

SEDAR 84

Southeast Fisheries Science Center

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Executive Summary

The SEDAR 84 St. Croix stoplight parrotfish (*Sparisoma viride*) stock assessment process consisted of four webinars between April 2024 and October 2024. The data available for the assessment included:

- An annual species-specific catch time series from a commercial logbook program
- Fishery-dependent length compositions from a commercial port sampling program
- Fishery-independent length compositions from a stratified random sampling survey of reef fish
- A fishery-independent index of abundance from a stratified random sampling survey of reef fish
- Life history information from otolith analysis and gonad histology

The assessment used Stock Synthesis, a statistical catch-at-age model (Methot et al., 2020). Stock Synthesis models were initially configured using an annual catch time series and compositions that were aggregated across the available years for each source of length data. Model development proceeded stepwise from the simplest configuration to those of moderate complexity. Those sequential steps included the inclusion of the index of abundance and annual fishery-independent length compositions. Models were run with and without the estimation of recruitment deviations. Finally, the sensitivity of the assessment outcomes was investigated using alternative inputs for longevity-informed natural mortality, parameterization of hermaphroditism, and reweighting of the effective sample size of the length composition data.

Model diagnostics checked for convergence, goodness-of-fit, model consistency, and prediction skill by evaluating gradients, residual plots, likelihood profiles, hindcast cross-validation, correlation analyses and Jitters. All of the configurations resulted in inconclusive results, evidenced by bounded parameters, low gradients, and high correlations between the scale of the average recruitment and the fishing mortality rate of the initial equilibrium state. Likelihood profile diagnostics indicate that the configurations explored could not reliably estimate the stock status. Thus, the overfished status of the St. Croix stoplight parrotfish stock remains unknown. However, the available data do not indicate a decline in the abundance index concurrent with a decrease in landings and show constant trends in size composition quarantines. These findings suggest that the St. Croix stoplight parrotfish is not likely to be undergoing overfishing in 2022.

1 Background

The stoplight parrotfish (*Sparisoma viride*) is a sequential protogynous hermaphrodite that inhabits coral reefs in the Caribbean Sea, Florida, Gulf of Mexico, Bermuda, and Brazil. It is an herbivorous species that is targeted in reef fish fisheries throughout much of the Caribbean, including St. Croix, USVI.

1.1 Management

St. Croix stoplight parrotfish is managed under the St. Croix Fishery Management Plan (Crabtree, 2019). In 2023, the Caribbean Fisheries Management Council transitioned from species-based to island-based fisheries management (Figure 1.1). The management measures in the new island-based fishery management plans became effective on October 13, 2022.

The Parrotfish 2 stock complex includes two indicator stocks and five other species. The indicator species are stoplight parrotfish and redbtail parrotfish (*Sparisoma chrysotum*). The allowable biological catch for the complex was established using tier 4a of the 4-tired ABC control rule. The allowable biological catch and the annual catch limit are 85,135 and 72,365 pounds whole weight, respectively.

The Southeast Fisheries Science Center provided a SEDAR 84 Data Workshop working paper summarizing federal management actions for stoplight parrotfish in St. Croix. On August 29, 2013, a 9-inch federal size limit was instituted by Final Regulatory Amendment 4. The size limit only applies in the U.S. EEZ surrounding St. Croix, defined as the federal waters ranging from 3 to 200 nautical miles (nm) (5.6 – 370 kilometers [km]) from the nearest coastline point of the U.S. Virgin Islands (Figure 1.2).

1.2 Assessment History

Before the current assessment, only one stock assessment had been attempted for St. Croix stoplight parrotfish (SEDAR, 2016). The St. Croix Stoplight Parrotfish SEDAR 46 evaluations were performed using the Data-Limited Methods Toolkit (Carruthers & Hordyk, 2018). The approach applied data-limited stock assessment models and management procedures. Ultimately, the results were not used for management advice.

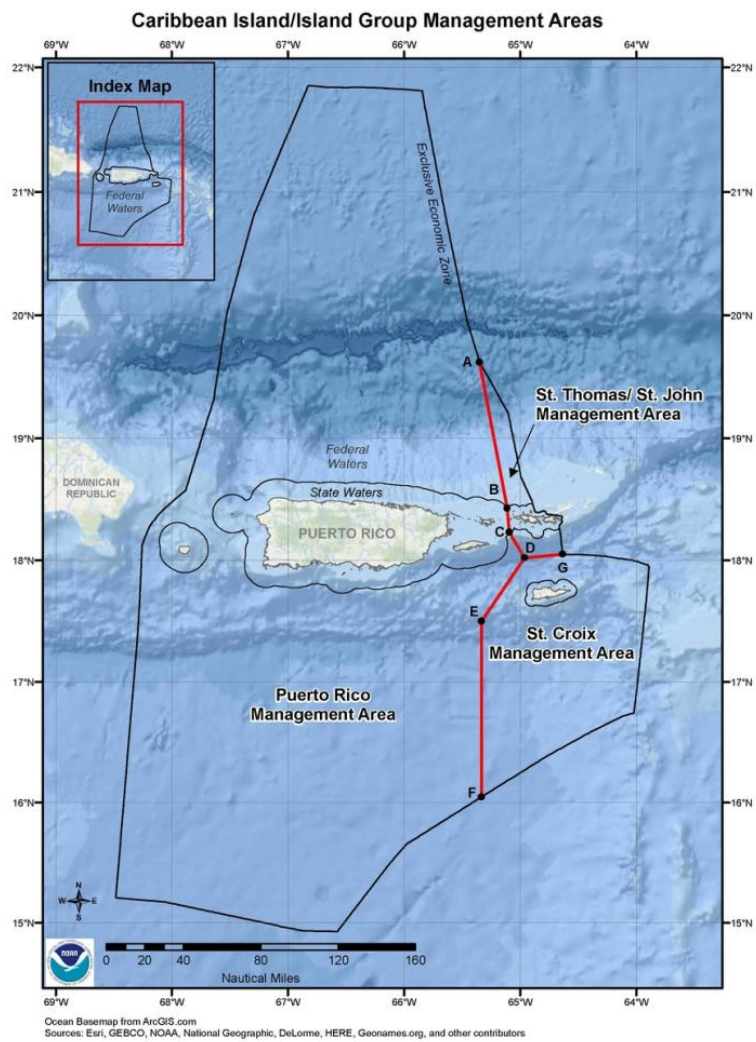


Figure 1.1: Jurisdictional boundaries of the Caribbean Fishery Management Council.

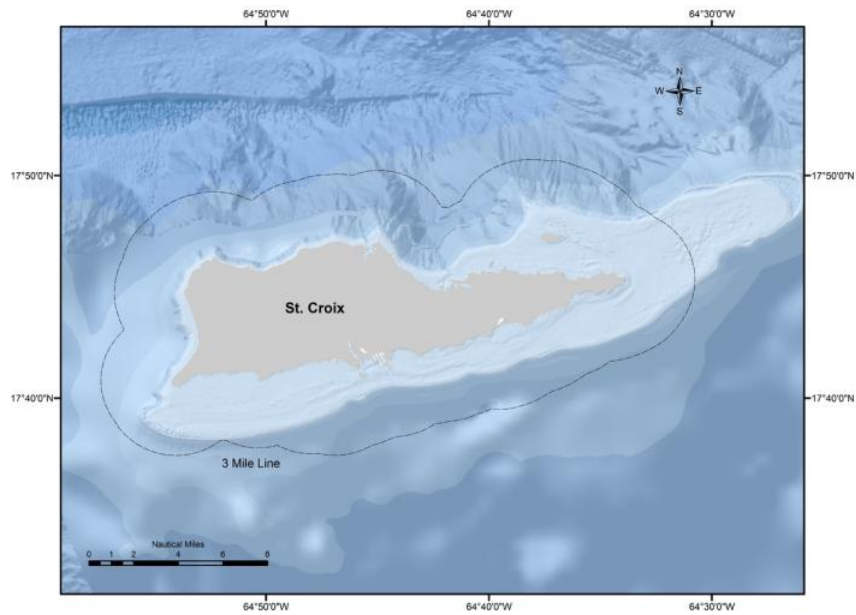


Figure 1.2: The U.S. EEZ is defined as the federal waters ranging from 3 to 200 nautical miles (5.6 – 370 kilometers) from the nearest coastline point of the US Virgin Islands.

2 Modeling Framework

Stock Synthesis was the modeling approach applied in this assessment because of its compatibility with the available data and consistent with standard practices.

Stock Synthesis is a statistical catch-at-age model that uses a population model, an observation model, and an estimation model and applies a likelihood function in the estimation process (Methot et al., 2020). Stock Synthesis, commonly referred to as SS3, has been applied extensively worldwide for stock assessment evaluations (Methot & Wetzel, 2013). It has also been used for previous data-limited and data-moderate SEDAR assessments, including the SEDAR 57 assessments and subsequent updates for Caribbean Spiny Lobster (*Panulirus argus*), and the SEDAR 80 assessments for Queen Triggerfish (*Belistes vetula*) (SEDAR, 2019, 2022).

The Stock Synthesis modeling framework is a compatible tool for SEDAR stock assessments in the U.S. Caribbean because it can accommodate a wide range of model complexities, from data-limited to highly detailed assessments (Cope, 2024). Stock Synthesis allows for the characterization of stock, fishing fleet, and survey dynamics through various parameters, which can be either fixed based on external data or estimated when sufficient assessment data are available. Additionally, it can incorporate complex biological dynamics, such as hermaphroditism and continuous recruitment, which are critical for accurately assessing St. Croix Stoplight Parrotfish.

Finally, R packages such as `r4ss` and `ss3diags` facilitate critical evaluations of model reliability and model comparisons (Carvalho et al., 2021; Taylor et al., 2021). For example, `R4SS` provides visualization and diagnostic tools to summarize and interpret fit, convergence, and key output metrics. `SS3diags` focuses on retrospective analyses, hind-casting, and residual pattern evaluations. The integration of these tools allows rigorous uncertainty analysis, streamlined sensitivity analyses, and enhanced transparency in decision-making.

3 Data-Informed Modeling Configurations

The data considered for use in the current assessment are documented in the SEDAR 84 US Caribbean Stoplight Parrotfish St. Croix Data Workshop Report (SEDAR, 2024). This section summarizes those data and their associated model configurations explored using Stock Synthesis.

Additional details for each data input are provided across the respective references identified below:

1. Landings from self-reported commercial fisher logbook data (Martínez Rivera et al., 2024)
2. Length compositions from shore-based port sampling of commercial landings (Godwin et al., 2024)
3. Length compositions from a fishery-independent stratified random sampling survey of reef fish (Grove et al., 2024)
4. Index of abundance from a fishery-independent stratified random sampling survey of reef fish (Grove et al., 2024)
5. Life history information from otolith analysis and gonad histology (Rivera Hernández & Shervette, 2024)

Based on the available data, the assessment was configured with one area, one season, one fleet, and one fishery-independent survey.

3.1 Commercial Dive Fleet

3.1.1 Catch Data

The catch data for the dive fleet came from the Caribbean Commercial Logbook program (Martínez Rivera et al., 2024). **The catch was input as biomass (in metric tons) and was treated as if it occurred over an entire fishing season, i.e., each fishing year.** The years of the available species-specific self-reported commercial fisher logbook data determined the start and end years of the Stock Synthesis models. **The start and end years of the model were 2012 and 2022, respectively.** Based on discussions at the data workshop characterizing catch by the predominant dive gear, **the assessment assumed no discarding nor discard mortality associated with the dive fleet.**

It is important to note that the stock was not at an unexploited equilibrium at the start year of the available time series. The fishery had been ongoing for decades, and the total fishing effort in St. Croix in 2012 was undergoing a meaningful decline; thus, an initial F was estimated for the dive fleet, and a corresponding initial equilibrium catch was input. In recent assessments, the initial equilibrium catch is initiated as the geometric mean of the first three years of available catches. However, because of the known decline in effort preceding the start year of the assessment, **the initial equilibrium catch was configured in initial runs as 30 metric tons**, a little over twice the geometric mean of the catches from 2012 - 2014.

The input standard error for the landings was set to 0.01. When implemented with few data inputs, Stock synthesis will inherently nearly exactly fit the annual landings time series, regardless of the input standard error.

Alternative model configurations associated with the dive fleet data are described later in this report. They included:

- A higher standard error of 0.3 was explored via sensitivity analysis
- The initial equilibrium catch was explored via likelihood profiling

3.1.2 Size Composition Data

Gear-specific annual length frequencies came from the commercial shore-based port-sampling Trip Interview Program (Godwin et al., 2024). These data were used to characterize the size-based selectivity pattern for the dive fleet. Since multiple fish can be obtained from a single sampled trip, the lengths are not independent observations. **The relative model weighting of the dive fleet length compositions was based on the number of trips sampled.**

Due to low sample sizes, the fishery-dependent commercial dive fleet length composition data were collapsed across all years

The length compositions of the commercial dive fleet were assumed to be representative of the total catch. Although a federal minimum size limit exists, it does not apply in USVI territorial waters extending from land to 3 nautical miles offshore. Discussion at the data workshop emphasized that the federal regulations do not conclusively affect retention.

A double normal function was used to model the relative vulnerability of capture by length for the dive fleet. However, only two parameters were estimated, effectively describing a logistic selectivity for the commercial dive fleet. The double normal function allows for domed or logistic selectivity. It combines two normal distributions; the first describes the ascending limb, while the second describes the descending limb. Domed selectivity was not explored for St. Croix Stoplight Parrotfish. However, achieving the logistic shape with the double normal Stock Synthesis pattern facilitated model configuration. The two parameters used to achieve a logistic selectivity shape were the size associated with peak selectivity and the width of the ascending limb.

3.2 Survey Data

3.2.1 Index of abundance

ADD YEARS

Annual abundance observations and associated standard errors were from the National Coral Reef Monitoring Program Reef Visual Census (Grove et al., 2024). In stock syntheses, **the survey was configured as an index in numbers with a lognormal error distribution.** The associated length composition data, described in the following subsection, suggested that **the index reflected the abundance of juveniles and adults.**

3.2.2 Size Composition Data

Since multiple fish can be observed from a single dive, lengths are not independent observations. **The relative model weighting of the National Coral Reef Monitoring Program survey length compositions across years was based on the number of paired dives.**

The three most recent years of the National Coral Reef Monitoring Program survey in St. Croix provided counts by individual lengths measured to the nearest centimeter. However, prior to 2017 the length observations were collected in 5-centimeter bins. **The length data inputs for both the dive fleet and the three years of the survey with 1-centimeter length measurements were binned to match the survey's 2012 and 2015 5-centimeter bins.**

Note that SS3 allows the length bins of the data inputs to be larger than the bins used in the population model. **Although the size bins of all the length data inputs were large (5 centimeters), the model's simulated population bin size was 1-centimeter bins, with a plus group for the largest bin, greater than or equal to 41 centimeters fork length.** Although the population is modeled at a higher resolution concerning bin size, the likelihood function, which aims to match the observed data inputs and the simulated population estimates, operates at the resolution of the data inputs.

A large proportion of small fish were observed in the National Coral Reef Monitoring Program survey. **The smallest two bins, [1 - 6) and [6 - 11), were collapsed into a single bin [1 - 11).**

The length compositions provided reasonable support that younger and older fish were available to the National Coral Reef Monitoring Program survey. **Selectivity for the National Coral Reef Monitoring Program survey was fixed at 1 for all sizes.**

Models were initially configured in Stock Synthesis with length compositions aggregated across the available years for each source of length data and proceeded stepwise from the simplest configuration to those of moderate complexity. The steps included the inclusion of annual

fishery-independent length compositions. The sequential model configurations are described later in this report.

3.3 Life History Data

The life history data used in the assessment included longevity-informed natural mortality, growth, length-weight, and maturity analyzed from 1,801 samples of Stoplight Parrotfish collected across the U.S. Caribbean from 2013 to 2023 (Rivera Hernández & Shervette, 2024). Based on the available information, **the Stoplight Parrotfish population was modeled from age 0 through age 20, and from 0 to 41 centimeters fork length, in 1-centimeter bins, with the largest values for each as plus groups.**

3.3.1 Growth

The SS3 growth formulation requires five parameters:

- Length at the youngest age
- Length at the maximum age
- Von Bertalanffy growth parameter (K)
- Coefficient of variation at the youngest age
- Coefficient of variation at the maximum age

Parameter estimates for Von Bertalanffy growth parameter (K) and the length at maximum age (L_{∞}) were based on samples of Stoplight Parrotfish collected across the U.S. Caribbean from 2013 to 2023 (Rivera Hernández & Shervette, 2024).

The estimated size at age zero from otolith analysis by Rivera Hernández & Shervette (2024) was modified in Stock Synthesis so that the length of the youngest age, age 0, was set to zero. Without this modification the model would be unable to fit to the substantial amounts of small (<10cm) stoplight parrot observed in the survey size composition data.

Coefficients of variation for both younger and older ages were initially set to 0.15. Ideally, growth coefficients of variation should be derived from observed length-at-age data, however the assumed values are consistent with species of moderate growth variability.

Alternative model configurations associated with the growth data are described later in this report. They included:

- A higher growth coefficient of variation of 0.25 for younger ages was explored via sensitivity analysis
- Higher growth coefficients of variation of 0.25 for both younger and older ages were explored via sensitivity analysis

3.3.2 Morphometric Conversion

The relationship between weight in grams and length in millimeters provided by Rivera Hernández & Shervette (2024) was converted to weight in grams and length in centimeters and used as a fixed model input. **The length-weight relationship was $W = 3.18 \times 10^{-5} L^2$, with weight in kilograms and length in centimeters.**

3.3.3 Maximum Age and Natural Mortality

Empirical estimates of natural mortality (M) can be derived using life history information such as longevity, growth, and maturity. For this assessment, the Natural Mortality Tool was used to estimate M (Cope & Hamel, 2022). Various methods were explored, incorporating factors such as maximum age, the Von Bertalanffy growth parameter (K), theoretical age at size zero (t_0), asymptotic size (L_∞), and age at 50% maturity.

Inputs for the Natural Mortality Tool were sourced from Rivera Hernández & Shervette (2024), who observed a maximum age of 20 years for stoplight parrotfish in the U.S. Caribbean. However, the average age of 1,649 sampled fish was 5.4 years, with fewer than 1% of aged individuals reaching 13 years or older. More broadly across the Caribbean, a lower maximum age of 9 years was observed, with a suggested maximum lifespan of 12 years. In contrast, a tagging study in Bonaire indicated a potential maximum longevity of 30 years (Choat et al., 2003).

Table 3.1 summarizes these studies and the empirical methods used to estimate M based on available life history data. The primary approach for determining natural mortality in this assessment was longevity-based (Hamel & Cope, 2022). Lower values of maximum age obtained by Choat et al. (2003) corroborate with the higher estimate of mortality calculated using a meta-analysis available in the FishLife R package Thorson (2019). Although additional methods incorporating growth and maturity were explored using the Natural Mortality Tool, their applicability remains uncertain due to the species' sex-changing nature. Specifically, the methods Hamel_K, Jensen_k 1, Jensen_k 2, Then_VBGF, Jensen_Amat, and Ri_Ef_Amat do not account for protogynous hermaphroditism Rikhter & Efanov (1976). Notably, the SEDAR 84 available inputs of age at 50% maturity reflect only the sexual maturity of females, while Von Bertalanffy's growth parameters (K), t_0 , and asymptotic size were fit across males, females, and transitional individuals combined.

A natural mortality value of 0.3 was used in the initial model runs. This value corresponds with a theoretical maximum age of 18 years, approximately the average of the various maximum age values reported by Choat et al. (2003) and Rivera Hernández & Shervette (2024). Model configurations incorporating alternative M values were explored through sensitivity analyses, which are discussed later in this report.

Table 3.1: Empirical estimates of natural mortality (M) can be derived using life history information and the Natural Mortality Tool (Cope & Hamel, 2022). The SEDAR assessment process working paper by Rivera Hernández & Shervette (2024) is equivalent to the source input listed as SEDAR84-AP-01.

Input Source	Input Type	Input	M	Method
Choat et al. (2003)	Maximum age	30	0.180	Hamel_Amax
SEDAR84-AP-01	Maximum age	20	0.270	Hamel_Amax
Meta-analysis	Scientific name	<i>Sparisoma viride</i>	0.397	FishLife
Choat et al. (2003)	Maximum age	12	0.450	Hamel_Amax
Choat et al. (2003)	Maximum age	9	0.600	Hamel_Amax
SEDAR84-AP-01	Growth (k)	0.39	0.604	Hamel_k
SEDAR84-AP-01	Growth (k)	0.39	0.585	Jensen_k 1
SEDAR84-AP-01	Growth (k)	0.39	0.624	Jensen_k 2
SEDAR84-AP-01	Growth (L ∞ , k)	33.2, 0.39	0.576	Then_VBGF
SEDAR84-AP-01	Growth (k)	0.33	0.512	Hamel_k
SEDAR84-AP-01	Growth (k)	0.33	0.495	Jensen_k 1
SEDAR84-AP-01	Growth (k)	0.33	0.528	Jensen_k 2
SEDAR84-AP-01	Growth (L ∞ , k)	33.8, 0.33	0.573	Then_VBGF
SEDAR84-AP-01	Age at 50% maturity	1.6	1.030	Jensen_Amat
SEDAR84-AP-01	Age at 50% maturity	1.6	0.924	Ri_Ef_Amat

3.3.4 Maturity, Fecundity, and Hermaphroditism

Maturity was modeled as a logistic function. Parameter estimates for maturity were based on 1,801 samples of Stoplight Parrotfish collected across the U.S. Caribbean from 2013 to 2023 (Rivera Hernández & Shervette, 2024). **The fecundity of Stoplight Parrotfish was estimated with a proxy (body weight * maturity at age).**

Protogynous hermaphroditism was parameterized into the SS3 assessment framework in two ways. **The initial method to model hermaphroditism used the average age of transition, an associated standard deviation, and a maximum transition rate input as fixed parameters in a two-sex model.** Additionally, the sex ratio between female and male fish at recruitment was 1, such that all individuals were recruited as females. Although this approach allows explicitly modeling numbers by sex and age over time, this approach could not capture the early age at transition and the overlap of both sexes directly observed across the range of ages studied by Rivera Hernández & Shervette (2024).

A second method for parameterizing hermaphroditism was explored as a sensitivity analysis. It involved using a female-only model and accounting for sex transition to males as a reduction in fecundity. A fecundity-at-age vector derived from a logistical fit to the Rivera Hernández & Shervette (2024) sex-at-age data was multiplied by maturity-at-age and fecundity-at-age.

A caveat of using a single-sex model is that the exclusion of males does not allow for any potential sperm limitation. Although protogynous hermaphrodites tend to have sex ratios skewed towards male at larger sizes, the largest and oldest stoplight parrotfish observed by Rivera Hernández & Shervette (2024) were female.

3.3.5 Stock Recruitment

A Beverton-Holt stock-recruit function was used to parametrize the relationship between spawning output and resulting recruitment of age-0 fish. The stock-recruit function requires three parameters:

- Steepness (h) characterizes the initial slope of the ascending limb (i.e., the fraction of recruits produced at 20% of the unfished spawning biomass)
- The virgin recruitment (R_0 ; estimated in log space) represents the asymptote or unfished recruitment levels.
- The variance term (σ_R) is the standard deviation of the log of recruitment (it both penalizes deviations from the spawner-recruit curve and defines the offset between the arithmetic mean spawner-recruit curve and the expected geometric mean from which the deviations are calculated).

Only the virgin recruitment (R_0) was estimated. **Sigma R and steepness were fixed at 0.7 and 0.99, respectively.** The primary assumption for steepness was that this stock is not a closed population, so recruitment may not be strongly tied to the local spawning stock biomass. **In initial model configurations, annual deviations from the stock-recruit function were not estimated.** In configurations where recruitment deviations were estimated, sigma R was explored via likelihood profiling.

Continuous recruitment was parameterized in SS3 using four settlement events. Equal proportions of recruits were assigned to each settlement event, and they were spaced such that recruitment would happen in months 1, 4, 7, and 10. This allowed growth to be staggered, reflecting a closer approximation of the observed stock dynamic of year-round spawning activity.

3.4 Summary of Data-Informed Modeling Configurations

- Based on the available data, the assessment was configured with one area, one season, one fleet, and one fishery-independent survey.

3.4.1 Dive Fleet

- The catch was input as biomass (in metric tons) and was treated as if it occurred over an entire fishing season, i.e., each fishing year.
- The start and end years of the model were 2012 and 2022, respectively.
- The assessment assumed no discarding nor discard mortality associated with the dive fleet.
- The input standard error for the landings was set to 0.01.
 - A higher standard error of 0.3 was explored via sensitivity analysis.
- The initial equilibrium catch was configured in initial runs as 30 metric tons.
 - The initial equilibrium catch was explored via likelihood profiling.
- The relative model weighting of the dive fleet length compositions was based on the number of trips sampled.
- Due to low sample sizes, the fishery-dependent commercial dive fleet length composition data were combined across all years.
- The length compositions of the commercial dive fleet were assumed to be representative of the total catch.
- A double normal function was used to model the relative vulnerability of capture by length for the dive fleet.

3.4.2 National Coral Reef Monitoring Program Survey.

- The index reflected the abundance of juveniles and adults.
- The survey was configured as an index in numbers with a lognormal error distribution
- The relative model weighting of the survey length compositions across years was based on the number of paired dives.
- The length data inputs for both the dive fleet and the three years of the survey with 1-centimeter length measurements were binned to match the survey's 2012 and 2015 5-centimeter bins.
- Although the size bins of all the length data inputs were large (5 centimeters), the model's simulated population bin size was 1-centimeter bins, with a plus group for the largest bin, greater than or equal to 41 centimeters fork length.
- The smallest two bins, [1-6) and [6-11), were collapsed into a single bin [1-11).

- Selectivity for the survey was fixed at 1 for all sizes.
- Models were initially configured in Stock Synthesis with length compositions aggregated across the available years for each source of length data and proceeded stepwise from the simplest configuration to those of moderate complexity.
 - The steps included the inclusion of annual fishery-independent length compositions.

3.4.3 Biology

- The Stoplight Parrotfish population was modeled from age 0 through age 20, and from 0 to 41 centimeters fork length, in 1-centimeter bins, with the largest values for each as plus groups.
- Parameter estimates for Von Bertalanffy growth parameter (K) and the length at maximum age (L_{∞}) were based on samples of Stoplight Parrotfish collected across the U.S. Caribbean from 2013 to 2023.
- The estimated size at age zero from otolith analysis by Rivera Hernández & Shervette (2024) was modified in Stock Synthesis so that the length of the youngest age, age 0, was set to zero.
- Coefficients of variation for both younger and older ages were initially set to 0.15.
 - A higher growth coefficient of variation of 0.25 for younger ages was explored via sensitivity analysis.
 - Higher growth coefficients of variation of 0.25 for both younger and older ages were explored via sensitivity analysis.
- The length-weight relationship was $W = 3.18 \times 10^{-5} L^{2.9}$, with weight in kilograms and length in centimeters.
- A natural mortality value of 0.3 was used in the initial model runs.
 - Alternative M values were explored through sensitivity analyses.
- Maturity was modeled as a logistic function.
- The fecundity of Stoplight Parrotfish was estimated with a proxy (body weight * maturity at age).
- The initial method to model hermaphroditism used the average age of transition, an associated standard deviation, and a maximum transition rate input as fixed parameters in a two-sex model.
 - A second method for parameterizing hermaphroditism was explored as a sensitivity analysis.

- A Beverton-Holt stock-recruit function was used to parametrize the relationship between spawning output and resulting recruitment of age-0 fish.
- Sigma R and steepness were fixed at 0.7 and 0.99, respectively.
- In initial model configurations, annual deviations from the stock-recruit function were not estimated.
 - In configurations where recruitment deviations were estimated, sigma R was explored via likelihood profiling.
- Continuous recruitment was parameterized in SS3 using four settlement events.

4 Model Development

Stock Synthesis models were initially configured using an annual catch time series and compositions that were aggregated across the available years for each source of length data. Model development proceeded stepwise from the simplest configuration to those of moderate complexity. Those sequential steps included the inclusion of the index of abundance and annual fishery-independent length compositions.

4.1 Model Diagnostics

4.1.1 Residual Analysis

The primary approach to address performance was a residual analysis of model fit to each data set (e.g., catch, length compositions, indices). Any temporal trend in model residuals or disproportionately high residual values can indicate model misspecification and poor performance. Ideally, residuals are randomly distributed, conform to the assumed error structure for that data source, and are not of extreme magnitude. Any extreme positive or negative residual patterns indicate poor model performance and potential unaccounted-for process or observation error.

4.1.2 Correlation Analysis

High correlation among parameters can lead to flat likelihood response surfaces and poor model stability. By performing a correlation analysis, modeling assumptions that lead to inadequate configurations can be identified. Because of the highly parameterized nature of stock assessment models, some parameters are expected to be correlated (e.g., stock recruit parameters). However, many strongly correlated parameters suggest reconsidering modeling assumptions and parameterization.

4.1.3 Jitter Analysis

Jitter analysis is a relatively simple method that can be used to assess model stability and to determine whether the search algorithm has found a global, as opposed to local, solution. The premise is that all starting values are randomly altered (or ‘jittered’) by an input constant value,

and the model is rerun from the new starting values. If the resulting population trajectories across many runs converge to the same solution, this provides reasonable support that a global minimum has been obtained. This process is not fault-proof; no guarantee can ever be made that the ‘true’ solution has been found or that the model does not contain misspecification. However, if the jitter analysis results are consistent, it provides additional support that the model is performing well and has come to a stable solution. For this assessment, a jitter value 0.2 was applied to the starting values, and 30 runs were completed. The jitter value defines a uniform distribution in cumulative normal space to generate new initial parameter values (Methot et al., 2020).

4.1.4 Retrospective Analysis

A retrospective analysis is a helpful approach for addressing the consistency of terminal year model estimates (e.g., SSB, Recruits, Fs) and is often considered a sensitivity exploration of impacts on key parameters from changes in data. The analysis sequentially removes a year of data at a time and reruns the model. Suppose the resulting estimates of derived quantities such as SSB or recruitment differ significantly. In such a case, serial over- or underestimation of important quantities can indicate that the model has some unidentified process error and could require reassessing model assumptions. It is expected that removing data will lead to slight differences between the new terminal year estimates and the estimates for that year in the model with the complete data. Estimates in years before the terminal year may have increasingly reliable information on cohort strength. Therefore, slight differences are usually expected between model runs as more years of size composition data are sequentially removed. Ideally, the difference in estimates will be slight and more or less randomly distributed above and below the estimates from the model with the complete data sets. A five-year retrospective analysis was carried out.

4.1.5 Profile Likelihoods

Profile likelihoods are used to examine the change in negative log-likelihood for each data source to address the stability of a given parameter estimate and to see how each data source influences the estimate. The analysis is performed by holding a given parameter at a constant value and rerunning the model. The model is run repeatedly over a range of reasonable parameter values. Ideally, the graph of change in likelihood values against parameter values will yield a well-defined minimum. When the profile plot shows conflicting signals or is flat across its range, the given parameter may be poorly estimated.

Typically, profiling is carried out for key parameters, particularly those defining the stock-recruit relationship (steepness, virgin recruitment, and sigma R). Profiles were explored across initial equilibrium catch, steepness, and virgin recruitment (R0).

4.1.6 Sensitivity Runs

Sensitivity analyses were considered to evaluate the impact on key derived quantities. Sensitivities included considering alternatives for the CV associated with catch, the method used to model hermaphroditism, and data weighting. Although the data-limited implementation of SS3 will inherently nearly exactly fit the annual landings, a higher CV of 0.3 was explored via sensitivity analysis. The second method for parameterizing hermaphroditism involved using a female-only model and accounting for sex transition to males as a reduction in fecundity. Lastly, the Dirichlet multinomial approach was used to reweigh the composition data. This method allows an internal estimation of sampling variance for each source of length composition data and adjusts the effective sample sizes (Methot & Wetzel, 2013).

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