pattern of BCG scores through time along most of FCR.

4. DISCUSSION

Three data sources were used in calibrating the Florida Coral Reef BCG – the Coral Reef Evaluation and Monitoring Project (CREMP, includes SECREMP, DT CREMP, and KEYS CREMP); the National Coral Reef Monitoring Program (NCRMP); and the Disturbance Response Monitoring (DRM) program (details on these programs are shown in Appendix D). Due to major differences between the programs that include site selection, survey locations, methodology, unequal sampling effort, sampling different times of year, and differences in metrics collected, each program's BCG scores were analyzed separately and then combined. We used the results to discuss how the program differences may affect the BCG scores, the problems with combining all data into one analysis, and the spatiotemporal patterns of BCG condition across the FCR.

4.1. **Monitoring Program Differences**

4.1.1. Survey design

The biggest distinction between survey programs is that CREMP (SECREMP, DT CREMP, and KEYS CREMP) assesses the same large area of reef (demographic survey = 40 m²) over time using permanent transects, whereas NCRMP and DRM assess smaller areas (NCRMP = 10 m²; DRM = 20 m²) that are randomly chosen each year resulting in different area reef surveyed annually. CREMP's consistency is a major asset because the program maintains consistent sampling effort through time and space (Figure 5). This comes with a tradeoff of less spatial coverage as the program only surveyed twenty-four subregion zone strata, however CREMP's project goals are to assess long term benthic community changes at representative sites over time (Ruzicka et al., 2022), not to assess all spatial strata. CREMP's fixed site monitoring facilitates direct temporal comparisons of reef condition over time. Since adding the demographic surveys to CREMP in 2014, they now collect the most data of the three programs at a given site and the same sampling effort at the same locations. Consequently, the CREMP BCG scores were the most consistent over time, had the narrowest distributed scores out of any program, and the random forest model had the lowest error rate. These results suggest that repeated sampling of permanent transects reduced the temporal variance in BCG scores. This illustrates that the BCG scoring can be used as a relative metric within a monitoring program to measure reef condition.

DRM and NCRMP are randomized surveys allowing them to cover thirty-nine subregion zone strata. The randomized surveys were much more variable across space and time. This variability arose from not surveying the same locations, unequal sampling effort, sampling different times of year, and differences in metrics collected. These surveys were designed to assess reef condition at the strata level by sacrificing the amount of information collected at one site to collect data at many more sites. The randomized surveys collect less robust site-specific information of smaller areas (demographic surveys: CREMP = 40 m²; DRM = 20 m²; NCRMP = 10 m²). Consequently, variability was much higher in these datasets which was reflective in their BCG scores and random forest model error.

NCRMP has higher data indicator resolution than DRM. NCRMP conducts both a coral demographic survey and a benthic cover line point interest survey that estimates ecologically important cover types of groups like macroalgae, sponges, and crustose coralline algae (CCA) presence (NOAA Southeast Fisheries Science Center; NOAA National Centers for Coastal Ocean Science, 2018). Macroalgae presence is a narrative rule in level 5 of the BCG scoring criteria and therefore will score higher up the BCG scale than data with no surveyed macroalgae (Bradley & Jessup, 2024). DRM possess the lowest data indicator of all programs as they only conduct coral demographics and do not include benthic cover data (Harrell, Stein, & Ruzicka, 2024). This is particularly limiting for BCG condition rules because macroalgae coverage at a site was a key indicator of condition for the experts creating the rules (Bradley and Jessup, 2024).

4.1.2. Within sample years

Differences in sampling effort across months within a sample year also varied significantly across programs. The CREMP program conducted over 66% of the surveys between May and the end of July and month had a significant effect on the BCG scores. Since the BCG model accounts for stress indicators such as bleaching and disease in the scoring, surveys conducted before signs of heat stress emerge, may help explain why CREMP had the lowest mean BCGs scores (4.7 ±0.6).

DRM was designed to assess bleaching, so data were collected later in the summer, during the highest heat stress and they were more likely to capture bleaching and disease. Over 75% of DRM surveys were conducted after August 30. This aligns with the timing of most bleaching events in south Florida, which tend to occur in months August through October (Lindsey, 2023). This design allowed DRM BCG scores to reflect thermal stress effects. There were higher BCG scores for most subregion-zones during what is considered extremely intense bleaching years of South Florida's history in 2014 and 2023 (NOAA Coral Reef Watch, 2025; Figure 25; Figure 25; Appendix C).

NCRMP sampling window peaked in August and September with over 50% of surveys conducted in those months, about 30% before August, and 20% after September. This distribution provided a mix of high and low stress periods throughout the sampling season, likely giving higher variability of BCG scores. NCRMP showed declines in reef condition since 2016 with higher probabilities of a BCG 5 until 2026 where the probability of being a BCG 6 became very high. This timing coincides with the migration of SCTLD across the FCR (Dobbelaere et al., 2022).

4.1.3. Between sample years

Large differences in sample effort within and between programs has occurred over time, which must be a consideration in any data analyses. CREMP demographic collections started in 2011 at a limited number of sites, but were very consistent between 2014 and 2024. There are no demographic data available for surveys prior to 2011. The DRM monitoring program sampled every year, but had extremely low sample counts of less than 100 sites in 2005, 2020, and 2021. In 2020, DRM effort doubled to around 400 samples and in 2023-2025 increased to about 600 samples. This unequal sampling can have effects on temporal analyses, especially if differences in effort were not weighted evenly across the strata.

Florida NCRMP sampling effort varied across space and time in challenging ways that must also be considered. NCRMP was designed as a biennial survey by region, but this was not always the case. In 2014, over 400 sites were sampled across the FCR. In 2015, 100 sites were sampled. In 2016 and 2018, about 300 sites were sampled, but in 2020 less than 100 were collected in the KJCAP and in 2021 about 150 were collected in the Keys. In 2022 about 350 samples were collected and in 2024 over 500. This uneven distribution of effort across space and time can influence many aspects of data analyses and should be taken with caution. It is recommended that the monitoring programs of NCRMP and DRM omit sample years with extremely low sampling effort. Likewise, the NCRMP monitoring program displays very low sampling effort specifically during the years 2015, 2020, and 2021 with uneven spatial sampling as well making it a good contender to omit these sample years from NCRMP's results for further analysis.

4.2. Problems combining all datasets into one analysis

It is important to emphasize patterns seen across the datasets may be related to reef condition, habitat type, region differences, or program sampling differences. Underlying natural reef conditions can be masked easily when programs are analyzed together due to their inconsistencies in sampling and objectives (Janousek, Hahn, & Dreitz, 2019). Combining program data can produce a false result, in this case striping effect due to the increased sampling size in specific years of NCRMP sampling. There were temporal and spatial variance within the strata when combining programs into a single analysis (Figure 3). In 2014, NCRMP began sampling on even years (with the exception of sampling in 2015 and 2021) introducing a lot more samples into the database. This caused large increases of effort in the database during NCRMP years resulting in uneven data distribution. Because NCRMP had the highest mean scores, the addition of uneven samples created an oscillating effect in BCG scores on even years over odd ones. This had profound effects on the Emerging Hot Spot analysis which showed oscillating and sporadic hot spots over most of the reef strata (Figure 39). This also produced noticeable annual striping in the expect BCG score plot and predictions of unusually high scores for 2024 (Figure 24). For these reasons, we don't recommend combining monitoring data from multiple programs into a single analysis without detailed considerations on the effects it may have on the outputs.

4.2.1. Between habitat strata

The Florida BCG was developed by conceptualizing the expected condition of a shallow forereef community in Florida. The narrative rules were the expectations of the experts for that habitat, however it was recognized that the FCR has biogeographic shifts in communities with increasing latitude. Applying the narrative rules developed for a specific habitat to all habitats likely created unreasonable expectations for some habitats. For example, the same BCG rules applied to Martin County inshore reef and the Tortugas Bank, even though Martin County inshore would never have the same community as the Dry Tortugas. This inequity in the scoring provides challenges when analyzing the BCG scores across strata because the scoring is not adjusted for the expected community in a given habitat. Therefore, it is recommended that BCG score comparisons are made within the context of subregion and habitat strata

4.3. **Spatial Temporal Trends**

4.3.1. Between habitat strata

Differences between strata scores were evident in all programs indicating that some strata were in better condition than others. This was very noticeable with the Mid Channel reefs and Offshore patch reef having lower scores than the forereef and inshore sites and with the Dry Tortugas having lower scores than other regions. This likely influenced the hot spot clustering analyses because the Mid Channel reefs are flanked by inshore and offshore strata with higher scores.

4.3.2. DRM

DRM had the longest historical time series and showed a noticeable rise in the probability of a BCG 5 across all strata since 2019. This rise coincided with an increase in sample effort but also with SCTLD and the 4th global bleaching event. The DRM Space Time Cube and Emerging Hot Spot analyses showed sporadic and diminishing hot spots in the Upper Keys and Biscayne National Park subregions and the Palm Beach subregions had consecutive cold spots. Both cluster patterns indicate a declining reef condition due to the presence of high surrounding BCG scores through time. Biscayne's diminishing hot spots indicated that reef condition declined for at least 19 out of the 21 sample years based on BCG scores and the amount of declined reef sites is steadily decreasing over time (Esri, 2026b; Ullah-Khan et al., 2023). These declines coincide with increasing urbanization and development of the nearby city and port of Miami that produces large amounts of groundwater runoff, pollution, increases sedimentation loads, and more (Principe et al., 2011). Wastewater outfall locations in close proximity to this subregion are well known to emit contaminated wastewater than has been traced back to a significant source of land-based source pollutions influencing coral communities within the region (Staley et al., 2017; Lirman et al., 2003). While extreme anthropogenic pressures have globally impacted corals, more recent studies of the coral communities surrounding Biscayne Bay indicate some resilience or stability within the environment as monitoring since 2018 in some studies report coral abundance is higher here in the urban proximity to the Port of Miami than nearby reefs (Enochs et al., 2023). A recent study conducted in 2016, assessed coral resilience in different reef zones and determined the mid channel reef zone in the Florida Keys was the second most resilient reef zone of the entire FCR (Maynard et al., 2017). With proximity to the highly urbanized port of Miami and outfall sewage location increased, coastal runoff and other nutrient signals may be less intense in this subregion even though it neighbors Biscayne Bay where reef decline is more significant (Whitall et al., 2019; Dobbelaere et al., 2026). Wastewater outfall locations are also a significant point of water quality decline for reefs however with the trajectory of the current push mostly northward, the subregions south of the Inlets or ports tend to have less impact from these poor water quality plumes (Futch, et al., 2011; Staley et al., 2017; Dobbelaere et al., 2026). Outfalls may pose a more significant risk than runoff as contamination from outfalls in the southern regions of FCR were the most significant source of land-based source pollution influencing community structure along the reefs (Staley et al., 2017).

The Dry Tortugas coral communities have historically been in the best condition relative to the rest of the FCR and BCG scores reflected this. The Dry Tortugas had the lowest historical scores of any region. However, in the last few years, BCG scores climbed significantly, indicating measurable reef condition decline. This change coincides with the emergence of SCTLD in 2021 and the recent impacts of the 4th global bleaching event, notably in 2023. BCG scores indicate that the severity and abundance of marine stressors to this region may have hit a tipping point as most recent time points in the Dry Tortugas have no significant cold spot since 2021 indicating the condition in the region is worsening. The declining BCG scores suggest that the frequency of stressors is outpacing the capacity of the reef to recover naturally (Towle et al., 2022; Jones et al., 2022).

4.3.3. NCRMP

When isolated, NCRMP BCG scores averaged higher than any other program, but showed consistent spatiotemporal patterns. NCRMP showed most consistent declines in reef condition since 2016 than DRM with higher probabilities of a BCG 5 until 2026 where the probability of being a BCG 6 became very high. This may be due to the inclusion of macroalgae in the surveys as stony coral cover has been consistently declining in every region with corresponding increases in macroalgae cover (Towle et al., 2022; CRCP, 2024; Jones et al., 2022). NCRMP BCG scores also showed in the Dry Tortugas and Martin County corroborating the DRM results. The increasing presence of hot spots around the Dry Tortugas suggests a significant declining condition in the region.

The persistence of hot spot clustering in the norther KJCAP through time may be indicative of declined reef health, but also the natural reef structure that exists in the northern latitudes as corals are naturally less diverse and abundant there (Burman et al., 2012). It is important to account for differences in the natural geological formation of the seascapes between the northern KJCAP and its southern counterparts are distinct in habitat type as benthic habitats were different in the northern regions of the KJCAP (Walker and Gilliam, 2013). Anthropogenic impacts like poor water quality and disease are likely also a factor playing into the persistent hot spots in the northern region as nitrogen enrichment is more significant from land-based pollutants in Martin County and the presence of SCTLD was documented widely after 2016 and 2017 (Collier et al., 2008; CDHC, 2020).

4.3.4. CREMP

CREMP BCG scores were mostly stable over time but varied significantly by strata, especially in the inshore and forereef zones which were generally higher than most other subregion-zones based on the random forest model. Lower Keys offshore reef sites tend to possess lowered water clarity than its neighboring zones, suggesting water quality may be a contributing factor to declining reef conditions and in turn higher BCG trends experienced in the inshore and forereef zones of the Lower Keys (Toth et al., 2022). Historically, there has been evidence of higher stressors experienced by the forereefs and inshore regions with reports of forereefs and inshore patch reefs off the Florida Keys and Dry Tortugas repeatedly loosing significant coral cover after major stressor events like the 2005 cold water bleaching event and the 2014 SCTLD onset (Jones et al., 2022). The introduction of SCTLD in 2014 became a major driver of reef decline through time as the disease spread across the entire reef tract at an unprecedented rate (Walton et al., 2018). According to a study assessing frequent disturbances on FCR, between 2015 to 2016, there was a 46% drop in stony coral cover within the KJCAP region and two years later in the

Florida Keys forereefs there was a reported 22% decline in stony coral cover (Jones et al., 2022).

In the Dry Tortugas, CREMP BCG scores oscillated between hot and cold while in 2024 exhibited lower than average BCG scores suggesting improving reef condition in the Dry Tortugas unlike the DRM and NCRMP results. In North Palm Beach inshore, BCG scores oscillated between hot and cold spot with 2024 indicating further declining reef condition with a hot spot.

4.3.5. SCTLD

SCTLD is known to be one of the most wide-spread diseases to occur along FCR. Historically, this disease has been reported to cause significant region-wide declines in coral densities and diversities (Walton, Haynes, & Gilliam, 2018). The disease outbreak of SCTLD is well known to be a multi-year stressor event that happens to coincide with the three warmest years on record at the time and two major bleaching events back-to-back (NOAA Coral Reef Watch, 2016). This multi-stressor, and multi-year event led to dramatic declines throughout the KJ-CAP region by 2016 and revealed approximately a 30% loss in coral density and more than a 60% loss in live stony coral tissue based on surveys conducted from 2012-2016 (Walton, Haynes, & Gilliam, 2018). This coral loss may be evident in the BCG score trends as the expected probabilities per BCG class of the NCRMP dataset identified the year 2016 with a much higher probability at being classed as a BCG level 5 or 6 than a level 3 or 4. The DRM heat map of expected BCG scores also identifies a shift in reef health attributed to the onset of SCTLD across most subregion zones for 2014 and 2016 to higher BCG scores of level 5.

4.4. **Practical Implementations of the BCG Model by State and Local Governments**

In 2013, scientists from Maryland, Delaware, Pennsylvania, Virginia, US EPA, consulting groups, and academia developed a BCG for the Northern Piedmont. Montgomery County, MD used this BCG to inform the public and county decision makers about the potential impact of development on Ten Mile Creek (TMC) watershed, a high-quality watershed with undisturbed/minimally disturbed conditions. Based on the analysis and BCG results, Montgomery County Planning and Montgomery County Department of Environmental Protection provided several possible development scenarios with predicted outcomes and recommended one that would allow some development in the TMC area while maintaining good environmental conditions. The County Council accepted the recommended option, and it was adopted on April 1, 2014 (EPA 2016).

Alabama, California and Minnesota have incorporated stream BCGs as part of their biological assessment and criteria programs (EPA 2021). For example, Minnesota uses the BCG as one tool to determine if aquatic life use has been attained for a site (MPCA 2018). EPA Region 9 uses Wetlands Program Development Grants to support coral reef biocriteria development for Hawaii and CNMI (Bradley et al. 2010). Region 9 considers coral reefs to be "special aquatic sites," grouping them alongside traditional wetlands for conservation. Region 9 has also used Pollution Prevention & Targeted Watershed Grants and Clean

Water Act Section 319 Grants to develop watershed management plans and establish BMPs to protect coral reefs.

A comprehensive list of potential BCG applications is shown at Appendix F.

4.5. How Can the BCG Be Used?

Model results can be used for screening biological conditions and are appropriate for inclusion in annual condition reports. Results can also be used to select locations for reef restoration and to evaluate restoration effectiveness. It is not recommended that the model results be used for regulatory decision-making related to coastal construction permitting and compensatory mitigation planning, unless the decisions are supported by multiple corroborating lines of evidence.

5. RECOMMENDATIONS

Standardize Randomized Monitoring Surveys. Our analyses showed that combining all monitoring program data into one analysis created artifacts due to the varying sampling effort, methodologies, and time of year. We recommend that the program managers and their senior scientists take a serious look at how to leverage each randomized program to create the most robust holistic monitoring dataset that could be used by all.

Ideally, the randomized Florida coral reef monitoring programs could be orchestrated to enhance their value and benefits by facilitating the combination of multiple programs for data analyses. Adding NCRMP-like benthic point counts to DRM surveys would enhance the data collections by tabulating macroalgae coverage in the highest heat stress periods, a time when macroalgal growth is peaking and would correlate highest to coral overgrowth impacts. Conducting fewer NCRMP surveys every year would provide immense value by removing the biennial pulses of increased effort. These simple changes would facilitate the combination of annual NCRMP and DRM surveys to output a statistically robust sampling usable by both programs. These changes may reduce DRM-specific annual efforts, but if done in concert with annual NCRMP surveys, the overall effort would be larger.

Furthermore, the South Florida/Caribbean Network (SFCN) conducts long-term coral reef monitoring as part of the nationwide Inventory and Monitoring Division of the National Park Service. SFCN data were not usable for the BCG because it only collects benthic cover data. Adding demographics to their surveys would allow their data to be used in BCG analyses.

Ensure the BCG decision rules work both ways. The BCG decision rules were based on a descending decision tree and have not been tested to see if they make sense in the opposite direction (an improving condition). Currently if certain criteria are not met, the narrative rules jump to the next set of rules for a higher score and so on until the criteria are met. Little to no consideration was made in thinking if these narrative rules make sense in determining an improving condition. We recommend to rigorously test and alter the BCG decision rules if necessary to ensure it makes sense in determining lowering BCG scores, especially in the lens of coral reef restoration activities.

Collect Consistent Juvenile Data Across Programs. Juvenile data are the key indicator of coral demographic species shifts and coral recovery. The juvenile data between monitoring program was inconsistently collected limiting their usefulness. Current juvenile methods per program are documented in the Users' Guide for the Florida BCG Calculation Tool and summarized below in Table 10. The NCRMP program had the most consistent reporting of juveniles and was the only program used to distinguish a juvenile coral group for the second update to BCG scores. We recommend that monitoring programs standardize juvenile coral methodologies and ensure collection more consistent across regions and data collectors.

Table 10. Record of juvenile reporting methods for each monitoring program's survey.

Program	**Protocol**	**Discussion**
NCRMP	Recorded colonies less than 4cm as Juvenile without measurements	399 observations out of 44,228 total colonies were measured
CREMP	Maximum and height measurements recorded for all colonies; juveniles were not distinguished with a field in the dataset	Small colonies (1-3cm) were uncommon • 91 observations out of 103002 total colonies in the FKEYS_CREMP data set • 10 observations out of 19402 total colonies in the DT_CREMP data set • 0 observations out of 22601 total colonies in the SEFL_CREMP data set
DRM	Maximum and height measurements recorded for all colonies; juveniles were not distinguished with a field in the dataset	Small colonies (1-3cm) were uncommon (234 observations out of 178630 total colonies in the data set)

Develop separate numeric rules for the KJCAP region. The Florida Coral Reef is very complex, with a multitude of distinct habitat types within and among the biogeographic ecoregions. A simplified preliminary site classification scheme was used when developing the Florida Coral BCG and terminology was generalized to apply across the regions. This classification scheme was used to select samples across all regions and habitat types, and to reflect variations in biological expectations. To make the BCG more applicable across the FCR, we recommend developing separate numeric rules for the KJCAP region

Develop Reef Fish BCG for Florida. The BCG framework has been applied to assess reef fish communities in the US Caribbean. This model could be calibrated for Florida reefs, by establishing an expert panel and following the process used for developing the Florida coral BCG. Fish and coral communities respond differently to stressors and together they can be combined for a robust assessment of biological condition.

Maintain Current Coral Data on Florida's DSS. Following coral demographic surveys, the data should be standardized for the BCG and added to the Florida coral database, which is maintained on the DSS. Standardized downloads based on management needs should be added as an option to the DSS. At a minimum, these would include coral management areas (e.g., FKNMS, Dry Tortugas National Park, Biscayne Bay NPS, and the KJCAP). These may be further subdivided as needed (e.g., lower, middle and upper Keys). This will facilitate BCG analysis for managers.

Maintain the Florida Reef Story Map. A StoryMap website (link: Florida Coral Reef BCG) was generated and distributed to communicate information about the Florida Coral Reef BCG, including background on Florida's coral reef, model development, calculation, and application development. The StoryMap contains information that is non-technical and is a valuable tool for outreach to a broad public audience. As new information becomes available through ongoing analysis, the StoryMap should be revised to communicate current activities. For example, findings from the current analysis and to utility of the DSS could be summarized in the StoryMap with links to reports and the DSS website.

Investigate using BCG as Biocriteria in FL's WQ program. The Clean Water Act (CWA) objective is to restore and maintain the chemical, physical and biological integrity of our Nation's waters. The CWA and coral reef biological criteria (biocriteria) can be used as part of a comprehensive framework to protect coral reefs through enforceable coastal and watershed regulations. The designated use of a water body is the most fundamental articulation of the water body's role in the aquatic environment as defined by society. All of the water quality protections established by the CWA follow from a water body's designated use. Florida DEP uses biological assessments to measure designated use attainment for streams, lakes and wetlands. Currently, Florida does not assess coral reefs as part of their water quality assessment program, however, the coral BCG could be used to help determine designated uses for coral reef aquatic life and the extant Florida coral database could further be used for determination of aquatic life attainment under the CWA.

Develop rules for BCG Levels 1 and 2. It was suggested that narrative and numeric rules should be developed for BCG levels 1 and 2. The best observed condition in Florida was BCG Level 3 and rules were developed for levels 3, 4 and 5. The three demographic datasets used in the development of the BCG only go back to 2005. There was earlier monitoring data that could possibly be retrieved and assessed, with several caveats. First, metadata for the programs, including methodology is needed. Second, the datasets should go back to a period prior to the first disease events, which occurred in the late 1990s. As an alternative, data from other Caribbean regions could be used if the coral reefs were considered to be comparable to those found in Florida.

Develop a Generalized Stressor Axis (GSA) for Florida. Coral reef ecosystems are subjected to the cumulative impacts of multiple stressors. Coral reef ecosystems are non-linear systems, and land-based stressors from multiple watersheds may impact a given reef as they become dispersed by wave action, wind and oceanic currents. For the BCG, the x-axis represents the cumulative spatial/temporal co-occurrence of multiple stressors in a generalized stressor axis (GSA), much as the y-axis generalizes biological condition. A GSA is needed for Florida's coral reef and other coastal and marine habitats. A comprehensive GSA will require refinement in stressor modeling.

One potential approach to developing the GSA would be the Landscape Development Intensity Index (Brown and Vivas 2003, 2005). The Florida Department of Environmental Protection (DEP) uses the LDI as a tool to estimate potential land use impacts on streams, lakes, and wetlands. The LDI was also used to characterize anthropogenic activity on coral reefs in the US Virgin Islands (Oliver et al. 2018).

A spatially explicit approach that integrated land-based pollution, thermal anomalies, and fishing pressure was developed as the GSA for Puerto Rico. Land-based pollution was represented by the LDI, thermal anomaly data from NOAA's Coral Reef Watch Program (CRW), and commercial fishing intensity data based on fish catch data (Bradley et al. 2020).

Possible Use of Flags. While model development was based on the preliminary site classification scheme, the experts also discussed ways to better refine the model to address reef variability between regions and habitats. Several flags were suggested to highlight exceptional reef conditions that would require additional scrutiny of model results, including reef depth, a spatial areal extent for branching species and historic monotypic acroporid stands. Additional analysis is recommended to determine if these (and possibly other) flags could improve assessment results.

Recommended Areas for Restoration. The BCG score analysis could be utilized to help site areas for coral restoration. Sites with historical cold spots like the Mid Channel reefs in the Keys and Biscayne National Park might be ideal for restoration. Further scrutiny of the data from these sites should be done to understand the differences affecting the historical change in BCG scores.

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6.1. Monitoring Program Data Websites

DRM: https://coraldrm.org/

SECREMP: https://geodata.myfwc.com/documents/9e7c8cca866a4b60a6c97b38fd2366d0/about

KEYS CREMP: https://geodata.myfwc.com/documents/cb844b931a2748b1a9d4c1d262cb558f/about

DT CREMP: https://geodata.myfwc.com/documents/e88a085a263a4ed28d9b864951602316/about

NCRMP: https://ncrmp.coralreef.noaa.gov/pages/Data%20Download

7. APPENDICES

APPENDIX A: LIST OF PARTICIPANTS

Presenters (for all three webinars)
Ben Jessup (Tt)
Pat Bradley (Tt)
Brian Walker (NSU)
Maya Becker (NSU)

Participants (and affiliations)

March 2, 2026

Maddie Cholnoky	NOAA
Alexandra Fine	NOAA
Susan K. Jackson	EPA
Karen Neely	Nova SE Univ
Kathleen Czaia	Florida DEP
Lara Bracci	Florida DEP
Cailin Harrell	FWC
Christina Mallica	FWC
Nick Alcaraz	FWC

April 8, 2026

Stephanie Schopmeyer	FWC
Lindsay Huebner	FWC
Laura Jay Grove	NOAA
Xaymara Serrano	NOAA
Debbie Santavy	EPA (retired)
Sukanya Dayal	Florida DEP
Katie Johnson	Loggerhead
Angela Delaney	Broward

May 12, 2026

Maurizio Martinelli	FL DEP
Karen Bohnsack	NOAA
Michael Barbour	Mote Laboratory
Debbie Santavy	EPA
Alycia Shatters	FL DEP

All Invitees

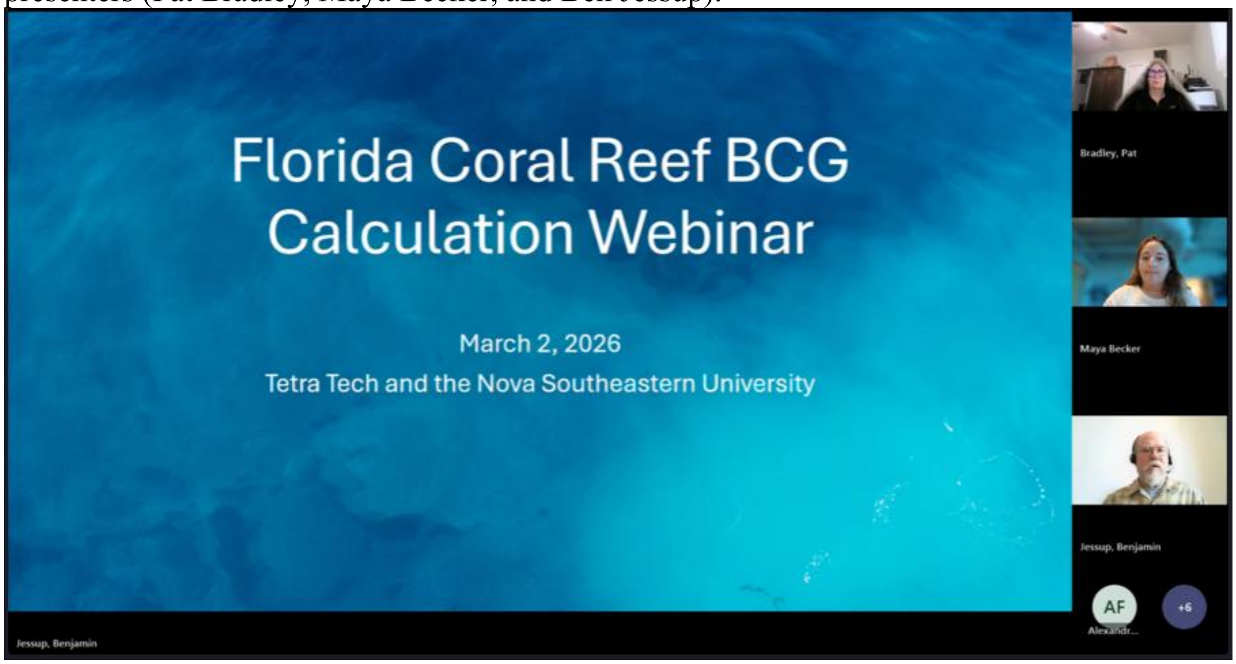
Name	Organization	email
Andrew W. Bruckner	Florida Keys National Marine Sanctuary	andy.bruckner@noaa.gov
Caitlin Lustic	The Nature Conservancy	clustic@tnc.org
Erica Towle	NOAA , Coral Reef Conservation Program	erica.towle@noaa.gov
Jocelyn Karazsia	NOAA National Marine Fisheries Service, Southeast Region, Habitat Conservation Division, West Palm Beach Office	Jocelyn.karazsia@noaa.gov
Melanie McField	Smithsonian Trust, Healthy Reefs for Healthy People Initiative	mcfield@healthyreefs.org
Mike Feeley	National Park Service, Dry Tortugas National Park	michael_feeley@nps.gov
Nicholas Parr	Florida Department of Environmental Protection	Nicholas.parr@floridadep.gov
Rob Ruzicka	Florida Fish and Wildlife Conservation Commission , Florida Fish and Wildlife Research Institute	Rob.Ruzicka@MyFWC.com
T. Shay Viehman	NOAA Center for Coastal Ocean Service (NCCOS)	shay.viehman@noaa.gov
Mollie Cordo	Florida Department of Environmental Protection	mollie.cordo@floridadep.gov
Maurizio Martinelli	Florida Department of Environmental Protection	maurizio.m.martinelli@floridadep.gov
Allie Shatters	Florida Department of Environmental Protection	alycia.shatters@floridadep.gov
Karen Bohnsack	NOAA, Florida Keys National Marine Sanctuary	Karen.Bohnsack@noaa.gov
Maddie Cholnoky	NOAA, Florida Keys National Marine Sanctuary	madeline.cholnoky@noaa.gov
David Burke	NOAA, Florida Keys National Marine Sanctuary	David.Burke@noaa.gov
Susan K. Jackson	USA EPA, Office of science and Technology	Jackson.susank@epa.gov
Katherine Weiler	USEPA, Office of Wetlands, Oceans, and Watersheds (OWOW)	weiler.katherine@epa.gov
Nicholas Rosenau	USEPA, Office of Wetlands, Oceans, and Watersheds (OWOW)	rosenau.nicholas@epa.gov
Jordan West	USEPA, Center for Public Health and Environmental Assessment (CPHEA)	west.jordan@epa.gov
Marina Villoch Diaz Maurino	MOTE Marine Labotatory	mvilloch@mote.org
Talli Vardi	Coral Restoration Consortium	
Anna Hamilton	Tetra Tech	anna.hamilton@tetratech.com
Mike Barbour	tetra tech retired	michaeltbarbour@yahoo.com
Victoria Barker		victoria.barker@noaa.gov
Karen Neely		karenlynnneely@gmail.com
Don Behringer	UF IFAS	behringer@ufl.edu
Richard Dodge	NOVA SE	dodge@nova.edu
Philip Dustan	College of Charleston	dustanp@cofc.edu
Piero Gardinali	Institute of Environment, Southeast Environmental Research Center	gardinal@fiu.edu
Dana Wusinich Mendez		dana.wusinich-mendez@noaa.gov

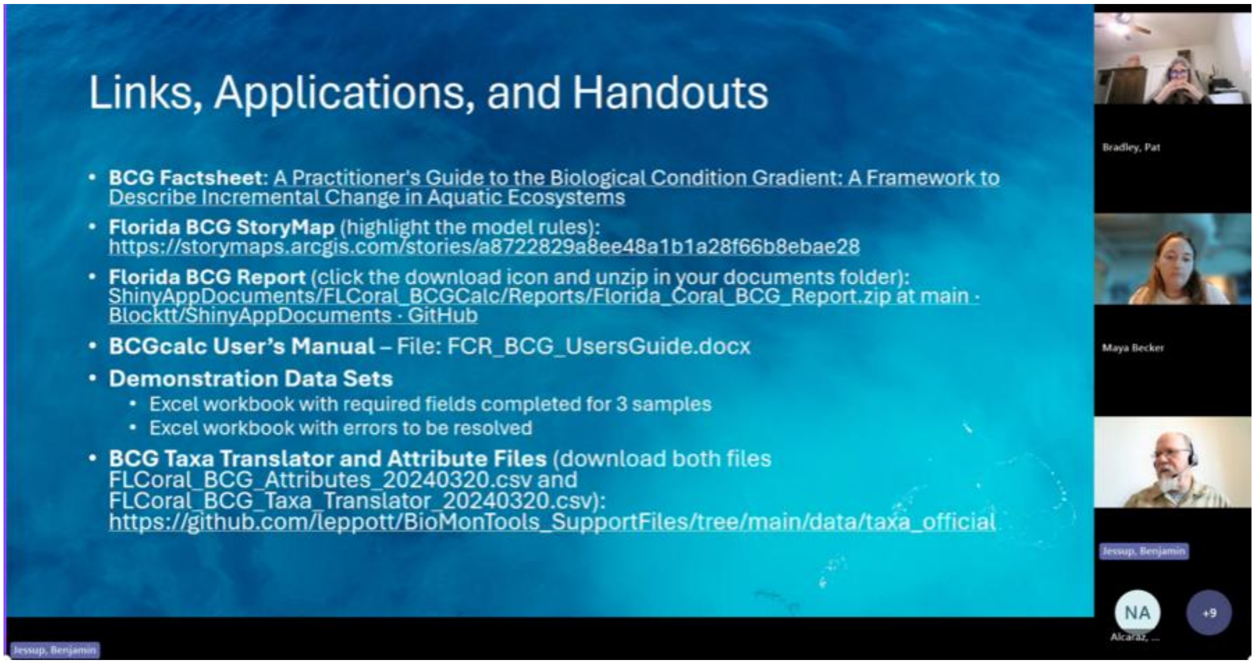
Name	Organization	email
Joshua Voss	Harbour Branch Oceanic Institute	jvoss2@fau.edu
Stephanie Schopmeyer	FWC FWRI	stephanie.schopmeyer@myfwc.com
Laura Jay Grove	NOAA Fisheries Science Center	jay.grove@noaa.gov
Jennifer Koss		jennifer.koss@noaa.gov
Kathleen Czaia		kathleen.czaia@floridadep.gov
Amanda Bourque		amanda_bourque@nps.gov
Bill Hoffman	Smithsonian - Ft Pierce Field Station	hoffman@si.edu
Debbie Santavy	EPA - Retired	santavyd@bellsouth.net
Wade Lehmann	EPA Region 4, Water Division	lehmann.wade@epa.gov
Jessica Patronis	DEP Water Quality Program	jessica.patronis@floridaDEP.gov
Lara Bracci	Florida Department of Environmental Protection	lara.bracci@floridaDEP.gov
Stephanie Stinson	Florida Department of Environmental Protection	stephanie.stinson@floridaDEP.gov
Allison Holevoet		al.holevoet@ufl.edu
amelia lynch		amelia_lynch@nps.gov
Jessica B Robinson		Jessica.B.Robinson@FloridaDEP.gov
cailin harrell		cailin.harrell@myfwc.com
caroline donovan		caroline.donovan@noaa.gov
christina mallica		christina.mallica@myfwc.com
joanne walczak		jwalczak@marinelife.org
kathryn lesneski		kathryn.lesneski@noaa.gov
Lindsay Huebner		Lindsay.Huebner@myfwc.com
mark ladd		mark.ladd@noaa.gov
nick alcaraz		nick.alcaraz@myfwc.com
taylor tucker		taylor.tucker@floridadep.gov
xaymara serrano		xaymara.serrano@noaa.gov
Sukanya Dayal		Sukanya.Dayal@FloridaDEP.gov
Alexandra Fine		Alexandra.fine@noaa.gov
Kristi Kerrigan		Kristi.Kerrigan@fau.edu
Katie Johnson		kjohnson@marinelife.org
Angela Delaney		ANDELANEY@broward.org

APPENDIX B: TRAINING WORKSHOPS

SCREENSHOTS FROM THE TRAINING AND DEMONSTRATION WEBINARS

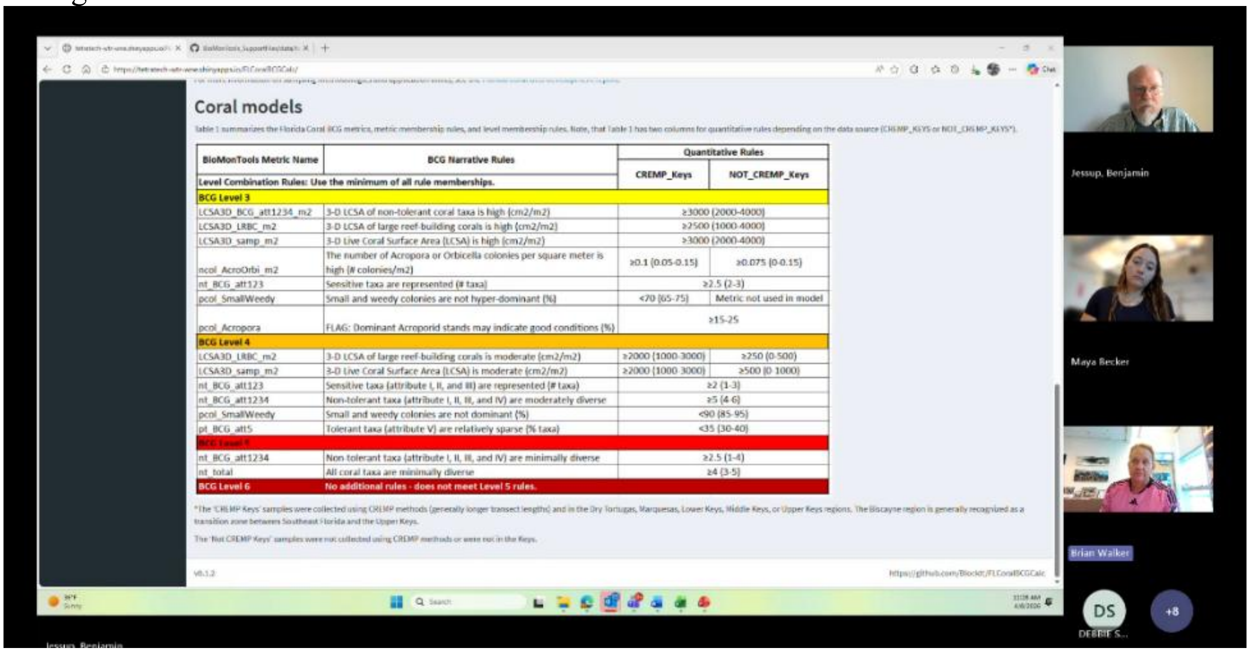
Screenshots of the March 2 webinar, including the opening PowerPoint slide, the agenda, and the materials provided for the webinar participants. The slides also show 3 of the presenters (Pat Bradley, Maya Becker, and Ben Jessup).





Screenshot of the April 8 webinar, showing the two primary presenters (Ben Jessup and Maya Becker) and icons for the other participants.

Screenshot of the April 8 webinar, showing the BCG model rules that were discussed during the webinar.



Screenshot of the May 12 webinar, showing the presenters and some participants.

APPENDIX C: MAJOR STRESSORS

MAJOR STRESSOR EVENTS ALONG FLORIDA'S CORAL REEF

This is a partial listing of major environmental conditions and disturbances in Florida's coral reef. The following chronological listing of natural and anthropogenic disturbances to Florida's coral reef includes representative events that are presumed to affect reef biological conditions. The list is not comprehensive. The original list can be found in the report: Calibration of the Biological Condition Gradient (BCG) for Florida's Coral Reef (Bradley & Jessup, 2024)

2005 – Hurricanes Katrina and Wilma hit the Florida Keys, overturning coral colonies and scouring the bottom (Waddell et al. 2008). While elevated SSTs occurred in the Florida Keys there was only minor to patchy coral bleaching. Florida's corals escaped the severe coral bleaching that was recorded throughout much of the Wider Caribbean (Causey 2008).

2006 – Elkhorn (*Acropora palm*ata) and staghorn coral (*Acropora cervicornis*) were listed as threatened species under the Endangered Species Act.

2006 – BBD reportedly transferred by butterfly fish *Chaetodon capistratus* after feeding on infected corals, with presumptive transmission occurring orally and fecally by fish (Aeby and Santavy 2006).

2008 – Tortugas multispecies rapid tissue loss disease (TMRTL) in Dry Tortugas National Park (DTNP) (Brandt et al. 2012). Affecting 14 scleractinian species. Disease signs most similar white plague (sensu Richardson et al. 1998b, 2001; figs. 2-3). Included thin white film on denuded skeleton.

2010 – A cold front passed through the Florida Keys, suddenly reducing seawater temperature. Corals with narrow thermal tolerance sustained high mortality (e.g., *Acropora cervicornis*, *Orbicella annularis, O. faveolata, Porites astreoides* and *Colpophyllia natans*, *Dendrogyra cylindrus)* on inshore reefs. *Siderastrea siderea,* which has a wide thermal tolerance, was not affected by this cold anomaly (Colella et al. 2012; Kemp et al. 2016; Lirman et al. 2011; Gilliam and Moulding 2012).

2011 – The summer saw the most significant coral bleaching event since 2005. Most of the Florida Reef Tract between the Lower Keys up through Martin County was impacted with moderate bleaching based on their survey conducted between the months of August to October (Meaghan Johnson, 2011).

2013-2014 – The 16-month dredging operation at the Port of Miami resulted in between half to 90 percent of nearby reefs being buried by sediment, resulting in widespread coral death. Over half a million corals were killed within 550 yards (500 meters) of the dredged channel, and dredging impacts may have spread across more than 15 miles (25 kilometers) of Florida's reef tract (Cunning et al. 2019), with a loss of 278 total acres of coral reef.

2014 – The boulder star coral (*Orbicella franksi*), mountainous star coral (*Orbicella faveolata*), lobed star coral (*Orbicella annularis*), rough cactus coral (*Mycetophyllia ferox*) and pillar coral (*Dendrogyra cylindrus)* were listed as threatened species under the Endangered Species Act.

2014 – An intense bleaching event occurred during the summer, followed by a new emergent disease, Stony Coral Tissue Disease (SCTLD), which was first reported off the coast of Miami-Dade County in September (Precht et al., 2016; Precht, 2019; FDEP, 2019). SCTLD affects more than 20 species of scleractinian (stony) corals (Lunz et al. 2017), destroying the corals' soft tissue, killing them within weeks or months of becoming infected (Meiling et al. 2021).

2014 – Stony Coral Tissue Disease ISCTLD) reported off the coast of Miami-Dade County (Precht et al 2016; Walton et al. 2018).

2015 – Moderate to severe coral bleaching events were recorded throughout the regions of southeast Florida. Severe bleaching was evident throughout the zones of Broward-Miami, Biscayne, Upper Keys, Middle Keys, Lower Keys, and the Dry Tortugas (Meaghan Johnson, 2015).

2015 – SCTLD reached Broward County and Biscayne National Park (Muller et al. 2020). 2015 - The final piece of the Monroe County's wastewater master plan, as well as the largest and most complex, the $196.5 million Cudjoe Regional Wastewater System that includes a deep injection well and covers Mile Marker 17 to Mile Marker 33 began operations.

2016 – SCTLD reached Palm Beach County and the upper Keys (Muller et al. 2020).

2017 – Hurricanes Irma and Maria damaged corals, most particularly the ESA listed coral species, *Acropora cervicornis* and *Orbicella annularis* (NOAA 2023).

2017 – SCTLD reached Martin County and the middle Keys in 2017. Half of Florida's 45 reef-building coral species had been affected by 2017, including five species listed under the Endangered Species Act (Muller et al. 2020).

2018 – SCTLD reached the lower Keys (Muller et al. 2020).

2020 – SCTLD reached the western end of the Marquesas in August 2020 (Dobbelaere et al.

2022).

2020-2021 – 90,749 gallons of raw sewage leaked from the Lower Keys wastewater facilities (Miami Herald 2024).

2021 – SCTLD reached the Dry Tortugas (Dobbelaere et al. 2022).

2022 – Sewage spills in Miami/Dade County and lower Keys (Miami Herald 2023).

2022 – Mild Bleaching event report throughout the Florida Reef Tract during summer months August to October. The counties of Martin and Palm beach experienced severe bleaching events throughout the season even though the remainder of the reef tract maintained low bleaching rates (Stein and Ruzicka, 2022).

2023 - Florida's Coral Reef experienced the worst coral bleaching event ever recorded. Coinciding with an El Niño year, unusually hot waters started in mid-July, a month earlier than the typical peak heating months of August and September. Water temperatures didn't cool off until October, nearly doubling the abnormally hot temperatures compared to any of the previous bleaching years in Florida (FWC 2024).

2024 - Fort Lauderdale now has more than 300 miles of navigable canals – 165 miles designated as residential canals.

2024 - A mild to moderate bleaching event occurred throughout Florida’s Coral Reef. Approximately 55% of all sites surveyed by DRM during the months August to October were considered milt to moderately bleached or pale. (Harrell et al., 2024)

STONY CORAL TISSUE LOSS DISEASE SUSCEPTIBILITY

This list was provided by Florida DEP. It is intended to provide a general guide for SCTLD susceptibility by species in Florida. Designations may differ through space and time. Highly

Susceptible: Species that experience early onset of SCTLD during an outbreak and experience relatively rapid tissue loss and high prevalence and mortality rates. Several species are considered 'canaries in the coal mine' that help determine if SCTLD is affecting a given reef. Susceptible Species: Species that succumb to SCTLD, but the onset of tissue loss typically occurs several weeks after onset in highly susceptible species (nb: lower numbers may also show disease signs along with highly susceptible species). Presumed Susceptible: Presumed susceptible but insufficient data to categorize onset. Normally unaffected: During outbreaks, corals that are rarely or not affected by SCTLD.

Species	**Notes**
Highly Susceptible Species	
Colpophyllia natans (boulder brain coral)	
Dendrogyra cylindrus (pillar coral)*	
Dichocoenia stokesii (elliptical star coral)	
Diploria labyrinthiformis (grooved brain coral)	
Eusmilia fastigiata (smooth flower coral)	
Meandrina jacksoni (white valley maze coral)	
Meandrina meandrites (maze coral)	
Pseudodiploria clivosa (knobby brain coral)	
Pseudodiploria strigosa (symmetrical brain coral)	
Susceptible Species	
Agaricia agaricites (lettuce coral)	
Montastraea cavernosa (large-cup star coral)	"Highly Susceptible" in some regions.
Mussa angulosa (spiny flower coral)	
Mycetophyllia aliciae (knobby cactus coral)	
Mycetophyllia ferox (rough cactus coral)	
Mycetophyllia lamarckiana (ridged cactus coral)	
Orbicella annularis (lobed star coral)*	
Orbicella faveolata (mountainous star coral)*	
Orbicella franksi (boulder star coral)*	
Porites astreoides (mustard hill coral)	"Normally Unaffected" in some regions.
Siderastrea siderea (starlet coral)	"Highly Susceptible" in some regions.
Solenastrea bournoni (smooth star coral)	
Stephanocoenia intersepta (blushing star coral)	

Species Presumed to be Susceptible	
Agaricia tenuifolia (thin leaf lettuce coral)	
Favia fragum (golfball coral)	
Helioseris cucullata (sunray lettuce coral)	
Isophyllia spp. (cactus corals)	
Madracis auretenra (pencil coral)	"Normally Unaffected" in some jurisdictions.
Scolymia spp. (disc corals)	
Siderastrea radians (lesser starlet coral)	
Acropora cervicornis (staghorn coral)*	
Acropora palmata (elkhorn coral)*	
Acropora prolifera (fused staghorn coral)	
Cladocora arbuscula (tube coral)	
Oculina spp. (bush corals)	
Tubastraea coccinea (orange cup coral)	
Porites divaricata (thin finger coral)	
Porites furcata (branched finger coral)	
Porites porites (finger coral)	

APPENDIX D: MONITORING PROGRAM SAMPLING DESIGNS USED IN FLORIDA BCG ANALYSIS

Program	Region Covered	Design	Years Surveyed	Methods	Habitats
Coral Reef Evaluation and Monitoring Program (**CREMP**), Florida Fish and Wildlife Conservation Commission	Florida Keys National Marine Sanctuary 3 Regions – Lower Keys, Middle Keys and Upper Keys	Fixed stations selected using a stratified, random sampling design (EMAP) based on habitat type 40 reefs 1996 – 2000: Four monitoring stations at each site are delineated with permanent pins. 2001-2009 went down to 2-3 stations per site 2010 – present: back to four stations	Annually, since 1996	Within each station, field sampling consists of a station species inventory (SSI), video transects, stony coral colony fate tracking and water temperature	Nearshore hardbottom Patch reefs Shallow spur and groove reefs (~3 to 6m depth) Deep spur and groove reefs (~10 to 20m depth)
Southeast Coral Reef Evaluation and Monitoring	Kristin Jacobs Coral Aquatic	Status and Trends	Annually, since 2003	Field sampling consists of a station species inventory (SSI),	Outer reef Middle reef

Project (**SECREMP**) monitored by the National Coral Reef Institute at Nova Southeastern University Oceanographic Center	Preserve (Palm Beach, Broward, Dade, and Martin counties)	Fixed sites selected as representative of the four reef habitats 22 reefs Four monitoring stations at each site are delineated with permanent pins.		video transects, and stony coral colony fate tracking Water temperature at all sites. Also 2 octocoral species	Inner reef Nearshore ridge complex
Coral Reef Evaluation and Monitoring Program Dry Tortugas (**CREMP DT**), Florida Fish and Wildlife Conservation Commission	Dry Tortugas	Status and Trends Fixed sites were selected as representative samples of the coral reefs of the Dry Tortugas and with the intention of targeting certain coral species Four monitoring stations at each site are delineated with	Annually, since 1999	Field sampling consists of a station species inventory (SSI), video transects, and stony coral colony fate tracking, except at monotypic Acroporid stands	Pinnacle Reefs Patch Reefs with ESA-listed corals Reefs with historic monitoring

		permanent pins. 11 reefs in DTNP and 1 reef in DTER			
National Coral Reef Monitoring Program (**NCRMP**), National Oceanic and Atmospheric Administration (NOAA)	All Florida and U.S. Caribbean reefs, including the Florida Keys, Dry Tortugas, and Southeast Florida	Probabilistic; health and condition of US Coral Reef Ecosystems – coral equivalent to EPA's National Aquatic Resource Surveys		A line point intercept (LPI) method is used to quantify benthic cover, tallying the benthic elements that fall under specified intervals along transects. Coral population structure (size-frequency and colony density) is derived from coral demographic surveys (DEMO) along 10m belt transects. However, the TotTranLngth_M field records the actual length of the observed transect, which is not always 10m.	
Disturbance Response Monitoring (**DRM**), Florida Fish and Wildlife Conservation	All Florida reefs, including the Florida Keys, Dry Tortugas, and	Probabilistic, stratified random sampling	2005 – present Surveys are conducted annually	Surveys consist of four independent 1x10 m belt transects. Transects 1 and 2 included	

Commission (FWC)	Southeast Florida	Bleaching response to temperature anomalies Also monitoring SCTLD since 2014, including disease severity and which species it is affecting	during late summer and autumn (August–October) when sea surface temperatures (and thermal stress) peak	surveys of all stony coral species >4cm while Transects 3 and 4 targeted a subset of 10 coral species (>4cm) known to be highly susceptible to SCTLD.	

APPENDIX E: EMERGING HOT SPOT

TABLE OF EMERGING HOT SPOT PATTERN DEFINITIONS

	Pattern name	Definition
	No Pattern Detected	Does not fall into any of the hot or cold spot patterns defined below.
	New Hot Spot	A location that is a statistically significant hot spot for the final time step and has never been a statistically significant hot spot before.
	Consecutive Hot Spot	A location with a single uninterrupted run of at least two statistically significant hot spot bins in the final time-step intervals. The location has never been a statistically significant hot spot prior to the final hot spot run and less than 90 percent of all bins are statistically significant hot spots.
	Intensifying Hot Spot	A location that has been a statistically significant hot spot for 90 percent of the time-step intervals, including the final time step. In addition, the intensity of clustering of high counts in each time step is increasing overall and that increase is statistically significant.
	Persistent Hot Spot	A location that has been a statistically significant hot spot for 90 percent of the time-step intervals with no discernible trend in the intensity of clustering over time.
	Diminishing Hot Spot	A location that has been a statistically significant hot spot for 90 percent of the time-step intervals, including the final time step. In addition, the intensity of clustering in each time step is decreasing overall and that decrease is statistically significant.
	Sporadic Hot Spot	A statistically significant hot spot for the final time-step interval with a history of also being an on-again and off-again hot spot. Less than 90 percent of the time-step intervals have been statistically significant hot spots and none of the time-step intervals have been statistically significant cold spots.
	Oscillating Hot Spot	A statistically significant hot spot for the final time-step interval that has a history of also being a statistically significant cold spot during a prior time step. Less than 90 percent of the time-step intervals have been statistically significant hot spots.
	Historical Hot Spot	The most recent time period is not hot, but at least 90 percent of the time-step intervals have been statistically significant hot spots.

	New Cold Spot	A location that is a statistically significant cold spot for the final time step and has never been a statistically significant cold spot before.
	Consecutive Cold Spot	A location with a single uninterrupted run of at least two statistically significant cold spot bins in the final time-step intervals. The location has never been a statistically significant cold spot prior to the final cold spot run and less than 90 percent of all bins are statistically significant cold spots.
	Intensifying Cold Spot	A location that has been a statistically significant cold spot for 90 percent of the time-step intervals, including the final time step. In addition, the intensity of clustering of low counts in each time step is increasing overall and that increase is statistically significant.
	Persistent Cold Spot	A location that has been a statistically significant cold spot for 90 percent of the time-step intervals with no discernible trend in the intensity of clustering of counts over time.
	Diminishing Cold Spot	A location that has been a statistically significant cold spot for 90 percent of the time-step intervals, including the final time step. In addition, the intensity of clustering of low counts in each time step is decreasing overall and that decrease is statistically significant.
	Sporadic Cold Spot	A statistically significant cold spot for the final time-step interval with a history of also being an on-again and off-again cold spot. Less than 90 percent of the time-step intervals have been statistically significant cold spots and none of the time-step intervals have been statistically significant hot spots.
	Oscillating Cold Spot	A statistically significant cold spot for the final time-step interval that has a history of also being a statistically significant hot spot during a prior time step. Less than 90 percent of the time-step intervals have been statistically significant cold spots.
	Historical Cold Spot	The most recent time period is not cold, but at least 90 percent of the time-step intervals have been statistically significant cold spots.

APPENDIX F: POTENTIAL APPLICATIONS OF THE BCG (Modified from Bradley et al., 2010)

Management Area	Description	Application of the BCG
Marine Protected Areas (MPAs)	• Selecting MPA Sites • Managing MPAs • Effectively manage the waters between MPAs	• To identify waterbodies that have outstanding biological condition and require protection • To establish thresholds against which to measure effectiveness of MPAs • With establishment of designated uses, to protect those uses (i.e., ecosystem connectivity)

Managing Tourism	• Mooring Buoys • Permits – diving, fishing, boating	• To identify locations with outstanding biological condition that would benefit from the protection of mooring buoys • With establishment of designated uses, to protect those uses
Watershed Management	Developing and implementing watershed management plans	• To support setting goals for watershed and regional planning • To prioritize watershed goals and actions • To establish thresholds against which to measure effectiveness of permits or other management actions
Coastal Zone Management	Regulating Coastal Development	• To support setting goals for watershed and regional planning • To prioritize watershed goals and actions • To develop management plans
Habitat Connectivity	Maintain connectivity between coral reefs and associated habitats such as mangroves, sea grass beds, and lagoons	• All nearshore environments are protected by the Clean Water Act (CWA) • Coral reefs, mangroves, sea grass beds, and lagoons can be specifically protected when they are identified in water quality standards
Coral Restoration	Restoring coral reefs damaged by boats and anchors, coral disease, or coral bleaching	• To select sites for coral restoration • To establish thresholds against which to measure effectiveness of restoration efforts
Managing Endangered Species (Endangered Species Act)	Protecting rare, threatened and endangered species	• To establish expected or desired levels of individual species (e.g., abundance, biomass). • To establish thresholds against which to measure effectiveness of legal protection
National Environmental Policy Act (NEPA) of 1969	Environmental Impact Statements	• To identify where site-specific criteria modifications may be needed to effectively protect a waterbody • To assess the overall ecological effects of regulatory actions

		• Providing a threshold against which to measure detrimental effects on biological communities
CWA Section 104(b)(3) Wetlands Program Development Grants	Funding support for protection of wetlands and special aquatic resources (coral reefs, seagrasses and mangroves)	• To determine the causes, effects, extent of pollutants • To develop the generalized stressor gradient for the BCG •To develop BCGs for adjacent marine ecosystems and the coral reef fish community
CWA Section 106 Grants for Pollution Control Programs	Funding support for state and local programs implementing the CWA	• Conduct biological monitoring and use the BCG to improve TMDLs in related to coral reef pollutants
CWA Sections 205(j) and 604(b) Water Quality Management Planning	Funding support for states and local agencies for water quality planning	• To develop water quality criteria, including biocriteria
CWA Section 301(h) Effluent Limitations	Waiver to defer secondary treatment if discharge does not adversely affect biological communities	• Providing a threshold against which to measure detrimental effects on biological communities
CWA Section 312 Marine Sanitation Devices	No discharge zones	• To identify appropriate locations for no-discharge zones • To identify locations with outstanding biological integrity that would benefit from a no-discharge zone status • To establish thresholds to gauge the effectiveness of no-discharge zones
CWA Section 319 Nonpoint Source Program (NPS)	NPS reporting, including identification of categories NPS pollution and measures used to reduce that pollution	• Assessing impacts of NPS pollution • Determining effectiveness of NPS controls • Site-specific assessment of BMPs for NPS
CWA Section 401 State Water Quality Certification	Required certification that any discharge from a proposed project is consistent with the CWA, including attainment of	•Provides a threshold against which to measure dredge/fill impacts on biological communities •Identify acceptable sites for disposal of dredge and fill material

	applicable state ambient water quality standards	
CWA Section 402 National Pollutant Discharge Elimination System (NPDES)	Regulating discharges from point sources to the waters of the United States.	•Determining condition of a waterbody prior to issuance of a permit •Providing a threshold against which to measure discharger impacts on biological communities •Evaluating effectiveness of implemented controls •Helping to verify that NPDES permit limits are resulting in achievement of state water quality standard
CWA Section 403 Ocean Discharge Program	Establishes special requirements for point source permits for discharges into all three ocean regions defined in the CWA (e.g., the territorial sea, the contiguous zone and the ocean)	•Determining condition of a waterbody prior to issuance of a permit •Providing a threshold against which to measure discharger impacts on biological communities •Evaluating effectiveness of implemented controls •Helping to verify that NPDES permit limits are resulting in achievement of state water quality standard
CWA Section 404 Permits for Dredged or Fill Material	Permit program to regulate the discharge of dredged and fill material into waters of the U.S. Jointly managed by EPA and U.S. Army Corps of Engineers. The Corps handles the actual issuance of permits (both individual and general); it also determines whether a particular plot of land is a wetland or water of the United States. The U.S. Fish and Wildlife Service and National Marine Fisheries Service play special advisory roles because of their expertise regarding wildlife habitat. EPA issues certain guidelines and policies, including methods	•Provides a threshold against which to measure dredge/fill impacts on biological communities •Identify acceptable sites for disposal of dredge and fill material •Determine the effects of the disposal.

	for determining whether a particular tract is a wetland. EPA can actually veto a Corps-issued permit (a step rarely taken). EPA is also responsible for determining whether portions of the 404 program should be turned over to a state.	
CWA Section 603 Clean Water State Revolving Fund (CWSRF)	Authorizes annual capitalization grants to States who in turn provide low interest loans for a wide variety of water quality projects.	• Provides a threshold against which to measure the degree to which water quality projects reduce human impacts on biological communities