S84_AWReport_SLP_STX

Southeast Fisheries Science Center

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Assessment Process Report 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 commercial logbooks
- Fishery-dependent length compositions from commercial port sampling
- Fishery-independent length compositions from a reef fish survey
- A fishery-independent index of abundance from a reef fish survey
- 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 V3.30.22 models were initially configured with an annual catch time series, while length composition data from each source were aggregated across all available years. 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, sensitivities of assessment outcomes were investigated using alternative inputs for longevity-informed natural mortality, coefficient of variation on growth, parameterization of hermaphroditism, and uncertainty on initial model equilibrium catch.

Model diagnostics assessed convergence, fit, and consistency using gradients, residuals, likelihood profiles, hindcast cross-validation, and jitter analyses. Those diagnostics revealed that, although data contrast was limited and recruitment estimates were highly uncertain, the available length and catch data—particularly from fishery-independent sources—provided information that the models can use to determine potential catch advice, particularly in a grid or model ensemble approach that accounts for key model assumptions and data-limited caveats.

Sensitivity analyses evaluated the effects of assumptions about natural mortality, growth variability, hermaphroditism, and initial equilibrium catch conditions. While these scenarios showed that key uncertainties can influence estimated productivity and biological reference points, nearly all models across the suite supported the conclusion that overfishing is not occurring and the stock is not overfished. A few sensitivity runs did indicate potential concern under specific combinations of assumptions, particularly with lower initial equilibrium catch and higher natural mortality.

1 Introduction

1.1 Workshop Time and Place

The SEDAR 84 Assessment Process was held via webinars from April to November 2024.

1.2 Terms of Reference

1. Develop and apply assessment tools that are compatible with available data and consistent with standard practices. Document input data, model assumptions and configuration, and equations for each approach considered.
2. To the extent possible given data limitations, provide management benchmarks and status determination criteria, including:
    a. Maximum Fishing Mortality Threshold (MFMT) = F_{MSY} or proxy
    b. MSY proxy = yield at MFMT
    c. Minimum Stock Size Threshold (MSST) = SSB_{MSY} or proxy
    d. If alternative status determination criteria are recommended, provide a description of their use and a justification.
3. To the extent possible, develop projections to support estimates of maximum sustainable yield (MSY, the overfishing limit (OFL) and acceptable biological catch (ABC) as described below. If projections are not possible, and alternative management procedures are recommended, provide a description of their use and a justification.
    a. Unless otherwise recommended, use the geometric mean of the three previous years' fishing mortality to determine $F_{Current}$
    b. Project F_{MSY} or proxy
    c. If the stock is overfished:
        i. Project $_{F0}$
        ii. Project $F_{Rebuild}$
4. Provide recommendations for future research and data collection.
5. Provide an Assessment Workshop Report to address these Terms of reference and fully document the input data and results.

1.3 List of Participants

Assessment Panel	
Adyan Rios (Lead Analyst)	NMFS/SEFSC
Richard Appeldoorn	SSC
J.J. Cruz-Motta	CFMC SSC, UPRM
Matt Damiano	NMFS/SEFSC
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Appointed Observers	
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Observers	
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Observers	
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1.4 List of Assessment Process Working Papers and Reference Documents

1.4.1 Documents Prepared for the Assessment Process

Document #	Title	Authors	Date Submitted
SEDAR84-AP-01	Report on the status of U.S. Caribbean Stoplight Parrotfish Sparisoma viride age, growth, and reproductive biology for the SEDAR84 Stock Assessment	Jesús M. Rivera Hernández and Virginia Shervette	6 July 2024

1.4.2 Reference Documents

Document #	Title	Authors
SEDAR84-RD11	The Commercial Yellowtail Snapper Fishery off Puerto Rico, 1983-2003	Nancie J. Cummings
SEDAR84-RD12	S8-DW-08: The commercial reef fish fishery in Puerto Rico with emphasis on yellowtail snapper, Ocyurus chrysurus: landings and catch per unit of effort from 1983 through 2003	Nancie J. Cummings and Daniel Matos-Caraballo
SEDAR84-RD13	The Net Buyback and Ban in St. Croix, U.S. Virgin Islands	Juan J. Agar, Flavia Tonioli, Chloe Fleming

2 Data-Informed Modeling Decisions

The data available for use in the current assessment are documented in the SEDAR 84 US Caribbean Stoplight Parrotfish St. Croix Data Workshop Report (SEDAR, 2024). Provided here is a summary of those data with a focus on the associated model configurations explored using Stock Synthesis. Throughout this report, bolded text is used to highlight and summarize the model settings and configurations relevant to the various phases of model development.

Additional details for each data input are available in their respective references:

1. **Landings** from self-reported commercial fisher logbooks (Martínez Rivera et al., 2024)
2. **Length compositions** from shore-based port sampling (Godwin et al., 2024)
3. **Length compositions** from a fishery-independent survey of reef fish (Grove et al., 2024)
4. **Index of abundance** from a fishery-independent 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 commercial fleet, and one fishery-independent survey.

2.1 Commercial Fleet Data

2.1.1 Catch

The catch data for the commercial fleet came from the Caribbean Commercial Logbook program (Martínez Rivera et al., 2024). Beginning in 1996, part of the commercial landings was reported by species groups (e.g., snappers, groupers, parrotfishes, surgeonfishes, etc.), and by gear (hook and line, gill net, SCUBA, trap, etc.). All commercial fishery data reports included species groups beginning in 1998. In July of 2011, commercial landings were reported by species and gear. Various diving gears were combined to establish a dive gear group.

The catch of Stoplight Parrotfish in St. Croix from the dive group made up 80% of the reported landings. For the SEDAR 84 stock assessment, all gears (dive and other) were included into a single commercial fleet (Table 7.1). Potential outliers discussed during the assessment webinars were investigated and retained as valid trips.

In the SEDAR 84 Stock Synthesis models, **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 landings and effort 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.**

It is important to note that the stock was not unexploited at the start year of the available catch time series. The commercial landings of all parrotfish species reported in St. Croix in 2012 was undergoing a meaningful decline. From 1996 to 2009, combined landings of all parrotfish consistently exceeded 200,000 pounds, peaking in 2006 at over 430,000 pounds. Landings dropped sharply after 2010 and have remained below 100,000 pounds since 2013, with particularly low values after 2017 (SEDAR (2024), Table 3.1.3). Initial F was estimated for the commercial fleet and a corresponding initial equilibrium catch. A common option to define reference point for the initial equilibrium catch is to use the geometric mean of the first three years of available catches. However, because of the decline preceding the start year of the assessment, the assessment panel agreed on using a value higher than the geometric mean of the first three years. **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 0.3. When implemented with few data inputs, Stock Synthesis strongly prioritizes fitting the annual landings time series, often replicating the observed values almost exactly, particularly when small standard errors (e.g., 0.01) are used. The initial configurations with low input uncertainty resulted in the model tightly fitting both the observed landings and the input initial equilibrium catch. To allow the model greater flexibility in estimating the initial equilibrium catch, and avoid anchoring it too closely to the input value, a higher standard error of 0.3 was specified for the initial equilibrium catch. This increased uncertainty enables the model to balance trade-offs among other data sources and internal dynamics when estimating initial conditions. A description of the sequential model configurations and development process is provided later in this report.

A higher standard error of 2 was explored as part of the sensitivity analysis to evaluate the influence of extreme uncertainty in the initial equilibrium catch input. This value was intentionally selected to represent a scenario with minimal confidence, allowing the model to substantially down-weight this input and reveal how strongly model outputs depend on the assumed precision of the initial equilibrium catch.

Commercial discards reported by calendar year by Martínez Rivera et al. (2024) were not significant and based on the nature of spearfishing, the predominant dive gear. Based on expert judgment and available information, discards of Stoplight Parrotfish in the St. Croix commercial fishery are considered negligible, with minimal associated mortality (SEDAR

(2024)). Given the expectation of low discard rates, **discards were not explicitly included in the model inputs or parameterized through a retention function. The assessment assumed full retention of catch.**

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

- The initial equilibrium catch was explored via likelihood profiling.
- A higher standard error of 2 was explored via sensitivity analysis.

2.1.2 Length Composition

Gear-specific annual length frequencies for the commercial fleet came from the commercial shore-based port-sampling Trip Interview Program (TIP) (Godwin et al., 2024). The Trip Interview Program manages data from the U.S. Virgin Islands collected by Division of Fish and Wildlife personnel. Port sampling personnel collect length and weight data from fish landed by commercial fishing vessels, along with information about general area of capture and gear used. Data collection began in 1983 with frequent updates in best practices; the latest being in 2017. The Stoplight Parrotfish length data from St. Croix included 29,582 length observations across 1,028 unique port sampling interviews.

Although the catch data can be separated into dive and non-dive related gears, 98% of the length measurements for St. Croix Stoplight Parrotfish from 2012-2022 were associated with diving. Those data were used to characterize the commercial fleet's length-based selectivity pattern. Since multiple fish length measurements can be obtained from a single sampled trip, each length does not represent an independent observation. **The relative model weighting of the commercial fleet length composition data was based on the number of trips sampled**.

From 2012 - 2022, the data included 1,033 shore-based length measurements obtained across 66 trips. Five trips were flagged and removed as potential outliers with unusually large lengths. **Due to low sample sizes of both fish and trips, the fishery-dependent commercial fleet length composition data were collapsed across all years 2012-2022** by implementing the super-period approach in Stock Synthesis.

The Trip Interview Program length compositions of the commercial 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 commercial fleet. However, only two parameters were estimated, effectively describing a logistic selectivity for the commercial 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 configurations for SEDAR 84. The two parameters used to achieve a logistic selectivity shape were the length associated with peak selectivity and the width of the ascending limb.

2.2 Survey Data

2.2.1 Index of Abundance

The National Coral Reef Monitoring Program (NCRMP) supports reef fish sampling on hard-bottom habitats from 0 to 30 meters depth (Grove et al., 2021). In St. Croix, sampling began in 2001 and was conducted every year from 2001 to 2012 and then every other year starting in 2015. The data used in SEDAR 84 were from nonconsecutive years during 2012 - 2022 when the survey was conducted island-wide. Data collected prior to 2017 were calibrated to account for a transition from belt transect to a cylinder survey method.

Annual mean density and associated standard errors for SEDAR 84 were provided by Grove et al. (2024). In Stock Synthesis, the time series of mean density across all observed lengths **were input 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**.

2.2.2 Length Composition

The three most recent years (2017, 2019, 2021) of the National Coral Reef Monitoring Program survey in St. Croix provided counts by individual lengths estimated to the nearest centimeter. However, before 2017 the length observations were collected in 5-centimeter bins. **The length data inputs for both the commercial 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.**

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

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

The length composition data 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 lengths.**

Models were initially configured in Stock Synthesis with length composition data aggregated across the available years for each source of length data. Investigation of additional model configurations 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.

2.3 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). The largest fish was 43.3 centimeters fork length and the oldest was 20 years old.

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.**

Note that SS3 allows the length bins of the data inputs to be larger than the bins used in the population model. **Although the bin size of all the length data inputs were large (5 centimeters), the model's simulated population bin size was 1-centimeter bins.** When 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.

2.3.1 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 1,649 samples of Stoplight Parrotfish collected across the U.S. Caribbean from 2013 to 2023 (Rivera Hernández & Shervette, 2024). When t_0 was fixed to -0.06, K was 0.39 and L_∞ was 33.2 centimeters fork length. When t_0 was estimated, it was -0.52, K was 0.33, and L_∞ was 33.8 centimeters fork length.

The SEDAR 84 assessment models were configured using the parameter estimates associated with the fixed t_0. Furthermore, **the estimated length 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 the substantial amounts of small (<10cm) Stoplight Parrotfish observed in the survey length 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 (Ono et al., 2015; Schemmel et al., 2022).

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.

2.3.2 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 $W = 3.18 \times 10^{-5} * L^{2.9}$, with weight (W) in kilograms and length (L) in centimeters.**

2.3.3 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 in Stock Synthesis used the mean 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 for the explicit modeling of numbers by sex and age over time, it 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 males at larger lengths, the largest and oldest Stoplight Parrotfish observed by Rivera Hernández & Shervette (2024) were female.

2.3.4 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 (R0; estimated in log space) represents the asymptote or unfished recruitment levels.
- The variance term (sigma R) is the standard deviation of the log of recruitment and describes the amount of year-to-year variation in recruitment.

Only the virgin recruitment (R0) was estimated. **Sigma R and steepness were fixed at 0.7 and 0.99, respectively.** The 0.7 sigma R reflects slightly high variation in recruitment. A value of 0.6 is a moderate level of recruitment variability, with lower values indicating lower variability and more predictable year-to-year recruitment. 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.** Steepness and R0 were 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.

2.3.5 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 length zero (t_0), asymptotic length (L_∞), and age at 50% maturity.

Inputs for the Natural Mortality Tool were sourced from Rivera Hernández & Shervette (2024), which reported a maximum age of 20 years for Stoplight Parrotfish in the U.S. Caribbean. However, the mean age of 1,649 sampled fish was 5.4 years, with fewer than 1% of aged individuals reaching 13 years or older. A lower maximum age of 9 years was observed (with a suggested maximum lifespan of 12 years) for stoplight parrotfish collected in 1995-2000 from Bahamas, Panama, Venezuela, and Barbados, but fish analyzed for age were limited to collections from depths 15 m (Choat et al., 2003). In contrast, a study from Bonaire utilized repeated visual censuses that included marked fish to estimate growth and mortality rates and estimated that stoplight parrotfish can attain a maximum age of over 25 years (Rooij & Videler, 1997). Choat et al. (2003) interpreted results from Van Rooji and Veideler (1997) as follows: "Although no estimate of maximum lifespan is given, their survival curves suggest a maximum age of 30 years.".

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 7.2 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). 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 (Hamel, 2015; Jensen, 1996, 1997; Rikhter & Efanov, 1976; Then et al., 2015). Notably, immature males have not been documented for Stoplight Parrotfish and the SEDAR 84 available inputs of age at 50% maturity reflect only the sexual maturity of females, while the Von Bertalanffy growth parameters (K), t0, and asymptotic length were fit across males, females, and transitional individuals combined (Rivera Hernández & Shervette (2024)).

A natural mortality value of 0.27 was used in the initial model runs. This value corresponds with the maximum age of 20 years reported by Rivera Hernández & Shervette (2024). Model configurations incorporating an alternative M value associated with a higher maximum age were explored through sensitivity analyses, which are discussed later in this report.

2.4 Summary of Data-Informed Modeling Configurations

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

2.4.1 Commercial 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.
- Based on expert input and limited data, discards were not modeled. The assessment assumed full retention of catch.
- The input standard error for the landings was set to 0.3.
  - A lower standard error of 0.1 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 commercial fleet length composition data was based on the number of trips sampled.
- Due to low sample sizes, the fishery-dependent commercial fleet length composition data were combined across all years.
- The length compositions of the commercial 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 commercial fleet.

2.4.2 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 composition data across years was based on the number of paired dives.
- The length data inputs for both the commercial 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 bin size of all the length data inputs were large (5 centimeters), the model's simulated population bin size was 1-centimeter bins.
- The smallest two bins, (1 - 6 centimeters) and (6 - 11 centimeters), were collapsed into a single bin (1 - 11 centimeter).

- Selectivity for the survey was fixed at 1 for all lengths.

2.4.3 Life History

- 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 length 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.
- The length-weight relationship was W = 3.18 x 10^-5 L^ 2.9, with weight in kilograms and length in centimeters.
- A natural mortality value of 0.27 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 mean 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 (a female-only model and accounting for sex transition to males as a reduction in fecundity) 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.

- Continuous recruitment was parameterized in SS3 using four settlement events.

3 Model Development

3.1 Framework

Stock Synthesis V3.30.22 was the modeling approach applied in the current SEDAR 84 assessment because of compatibility with the available data and consistency 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 (*Balistes 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.

Stock Synthesis models were initially configured using an annual commercial catch time series and length composition data 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.

3.2 Overview

The SEDAR 84 model development process started with simple data-limited configurations, followed by exploring data-moderate configurations, individually and combined. The simplest configurations aggregated length composition data across years by implementing the super-period approach in Stock Synthesis. When using super-periods, the estimation model generates annual values, but the likelihood function will compare the expected composite to the data composite across the super-period. When using this approach on the length composition data, Stock Synthesis models will still aim to identify parameter values for selectivity that achieve a fit between the predicted and observed data.

The initial setup steps and description of the modeling scenarios documented in this report are listed in Table 7.3. For the SEDAR 84 Stoplight Parrotfish assessment, the data-moderate considerations explored included: (a) indices of abundance, (b) annual fishery-independent length compositions, and (c) recruitment deviations. Additional model configurations were not pursued. For example, annual fishery-dependent length composition data were not considered due to low sample sizes. Similarly, alternative dome-shaped selectivity patterns and selectivity-related time blocks were not explored, based on the reviewed fishery dynamics in St. Croix.

The Stock Assessment Continuum Tool was used to develop the initial model setup by importing CSV input files and utilizing its Shiny application interface (Cope, 2024). Starting from the Continuum Tool (ct) model, a series of sequential modifications were applied to represent three key biological and data-related complexities: hermaphroditism (m1), continuous recruitment (m2), and increased catch uncertainty (m3).

This report focuses on the results and sensitivities associated with the m3 models, evaluated under the various data configurations described in the previous section. While a full discussion of sensitivity runs is provided later in the report, they are also summarized in Table 7.3 to help familiarize the reader with the terminology used throughout. For instance, model **v1_m3_s4** refers to the first scenario (**v1**, which includes an index and annual fishery-independent length data), the third level modification (**m3**, reflecting hermaphroditism, continuous recruitment, and higher catch uncertainty), and the fourth sensitivity scenario (**s4**, assuming one sex). The numbering of model runs in Table 7.3 reflects a structured approach used to track configurations consistently across all three assessments. Not every model was used for every island because the data available varies, but the numbering stays the same so that the same model structure means the same thing across all islands and helps show how the models became more complex over time.

Due to the lack of an estimable spawner-recruit relationship across the explored models, a commonly used 40% spawning potential ratio (SPR) was used as a proxy for Maximum Sustainable Yield (MSY) and as the basis for management reference points (Shertzer et al., 2024). The SPR proxy reflects the ratio of expected lifetime reproductive potential under fished conditions compared to virgin conditions.

4 Model Diagnostics

Model diagnostics aimed to follow the conceptual process described by Carvalho et al. (2021). Their approach includes evaluating goodness of fit, information sources and structure, prediction skill, convergence, and model plausibility. Although Carvalho et al. (2021) advise detours and additional model explorations when initial diagnostic tests fail, advanced diagnostics, such as likelihood profiles, retrospective, and jitter analyses, were conducted even when initial tests failed to comprehensively communicate the various model configurations explored.

4.1 Convergence

Three approaches were used to check for model convergence. They were investigating for the presence of (1) bounded parameters, (2) high final gradients, and (3) a positive definite hessian. As described by Carvalho et al. (2021), checking for bounded parameters can indicate discrepancies with data or model structure. Additionally, small final gradients and a positive definite hessian can indicate that the objective function achieved good convergence.

The models presented in this report all had a positive definite Hessian, indicating that each reached a local minimum and a locally optimal fit. None of the models had parameters that were bounded, suggesting the optimization was not constrained by parameter limits. Finally, the parameter gradients in all models were small and well below 0.001, which is commonly used in the R4SS R package to identify large gradients (Table 7.7).

4.2 Correlation Analysis

High correlation among parameters can suggest model overparameterization and lead to 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.

High correlations (correlation coefficients greater than 0.95 or less than -0.95) were observed between the estimates of initial fishing mortality (Initial F) and unfished recruitment (R0), which exceeded -0.99 in all models except for version v3_m2, where it was slightly lower but still substantial at -0.90 (Table 7.4).

In the initial default configurations of both the m1 and m2 model scenarios, the standard error on the initial equilibrium catch was fixed at a low value of 0.01. This tightly constrained the model to the input catch of 30 metric tons effectively limiting flexibility in estimating the corresponding initial fishing mortality. To address this issue, the standard error was increased to 0.3, allowing the estimated initial catch to diverge from the fixed input value (Table 7.6). This adjustment reduced the overly strong correlation between Initial F and R0 by relaxing the constraint on initial fishing mortality. The effects of increasing the standard error beyond 0.3 are discussed further in the sensitivity analyses section.

All m2 and m3 model scenarios showed moderately high correlations (> 0.90) between the two parameters used to define the commercial fleet logistic selectivity: the length at peak selectivity and the width of the ascending limb. Correlations between these selectivity parameters is expected. While estimated values varied slightly among models, they produced similar length-based selectivity curves for the commercial fleet (Figure 8.1).

4.3 Evaluating Variance

To check for parameters with high variance, parameter estimates are reported with their resulting standard deviations. Table 7.7 presents the model-estimated values and standard deviations for the main active parameters. While it's important to consider the scale of each parameter, the results suggest that key parameters are not being estimated with high precision. In particular, the coefficients of variation for initial fishing mortality are relatively high across all models, indicating considerable uncertainty in these estimates.

Figure 8.2 illustrates how the estimate and uncertainty for the unfished recruitment (R0) and virgin spawning stock biomass change throughout the sequential steps of model development. In general, increasing the complexity of the model across the model scenarios explored results in lower values for both of these parameters. The uncertainty across the response surface for key parameters is further examined later in the report using likelihood profiles.

Stock Synthesis also provides estimates and standard deviations for derived quantities such as unfished spawning stock biomass, initial year spawning biomass, and the initial depletion. Initial depletion is defined as the initial biomass divided by the unfished biomass. Table 7.5 shows this information and it is also plotted in Figures 8.3a and 8.3b.

Compared to the other m3 model scenarios, Model v3_m3 had extremely high uncertainty for fishing mortality and the highest initial depletion reflected in the lowest spawning biomass ratio (SSB Initial/SSB Unfished) reported in Table 7.5. This ratio is also plotted as a time series of total biomass relative to virgin spawning biomass in Figure 8.3a. All of the m3 model scenarios resulted in relatively high uncertainty and limited contrast, with most years encompassing the 95% confidence intervals across their respective entire time series (Figure 8.3). The sensitivity runs described later build on the exploration of uncertainty in these model scenarios and help interpret conditions under which all of the model scenarios increasingly converge.

4.4 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 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 of 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).

Consistent with earlier results indicating that the models reached local minima (positive definite Hessian), the jitter analysis also performed well across all model scenarios (Figure 8.4). Importantly, no jitter runs produced a lower likelihood than the best fit already identified for each model.

4.5 Residual Analysis

The primary approach to investigate model 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 extremely positive or negative residual patterns indicate poor model performance and potential unaccounted-for process or observation error.

4.5.1 Catch

All models closely matched the observed 2012 - 2022 catch data, which was expected given the data-limited configurations. In these configurations, Stock Synthesis relies heavily on the input catch data, with minimal additional information to support estimation of values that differ from the observations. The effect of increasing the standard error on the catch to 0.3 during the model development m3 scenario was to give the model more flexibility in estimating initial equilibrium catch and corresponding initial fishing mortality. This adjustment allowed the model to explore alternative fits while remaining informed by the assumption of a larger level of historically sustained catch. Increasing the standard error from 0.01 in the m2 model scenarios to 0.3 in the m3 model scenarios resulted in lower estimates of the initial equilibrium catch (Table 7.6). This topic will be revisited in the sensitivity analyses, where model runs with even higher catch standard error of 2 are compared. Additional justifications for further allowing the estimated initial equilibrium catch to differ from the assumed initial equilibrium catch of 30 metric tons is further investigated via likelihood profiles (See Section 4.7.2).

4.5.2 Indices

For the models without recruitment deviation being estimated (model scenarios b_m2, and v1_m2), the predicted National Coral Reef Monitoring Program index is flat (Figure 8.5). In the model scenarios with estimated recruitment deviations (v3_m3 and v7_m3), there is some improved fit to the index. Notably, the highest uncertainty in the index was observed in 2015 and 2017, and none of the models fit well with the highest value observed in 2017 (Figure 8.5).

4.5.3 Length compositions

Figure 8.6 shows the cumulative fit across all years between the observed and predicted length composition for the two model scenarios that had aggregated length data (a_m3 and v3_m3). Figures 8.7, 8.8, and 8.9 provide the cumulative and the year-specific length compositions for the model scenarios that included annual fishery-independent length data (b_m3, v1_m3, and v7_m3).

Among the models with the annual fishery-independent length data (b_m3, v1_m3, and v7_m3), the model with recruitment deviation being estimated (v7_m3), has improved fits to the annual National Coral Reef Monitoring Program length composition data

(Figure 8.9b). In the scenarios without recruitment deviations (b_m3 and v_m3), the predicted composition is identical across years, which leads to overestimating the proportion of the smallest lengths and underestimating intermediate or large lengths in 2012, 2017, and 2021 (Figures 8.7b and 8.8b). This is also evident in Figure 8.10 where the observed and predicted mean length by year are plotted.

4.6 Retrospective Analysis

A retrospective analysis is a helpful approach for investigating 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 (Carvalho et al., 2021). The analysis sequentially removes a year of data 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 an 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 time series of 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 length composition data are sequentially removed. Ideally, the difference in estimates will be slight and randomly distributed above and below the estimates from the model with complete data set time series.

The results of a five-year retrospective analysis are plotted in Figures 8.11 and 8.12. When more than 3 years are removed, the estimates of key quantities change. The sensitivity to the removal of 2019 and 2018 data reflect some model instability. Although all retrospectives show wide 95% confidence intervals, the retrospective pattern was most divergent in the scenario with recruitment deviations and annual fishery-independent length data, scenario v7_m3.

4.7 Likelihood Profiles

Profile likelihoods are used to assess the stability of parameter estimates by examining changes in the negative log-likelihood for each data source and evaluating the influence of each source on 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 virgin recruitment (R0), initial equilibrium catch, and steepness.

4.7.1 Unfished Recruitment (R0)

Figure 8.13 shows the profile likelihood for the natural log of the unfished recruitment parameter of the Beverton – Holt stock-recruit function for St. Croix Stoplight Parrotfish across model scenarios (a_m3, b_m3, v1_m3, v3_m3, and v7_m3). All models show conflicting signals and relatively poorly defined minimums, with a range of equally plausible values reflected by only small changes in likelihood. Figure 8.14 shows the corresponding change in the MSY SPR 40% across the range of unfished recruitment values explored.

4.7.2 Initial Equilibrium Catch

Figure 8.15 shows the profile likelihood for the initial equilibrium catch for St. Croix Stoplight Parrotfish across model scenarios (a_m3, b_m3, v1_m3, v3_m3, and v7_m3). Except for model scenario v3_m3, the models suggest improved fit associated with smaller values of fixed initial equilibrium catch. Meanwhile, v3_m3 shows a minimum at 24 metric tons. Figure 8.16 shows the corresponding change in the MSY SPR 40% across the range of initial equilibrium catch values explored. This suggests that given further flexibility the initial equilibrium may be estimated lower and was further examined through sensitivity runs.

4.7.3 Steepness

Figure 8.17 shows the profile likelihood for the steepness parameter of the Beverton – Holt stock-recruit function for St. Croix Stoplight Parrotfish across model scenarios (a_m3, b_m3, v1_m3, v3_m3, and v7_m3). Except for model scenario a_m3, all models show lower likelihoods associated with higher values of steepness, driven by the fit to the length data. Figure 8.18 shows the corresponding change in the MSY SPR 40% across the range of steepness values explored.

4.8 Sensitivity Runs

Sensitivity analyses were conducted to evaluate the impact of key model assumptions on derived quantities. Details of the process and naming conventions are provided in Table 7.3. The analyses explored alternative assumptions for the CV on growth, fixed input for maximum age-informed mortality, the modeling approach for hermaphroditism, and the standard error applied to catch data.

For each model scenario and sensitivity run:

- Table 7.6 provides the initial equilibrium catch
- Tables 7.8 and 7.9 provide the MSY proxy (based on SPR 40%)
- Table 7.10 summarizes the fishing mortality rate and spawning stock biomass ratios relative to the rate and biomass of the stock associated with the MSY proxy (based on SPR 40%)

4.8.1 Growth CV

The first sensitivity scenario (s1) assumed the coefficient of variation (CV) for young fish was increased from 0.15 to 0.25. Of all the sensitivities explored, the m3_s1 sensitivities resulted in the smallest change to the derived quantities relative to the corresponding m3 sensitivity model configurations (Tables 7.6, 7.8, 7.9, and 7.10). Growth is a critical process in all stock assessment models, and in this assessment, the CV for young fish was a particularly relevant sensitivity to examine due to the large number of small individuals (less than 11 cm) observed in the fishery-independent survey length compositions. While additional sensitivities related to growth were considered, they will be revisited in the discussion section as part of the research recommendations. The current models use the best available growth parameters from Rivera Hernández & Shervette (2024).

4.8.2 Natural Mortality

The second sensitivity scenario (s2) explored a lower natural mortality of 0.18, corresponding to a higher maximum age of 30 years. Although the maximum age is often larger than the maximum age observed, particularly for species that have sustained historical fishing pressure, the Hamel (2015) method estimates natural mortality based on the maximum observed age. In this assessment, age is the only factor used to inform the estimate of natural mortality, making it important to consider the implications of assuming a lower M, which reflects a less productive stock. The m3_s2 sensitivity models showed notable differences from the corresponding m3 configurations. These differences included lower initial equilibrium catch, reduced MSY estimates, lower spawning stock biomass ratios, and higher fishing mortality ratios (Tables 7.6, 7.8, 7.9, and 7.10).

4.8.3 Single Sex Model

The third sensitivity scenario (s3) explored an alternative method for parameterizing hermaphroditism. This approach used a female-only model, accounting for sex transition by reducing fecundity rather than explicitly modeling males. Interestingly, this configuration produced estimates of initial catch that were identical to the corresponding m3 models, slightly higher MSY estimates, similar spawning stock biomass ratios, and slightly lower fishing mortality ratios (Tables 7.6, 7.8, 7.9, and 7.10). This result demonstrates that the direct parameterization—despite its caveats, particularly for species where not all females transition, can be restructured differently while yielding broadly consistent outcomes.

However, a key limitation of the m3_s3 single-sex models is the inability to capture potential sperm limitation due to the disproportionate removal of males, which may increase the risk of reduced reproductive output. As such, both model configurations provide useful perspectives and highlight the need for additional data and consideration to fully characterize uncertainty related to hermaphroditic biology in Stoplight Parrotfish. This uncertainty may represent a greater risk of overfishing compared to gonochoric species.

4.8.4 Standard Error on Catch

The fourth sensitivity scenario (s4) examined the effect of further relaxing the information that informs the initial model conditions. In the m3 model scenarios, a standard error of 0.3 was applied to the landings data (see Section 2.1.1). Compared to the m2 model scenarios, this resulted in lower estimates of initial equilibrium catch. However, likelihood profiles (see Section 4.7.2) showed improved fit at even lower fixed estimates of equilibrium catch. This led to the exploration of increased input uncertainty using a standard error of 2.0 associated with the input equilibrium catch.

Effectively, this provides greater flexibility in estimating initial conditions, which are known to be difficult to resolve without longer time series. The m3_s4 sensitivities produced much lower estimates of initial catch and MSY, higher fishing mortality ratios, and similar biomass ratios compared to the m3 models (Tables 7.6, 7.8, 7.9, and 7.10).

These results highlight the significance of uncertainty in initial conditions. While the model fit improved with lower assumed historical catches, this also suggested a less productive stock. This sensitivity underscores the value of longer historical data series. Without them, there is considerable uncertainty in defining the initial conditions, and the m3_s4 results imply that if early landings were smaller than assumed in the M3 models, the stock may be less productive.

Figure 8.19 shows that the estimates and associated uncertainty for unfished recruitment (R0) and virgin spawning stock biomass in the m3_s4 sensitivity scenarios are shifted toward smaller values compared to the m3 model results (See Figure 8.2). The time series of derived quantities for the m3_s4 scenarios are provided in Figure 8.20 and appear broadly similar to those from the m3 models shown in Figure 8.3.

4.8.5 Standard Error on Catch and Natural Mortality

The fifth sensitivity scenario (s5) explored the combined implications of two key sensitivities that had notable effects on model outcomes: increased uncertainty around initial equilibrium catch and lower natural mortality associated with higher maximum age. By evaluating both assumptions simultaneously, this scenario investigates the compounding uncertainty associated with the baseline M3 model configurations.

The combined effect of these changes resulted in lower estimates of MSY and initial catch and substantially higher estimates of relative fishing mortality (Tables 7.6, 7.8, 7.9, and 7.10). As shown in Figure 8.21, the estimates and uncertainty for unfished recruitment (R0) and virgin spawning stock biomass in the m3_s5 models are shifted to smaller values and show more consistency across configurations. The time series of derived quantities in Figure 8.22 indicate that the m3_s5 models converge on lower spawning output and higher fishing mortality relative to the M3 scenarios.

4.8.6 Single Sex Model, Standard Error on Catch, and Natural Mortality

Similar to the s3 sensitivity run, the sixth and final sensitivity scenario (s6) was conducted to evaluate whether the dynamics and implications observed in the s5 scenario persisted when the model was reconfigured as a single-sex model. The results from the m3_s6 sensitivity runs were closely aligned with those of the m3_s5 scenarios, indicating that the combined effects of lower natural mortality and increased uncertainty in initial catch are robust to the choice of sex structure in the model (Tables 7.6, 7.8, 7.9, and 7.10).

5 Discussion

This assessment presents a suite of model configurations developed to address key uncertainties in data and model structure, using an integrated framework to characterize the stock status of Stoplight Parrotfish in St. Croix. Overall, the results broadly indicate that overfishing is not occurring and the stock is not overfished. Despite the broad range of scenarios explored, nearly all model configurations supported this conclusion, with only one sensitivity (m3_s6) reflecting an overfishing status Table 7.10. Nonetheless, diagnostics and sensitivities highlighted critical caveats, primarily stemming from limited and low-contrast data inputs.

A major source of uncertainty stems from the unknown initial catch conditions. The short time series, coarse resolution in length binning, and absence of early fishery information make it challenging for the models to resolve the historical state of the stock.

Natural mortality and assumptions about the historical catch levels were two of the most influential parameters across model sensitivities. The combined sensitivity scenario (s5) showed that allowing the model to estimate initial catch and assuming lower natural mortality led to lower MSY estimates and higher fishing mortality ratios. These patterns were robust across both sex-structured and single-sex model configurations. These outcomes reinforce the value of structured sensitivity analyses to explore uncertainty and variability in model results. Looking ahead, future research should consider the development of model grids or ensemble approaches to formally capture uncertainty and improve the robustness of management advice.

Recruitment deviations, when estimated, are particularly uncertain, given the limited years of available data and large length bins. However, the availability of fishery-independent length data from the National Coral Reef Monitoring Program provides a valuable information source. The observed abundance of small fish may allow better inference of recruitment in future assessments. Finer resolution data (e.g., using 1 cm bins for specific years) could improve model performance and reduce uncertainty.

Integrated models such as Stock Synthesis are powerful not only for synthesizing multiple data sources but also for making key assumptions explicit and testable. Without this flexibility, assessments risk producing outputs that must be taken at face value, with little opportunity to evaluate the effects of underlying assumptions.

While not every species will have sufficient data for an integrated assessment, wherever possible, structured scenario testing—such as that conducted here—should be pursued to explore alternative hypotheses and better understand the drivers of population dynamics. Such efforts strengthen the scientific foundation for management advice and help balance the need for both rigorous and practical assessment frameworks.

Given that Stoplight Parrotfish is currently the only parrotfish species in the complex with a SEDAR assessment, it may be worth reconsidering if catch limits for the entire parrotfish unit should be based on the combined historical mean landings of two indicator species, as currently implemented, particularly if Stoplight Parrotfish catch continues to represent a significant portion of the total.

Additionally, this assessment assumes an open population with recruitment not tightly linked to local spawning stock. This is supported by high regional connectivity and long duration of pelagic larvae reported for Stoplight Parrotfish by Loera-Padilla et al. (2021). However, such high connectivity across the Greater Caribbean may warrant larger-scale stock definitions or spatially explicit metapopulation modeling approaches.

Finally, the stepwise modeling approach used in this assessment offers a framework that could be applied to other Caribbean species. Expanding the approach through targeted data collection and method development could improve the timeliness and robustness of stock assessments across the region. This will require continued support for long-term monitoring programs, higher-resolution data collection, and investment in model development and bridging exercises to deliver science-based, real-time management advice.

6 Assessment Process Research Recommendations

To mitigate some of the data uncertainties it is recommended to:

- Expand fishery-independent survey time series and resolution (e.g., retain and use 1-cm length bin data where available).
- Further evaluate natural mortality and growth assumptions. Collect and analyze additional life history data to reduce uncertainty around growth and natural mortality rates.
- Conduct focused research on historical catches and fishing history to inform and constrain early model conditions.
- Consider using simpler production models or age-structured models with fixed selectivity to isolate and evaluate different data inputs.
- Develop and evaluate model ensembles or uncertainty grids to guide catch advice under different plausible scenarios.
- Investigate stock connectivity to better understand local versus regional recruitment dynamics and their implications for informing steepness.
- Re-examine multiple indicator approach for the Parrotfish Two management unit given that SEDAR 84 only comprehensively evaluated data for *Sparisoma viride*.
- Research methods, including simulations, to "right-size" model complexity to match data availability, avoiding overparameterization in data-limited contexts.
- Support Management Strategy Evaluations that are robust to key uncertainties to guide harvest advice.
- Ensure the continuation of fishery-independent survey programs (e.g., National Coral Reef Monitoring Program) with consistent spatial and temporal coverage.
- Maintain and expand commercial catch monitoring programs. Expand port sampling and other fishery-dependent data collection to fill gaps in length composition and effort data.

7 Tables

Table 7.1: Commercial landings of Stoplight Parrotfish reported in St. Croix from 2012-2022 in metric tons and pounds by year, along with the percentage of the total commercial landings that came from each gear group.

Year	Metric Tons	Pounds	Dive Gears	Other Gears
2012	18.99	41,869	97%	3%
2013	15.32	33,773	98%	2%
2014	9.88	21,774	87%	13%
2015	11.25	24,808	68%	32%
2016	11.10	24,481	58%	42%
2017	10.67	23,533	68%	32%
2018	3.29	7,262	90%	10%
2019	3.42	7,540	80%	20%
2020	9.93	21,883	71%	29%
2021	11.07	24,412	90%	10%
2022	7.44	16,398	74%	26%
Total	112.37	247,733	82%	18%

Table 7.2: Empirical estimates of natural mortality (M) derived using life history information and the Natural Mortality Tool (Cope & Hamel, 2022). The SEDAR assessment working paper SEDAR84-AP-01 is equivalent to Rivera Hernández & Shervette (2024). The survival curve maximum age of 30 years, reflects data from Rooij & Videler (1997) interpreted by Choat et al. (2003) as follows: "Although no estimate of maximum lifespan is given, their survival curves suggest a maximum age of 30 years.". All models included in this report utilize the natural mortality estimate of 0.27 corresponding with the maximum age observed by Rivera Hernández & Shervette (2024), except three of the sensitivity scenarios (s2, s5, and s6) which utilize the 0.18 natural morality. Higher estimate of mortality result from the meta-analysis available in the FishLife R package (Thorson et al., 2017).

Input Source	Input Type	Input	M	Method
Survival curve	Maximum age	30	**0.180**	Hamel_Amax
SEDAR84-AP-01	Maximum age	20	**0.270**	Hamel_Amax
Meta-analysis	Scientific name	*Sparisoma viride*	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

Table 7.3: Summary of process and naming conventions used across different model development stages of the SEDAR 84 St. Croix Stoplight Parrotfish stock assessment. The numbering of model runs reflects a structured approach used to track configurations consistently across all three SEDAR 84 assessments.

Stage	Code	Sequential modeling steps
Initial	ct	model initialized with continuum tool (ct)
Initial	m1	ct + hermaphroditism and adjusted length at age zero
Initial	m2	m1 + continuous recruitment
Initial	m3	m2 + catch uncertainty
Scenario	null	catch and super-year length data
Scenario	a	index
Scenario	b	annual fishery-independent length data
Scenario	v1	index + annual fishery-independent length data
Scenario	v3	index + recruitment deviations
Scenario	v7	index + annual fishery-independent length data + recruitment deviations
Sensitivity	s1	higher CV on growth young
Sensitivity	s2	higher age and lower m
Sensitivity	s3	one sex (age-based fecundity = maturity * weight * sex ratio)
Sensitivity	s4	higher catch uncertainty
Sensitivity	s5	s2 + s4
Sensitivity	s6	s2 + s3 + s4

Table 7.4: St. Croix Stoplight Parrotfish correlations between estimated parameters across the m2 and m3 model scenarios. The table shows correlations greater than 0.9 or less than -0.9. Correlations that are greater than 0.95 or less than -0.95 are shown in red.

Scenario	Estimated Parameters		Correlation Coefficient
a_m2	Initial F	Unfished Recruitment (R0)	-0.997
a_m2	Commercial Selectivity Asend.	Commercial Selectivity Peak	0.901
a_m3	Commercial Selectivity Asend.	Commercial Selectivity Peak	0.901
b_m2	Initial F	Unfished Recruitment (R0)	-0.995
b_m2	Commercial Selectivity Asend.	Commercial Selectivity Peak	0.911
b_m3	Commercial Selectivity Asend.	Commercial Selectivity Peak	0.903
v1_m2	Initial F	Unfished Recruitment (R0)	-0.995
v1_m2	Commercial Selectivity Asend.	Commercial Selectivity Peak	0.913
v1_m3	Commercial Selectivity Asend.	Commercial Selectivity Peak	0.902
v3_m2	Initial F	Unfished Recruitment (R0)	-0.904
v7_m2	Initial F	Unfished Recruitment (R0)	-0.997
v7_m2	Commercial Selectivity Asend.	Commercial Selectivity Peak	0.919
v7_m3	Commercial Selectivity Asend.	Commercial Selectivity Peak	0.919

Table 7.5: St. Croix Stoplight Parrotfish derived quantities for unfished and initial spawning stock biomass in metric tons (mt) along with standard deviations (SD) and coefficient of variation (CV) by model scenario (a_m3, b_m3, v1_m3, v3_m3, and v7_m3). CV is calculated as the SD divided by the parameter estimate.

Derived Quantity	Scenario	Estimate	SD	CV
SSB Unfished (mt)	a_m3	98.13	26.13	0.27
	b_m3	78.64	25.59	0.33
	v1_m3	73.54	25.45	0.35
	v3_m3	60.88	13.84	0.23
	v7_m3	37.67	7.56	0.20
SSB Initial (mt)	a_m3	65.21	19.86	0.30
	b_m3	59.32	19.98	0.34
	v1_m3	55.69	20.07	0.36
	v3_m3	16.55	7.60	0.46
	v7_m3	27.84	5.49	0.20
Ratio SSB Initial:Unfished	a_m3	0.66	0.09	0.13
	b_m3	0.75	0.05	0.06
	v1_m3	0.76	0.05	0.06
	v3_m3	0.27	0.14	0.53
	v7_m3	0.74	0.05	0.07

Table 7.6: St. Croix Stoplight Parrotfish estimated initial equilibrium catch in metric tons by model scenario including across sensitivity runs. The input value was 30 metric tons with a standard error of 0.3.

Parameter	Scenario	a	b	v1	v3	v7
Commercial Equilibrium Catch	m2	29.99	29.98	29.98	30.00	29.98
	m3	25.39	15.66	14.24	28.39	8.00
	m3_s1	25.09	15.12	13.58	28.83	7.36
	m3_s2	12.28	9.89	8.90	18.23	6.92
	m3_s3	25.39	15.65	14.24	28.41	8.00
	m3_s4	5.74	3.78	2.24	24.30	0.00
	m3_s5	4.80	8.32	7.37	10.40	4.28
	m3_s6	4.80	8.32	7.37	10.40	4.28

Table 7.7: St. Croix Stoplight Parrotfish parameters, standard deviations (SD), and coefficient of variation (CV) by model scenario (a_m3, b_m3, v1_m3, v3_m3, and v7_m3). CV is calculated as the SD divided by the parameter estimate.

Parameter	Scenario	Estimate	SD	CV	Gradient
Commercial Selectivity Asend.	a_m3	2.25	0.98	0.44	-4.0e-06
	b_m3	2.27	0.98	0.43	1.1e-05
	v1_m3	2.26	0.98	0.43	1.9e-05
	v3_m3	2.48	0.83	0.33	1.6e-05
	v7_m3	2.56	0.85	0.33	-1.1e-05
Commercial Selectivity Peak	a_m3	25.85	1.79	0.07	4.1e-06
	b_m3	25.89	1.82	0.07	-1.6e-05
	v1_m3	25.87	1.81	0.07	-5.9e-05
	v3_m3	26.62	1.57	0.06	-1.4e-05
	v7_m3	26.98	1.74	0.06	1.3e-05
Initial F	a_m3	0.19	0.08	0.42	2.5e-06
	b_m3	0.12	0.03	0.25	-9.4e-06
	v1_m3	0.11	0.03	0.27	-3.3e-05
	v3_m3	1.20	1.20	1.00	1.4e-05
	v7_m3	0.12	0.03	0.25	1.3e-05
Unfished Recruitment (R0)	a_m3	5.51	0.27	0.05	-5.9e-06
	b_m3	5.29	0.33	0.06	1.4e-06
	v1_m3	5.28	0.35	0.07	7.8e-06
	v3_m3	5.09	0.23	0.05	-2.0e-05
	v7_m3	4.61	0.20	0.04	7.2e-06

Table 7.8: St. Croix Stoplight Parrotfish derived quantities of the MSY proxy (based on SPR 40%) in metric tons by model scenario (a_m3, b_m3, v1_m3, v3_m3, and v7_m3) and corresponding each model scenario's six sensitivity runs. CV is calculated as the SD divided by the parameter estimate. Estimates of the MSY proxy are also presented in pounds in Table 7.9.

Scenario	MSY Proxy	SD	CV
a_m2	38.12	6.36	0.17
a_m3	34.25	8.86	0.26
a_m3_s1	32.57	8.19	0.25
a_m3_s2	12.29	1.70	0.14
a_m3_s3	36.59	9.46	0.26
a_m3_s4	19.96	6.21	0.31
a_m3_s5	8.57	1.26	0.15
a_m3_s6	8.29	1.22	0.15
b_m2	50.10	9.01	0.18
b_m3	27.45	8.69	0.32
b_m3_s1	25.47	7.53	0.30
b_m3_s2	10.69	0.89	0.08
b_m3_s3	29.31	9.27	0.32
b_m3_s4	15.22	2.67	0.18
b_m3_s5	9.78	0.77	0.08
b_m3_s6	9.47	0.75	0.08
v1_m2	61.73	13.21	0.21
v1_m3	29.91	10.07	0.34
v1_m3_s1	27.63	8.52	0.31
v1_m3_s2	10.84	0.83	0.08
v1_m3_s3	32.67	10.98	0.34
v1_m3_s4	16.06	2.63	0.16
v1_m3_s5	9.96	0.72	0.07

Scenario	MSY Proxy	SD	CV
v1_m3_s6	10.28	0.75	0.07
v3_m2	26.31	1.60	0.06
v3_m3	25.23	5.61	0.22
v3_m3_s1	24.06	5.46	0.23
v3_m3_s2	16.17	3.33	0.21
v3_m3_s3	27.61	6.13	0.22
v3_m3_s4	22.64	8.94	0.39
v3_m3_s5	10.91	3.05	0.28
v3_m3_s6	11.26	3.15	0.28
v7_m2	63.84	18.39	0.29
v7_m3	15.76	3.08	0.20
v7_m3_s1	14.05	2.33	0.17
v7_m3_s2	8.91	0.81	0.09
v7_m3_s3	17.26	3.37	0.20
v7_m3_s4	10.09	1.12	0.11
v7_m3_s5	7.41	0.77	0.10
v7_m3_s6	7.65	0.79	0.10

Table 7.9: St. Croix Stoplight Parrotfish derived quantities of the MSY proxy (based on SPR 40%) in pounds by model scenario (a_m3, b_m3, v1_m3, v3_m3, and v7_m3) and corresponding each model scenario's six sensitivity runs.

Scenario	a	b	v1	v3	v7
m2	84,039	110,450	136,093	57,997	140,739
m3	75,500	60,510	65,947	55,620	34,751
m3_s1	71,811	56,150	60,908	53,047	30,975
m3_s2	27,089	23,571	23,896	35,651	19,638
m3_s3	80,660	64,612	72,036	60,859	38,041
m3_s4	44,007	33,559	35,413	49,915	22,241
m3_s5	18,890	21,570	21,949	24,055	16,333
m3_s6	18,286	20,874	22,658	24,832	16,856

Table 7.10: St. Croix Stoplight Parrotfish fishing mortality rate and spawning stock biomass ratios relative to the rate and biomass of the stock associated with the MSY proxy (based on SPR 40%). The relative fishing mortality ratio is expressed as a three-year geometric mean of the annual fishing mortality rates for 2020-2022 divided by the fishing mortality rate associated with MSY SPR 40%. Relative fishing mortality rates that are above one are shown in red font. The relative stock biomass ratio is expressed as the 2022 spawning biomass divided by the spawning stock biomass at MSY SPR 40%. Relative stock biomass ratios that are below 0.75 are shown in red font.

Metric	Scenario	a	b	v1	v3	v7
F Current / F SPR 40%	m2	0.13	0.09	0.06	0.22	0.05
	m3	0.14	0.18	0.14	0.23	0.33
	m3_s1	0.15	0.20	0.16	0.24	0.41
	m3_s2	0.60	0.74	0.64	0.61	0.89
	m3_s3	0.12	0.15	0.10	0.16	0.23
	m3_s4	0.26	0.38	0.30	0.25	0.53
	m3_s5	0.98	0.85	0.73	0.78	1.00
	m3_s6	1.07	0.93	0.64	0.69	0.88
SSB 2022 / SSB SPR 40%	m2	1.79	1.85	2.31	1.38	2.52
	m3	1.77	1.73	2.12	1.38	1.56
	m3_s1	1.75	1.70	2.08	1.38	1.40
	m3_s2	1.25	1.16	1.30	0.81	1.04
	m3_s3	1.75	1.71	2.14	1.40	1.59
	m3_s4	1.64	1.52	1.83	1.39	1.48
	m3_s5	1.05	1.10	1.23	0.90	1.08
	m3_s6	1.00	1.03	1.26	0.91	1.13

8 Figures

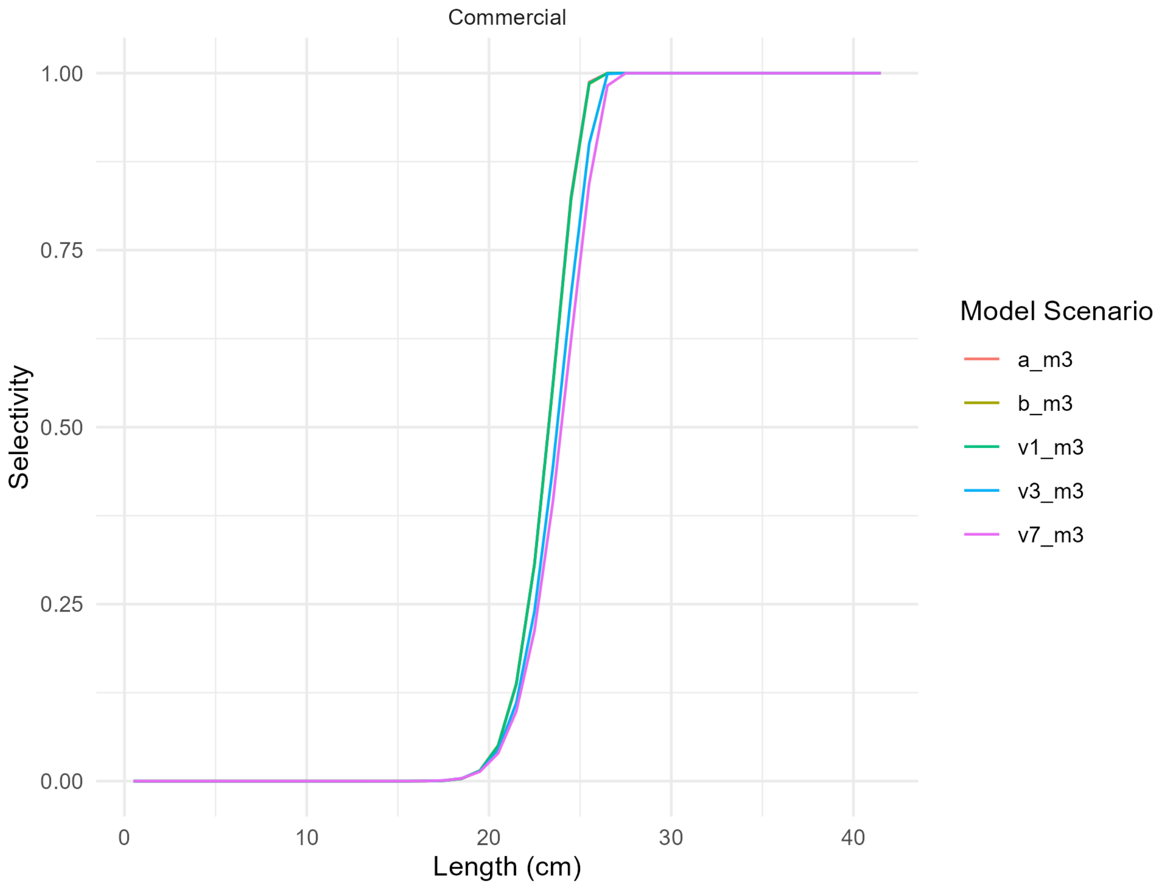
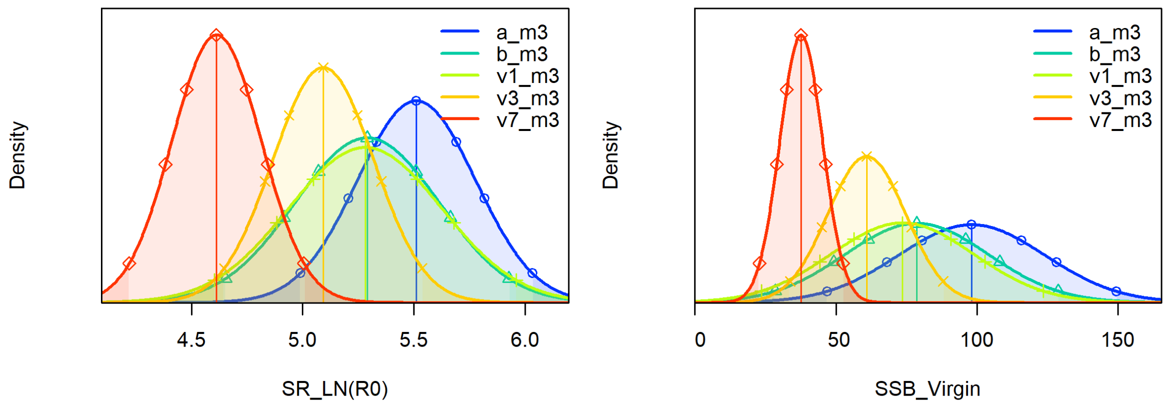


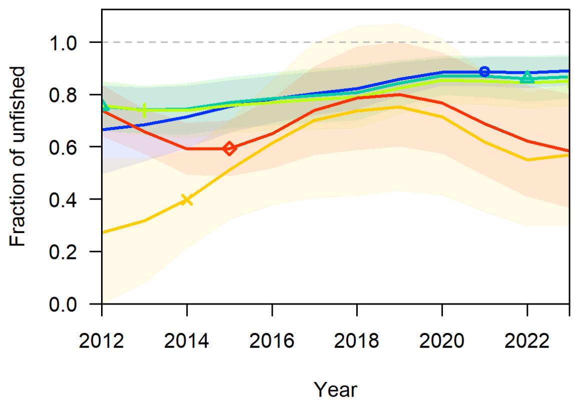
Figure 8.1: St. Croix Stoplight Parrotfish commercial fleet logistic selectivity across model scenarios (a_m3, b_m3, v1_m3, v3_m3, and v7_m3).Selectivity patterns reflect the probability that a fish of a given length will be caught by a particular fishing fleet or observed in a given survey.



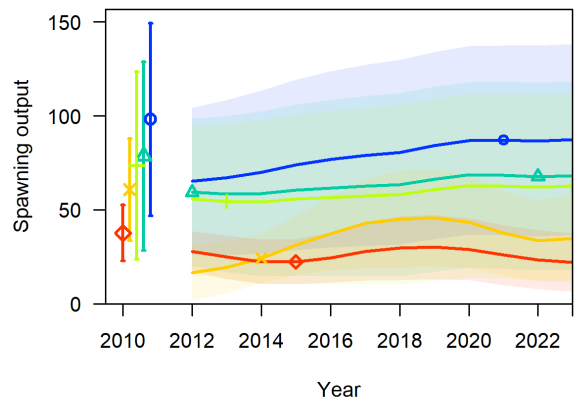
(a) Unfished recruitment

(b) Virgin Spawning Stock Biomass

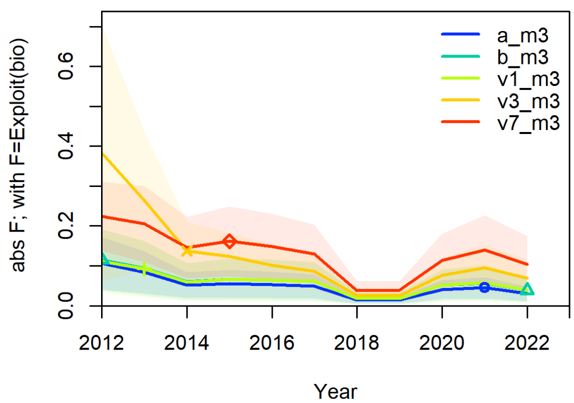
Figure 8.2: St. Croix Stoplight Parrotfish parameter distribution for (a) the natural log of the unfished recruitment parameter of the Beverton – Holt stock-recruit function and (b) virgin spawning stock biomass in metric tons across model scenarios (a_m3, b_m3, v1_m3, v3_m3, and v7_m3).



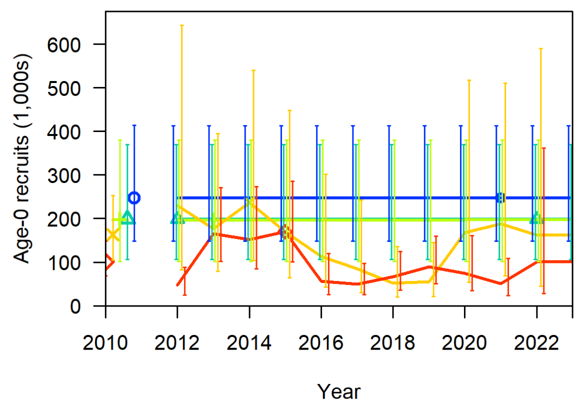
(a) Spawning Biomass Ratio



(b) Spawning Biomass

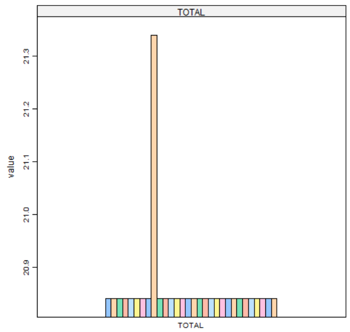


(c) Fishing Mortality

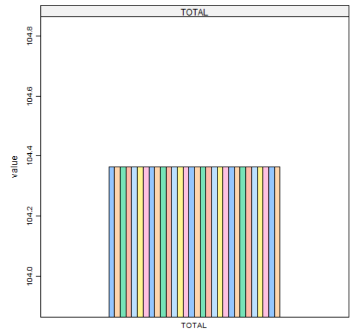


(d) Recruitment

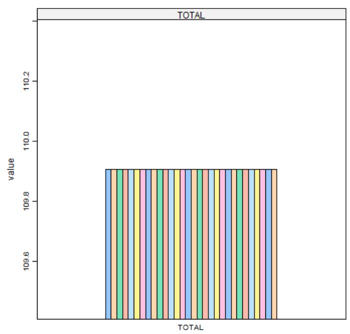
Figure 8.3: St. Croix Stoplight Parrotfish derived quantity time series across model scenarios (a_m3, b_m3, v1_m3, v3_m3, and v7_m3). Derived quantities plotted over time for (a) the relative spawning stock biomass (total biomass / virgin spawning stock biomass), (b) spawning stock biomass in metric tons, (c) fishing mortality (total biomass killed / total biomass), (d) and recruitment in thousands of fish. The shaded areas and vertical bars in the derived quantities time series represent 95% confidence intervals. The values plotted prior to the model start year of 2012 reflect the unfished conditions and associated 95% confidence intervals.



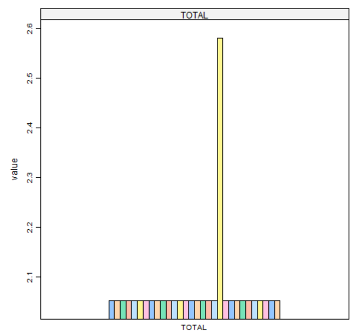
(a) Model a_m3



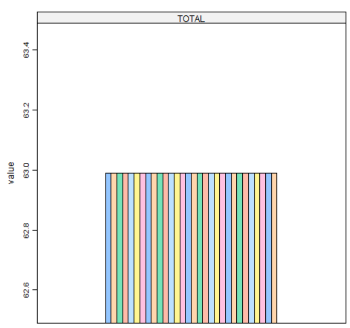
(b) Model b_m3



(c) Model v1_m3

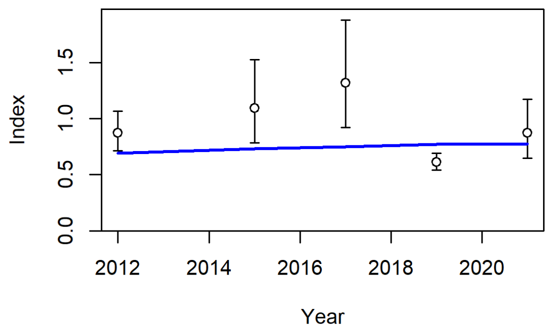


(d) Model v3_m3

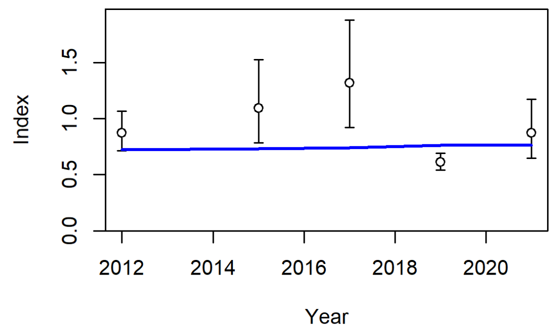


(e) Model v7_m3

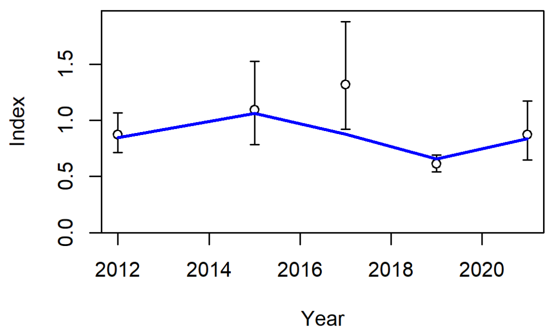
Figure 8.4: St. Croix Stoplight Parrotfish jitter analysis total likelihood across model scenarios (a_m3, b_m3, v1_m3, v3_m3, and v7_m3). Each panel gives the results of 30 runs of the corresponding model scenario where the starting parameter values for each run were randomly changed by 20% from each model's predicted values using a uniform distribution in cumulative normal space.



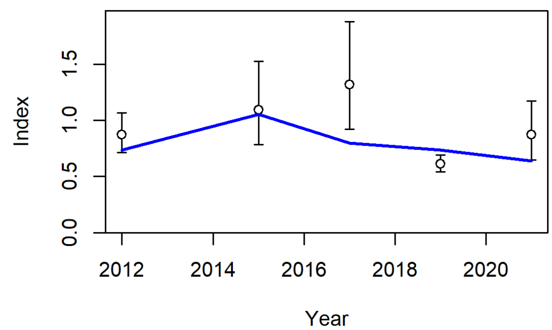
(a) a_m3



(b) v1_m3

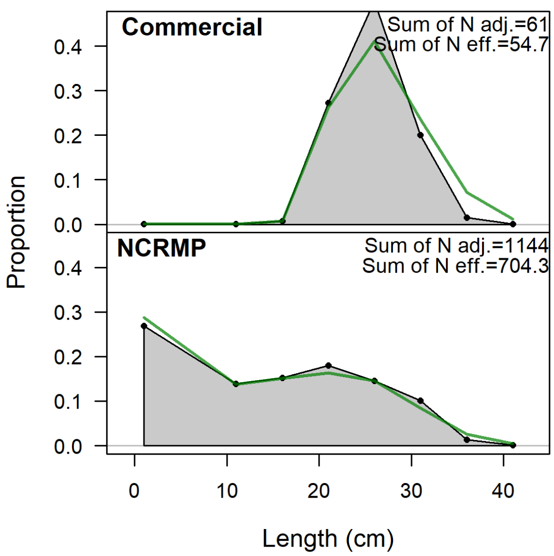


(c) v3_m3

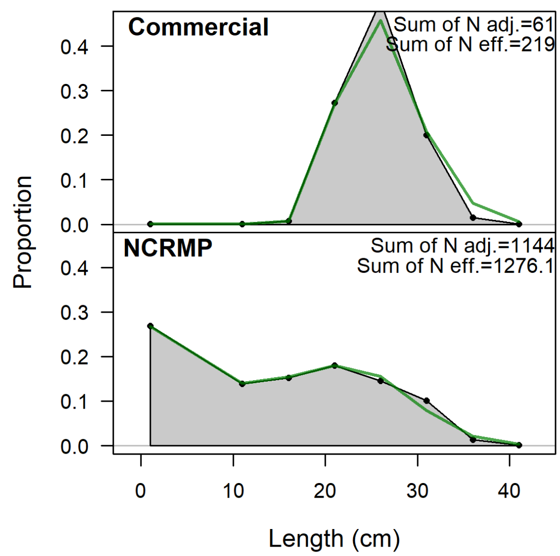


(d) v7_m3

Figure 8.5: St. Croix Stoplight Parrotfish National Coral Reef Monitoring Program observed (open circles) and predicted (blue line) indices of relative abundance and associated standard errors across model scenarios (a_m3, v1_m3, v3_m3, and v7_m3). Model scenario b_m3 is not provided as its configuration does not include an index. Error bars indicate a 95% uncertainty interval around observed index values based on the model assumption of lognormal error. Model scenarios a_m3 and v1_m3 do not estimate recruitment deviations, while model scenarios v3_m3 and v7_m3 do.

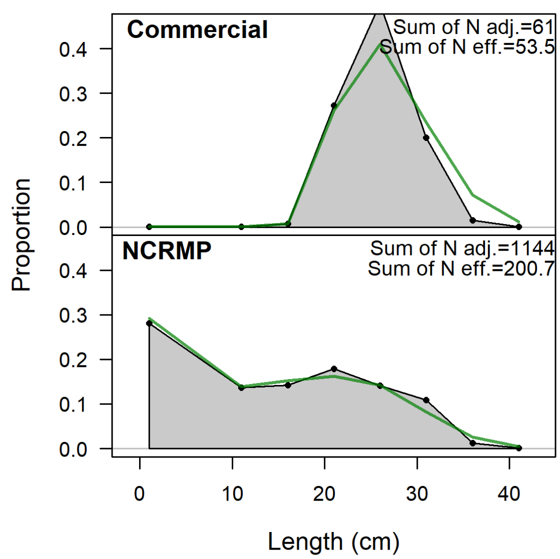


(a) a_m3 across all years

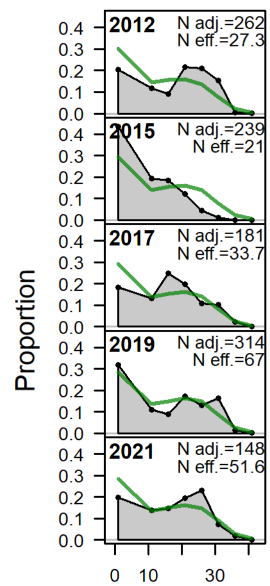


(b) v3_m3 across all years

Figure 8.6: St. Croix Stoplight Parrotfish observed and predicted length distributions in centimeters aggregated across years for the Commercial (TIP) and National Coral Reef Monitoring Survey (NCRMP) length compositions for the (a) a_m3 model scenarios. Green lines represent predicted length compositions, while gray regions represent observed length compositions. The effective sample sizes used to weight the length composition data are provided by N adj (the input sample size) and N eff (the calculated effective sample size) and are shown in the upper right corners. Since super years are utilized for the commercial fleet and the national coral reef monitoring survey in these model scenarios, the fits to annual data are not shown.

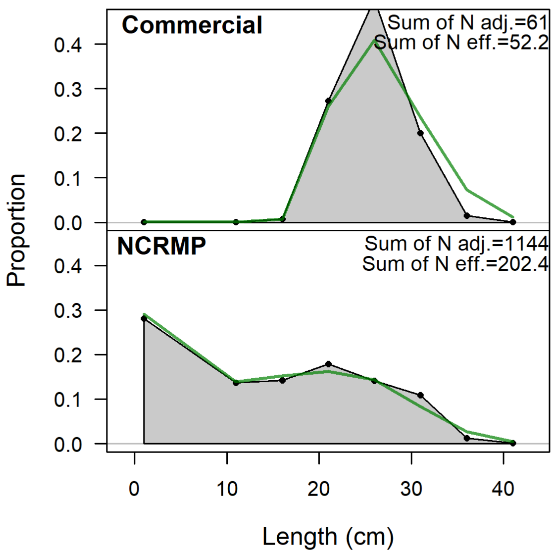


(a) b_m3 across all years

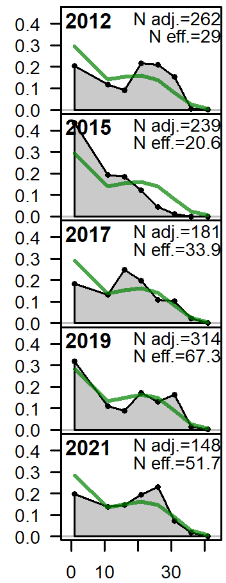


(b) b_m3 by year

Figure 8.7: St. Croix Stoplight Parrotfish observed and predicted length distributions in centimeters (a) aggregated across years and (b) by year for the Commercial (TIP) and National Coral Reef Monitoring Survey (NCRMP) length compositions for the b_m3 model scenarios. Green lines represent predicted length compositions, while gray regions represent observed length compositions. The effective sample sizes used to weight the length composition data are provided by N adj (the input sample size) and N eff (the calculated effective sample size) and are shown in the upper right corners.

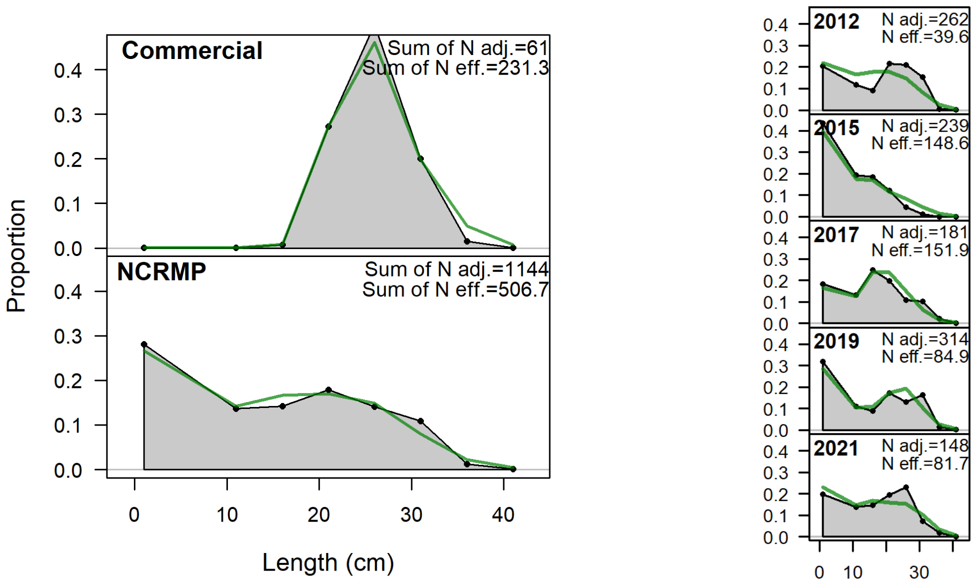


(a) v1_m3 across all years



(b) v1_m3 by year

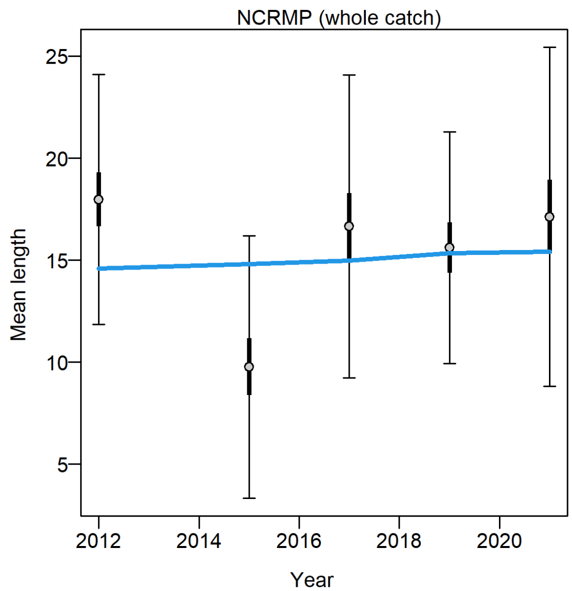
Figure 8.8: St. Croix Stoplight Parrotfish observed and predicted length distributions in centimeters (a) aggregated across years and (b) by year for the Commercial (TIP) and National Coral Reef Monitoring Survey (NCRMP) length compositions for the v1_m3 model scenarios. Green lines represent predicted length compositions, while gray regions represent observed length compositions. The effective sample sizes used to weight the length composition data are provided by N adj (the input sample size) and N eff (the calculated effective sample size) and are shown in the upper right corners.



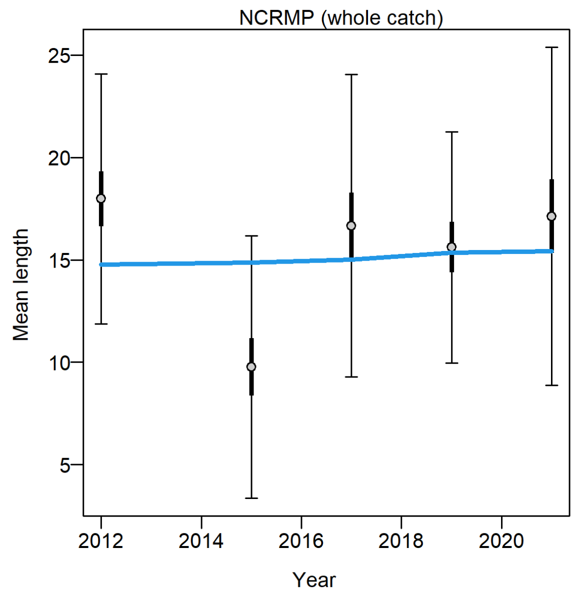
(a) v7_m3 across all years

(b) v7_m3 by year

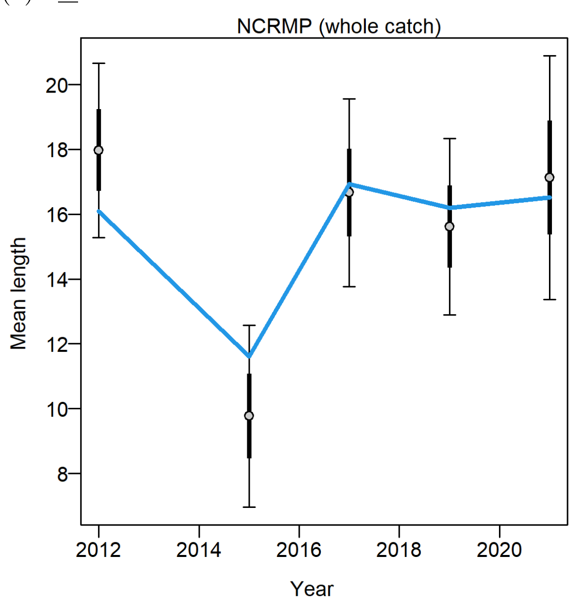
Figure 8.9: St. Croix Stoplight Parrotfish observed and predicted length distributions in centimeters (a) aggregated across years and (b) by year for the Commercial (TIP) and National Coral Reef Monitoring Survey (NCRMP) length compositions for the v7_m3 model scenarios. Green lines represent predicted length compositions, while gray regions represent observed length compositions. The effective sample sizes used to weight the length composition data are provided by N adj (the input sample size) and N eff (the calculated effective sample size) and are shown in the upper right corners.



(a) b_m3

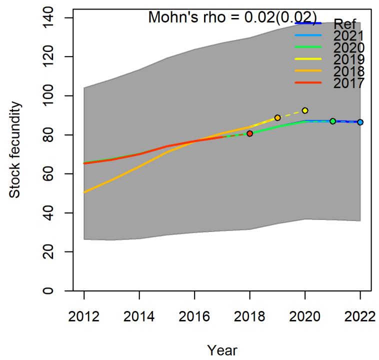


(b) v1_m3

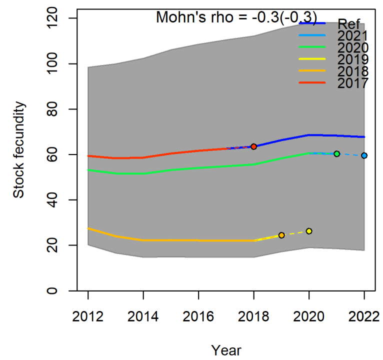


(c) v7_m3

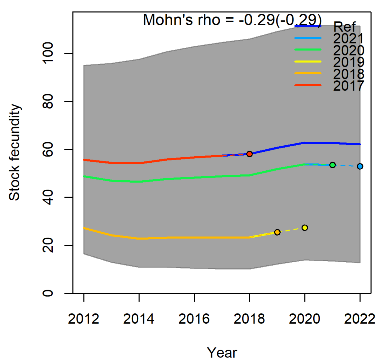
Figure 8.10: St. Croix Stoplight Parrotfish observed (open circles) and predicted (blue line) mean length in centimeters by year across model scenarios that include annual fishery-independent National Coral Reef Monitoring Survey (NCRMP) data without recruitment deviations (b_m3, v1_m3) and with recruitment deviations (v7_m3).



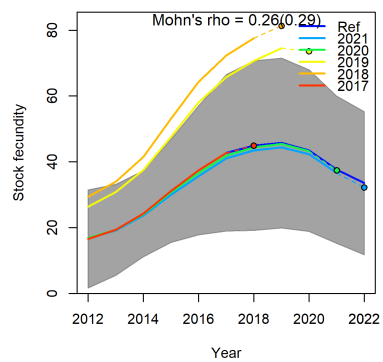
(a) a_m3



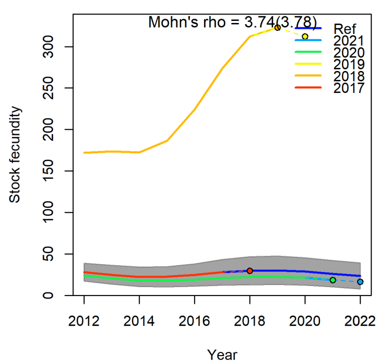
(b) b_m3



(c) v1_m3

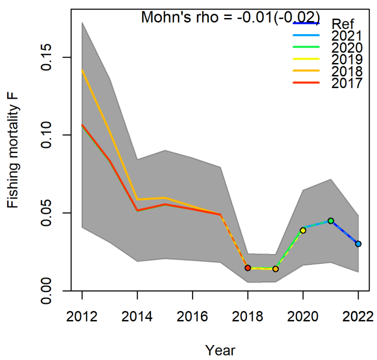


(d) v3_m3

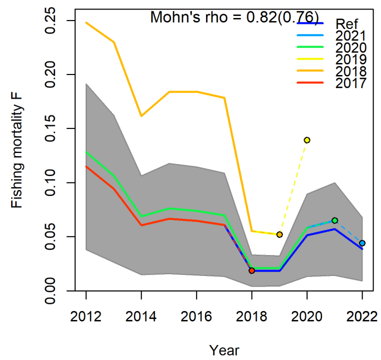


(e) v7_m3

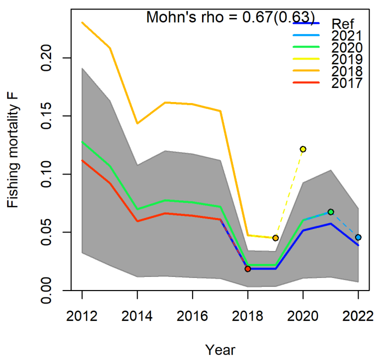
Figure 8.11: St. Croix Stoplight Parrotfish retrospective analysis of spawning stock biomass (SSB) conducted by refitting models after removing five years of observation, one year at a time sequentially. Mohn's rho statistics and the corresponding "hindcast rho" measure the severity of retrospective patterns. The reference models (Ref) include the full time series ending in 2022.One-year-ahead projections are denoted by color-coded dashed lines with terminal points. Grey shaded areas are the 95% confidence intervals.



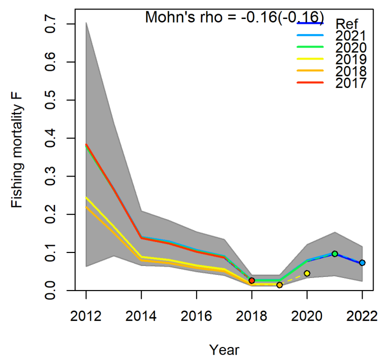
(a) a_m3



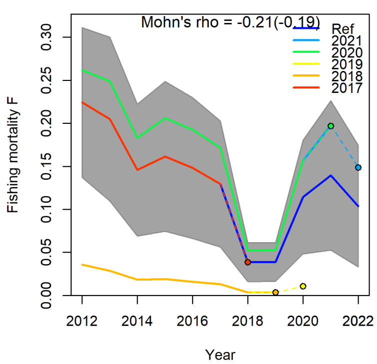
(b) b_m3



(c) v1_m3

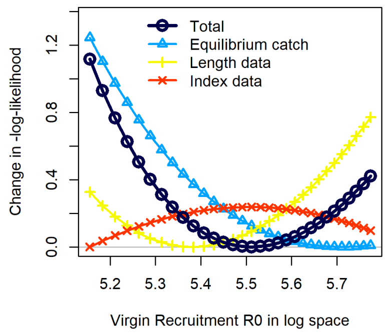


(d) v3_m3

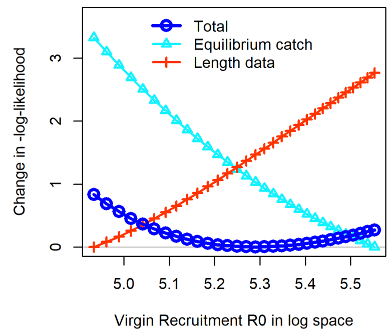


(e) v7_m3

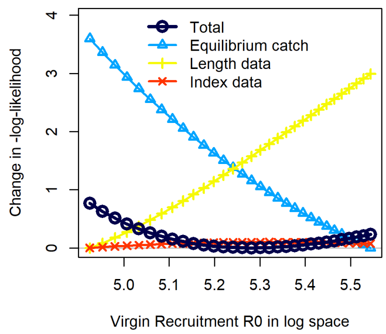
Figure 8.12: St. Croix Stoplight Parrotfish retrospective analysis of fishing mortality conducted by refitting models after removing five years of observation, one year at a time sequentially. Mohn's rho statistics and the corresponding "hindcast rho" measure the severity of retrospective patterns. The reference models (Ref) include the full time series ending in 2022. One-year-ahead projections are denoted by color-coded dashed lines with terminal points. Grey shaded areas are the 95% confidence intervals.



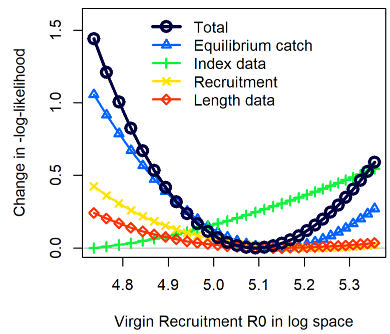
(a) a_m3



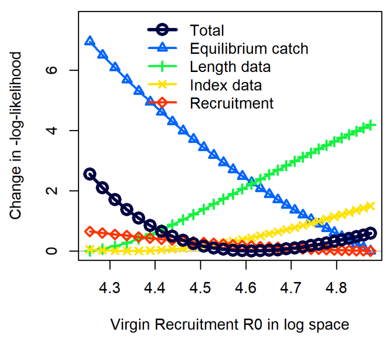
(b) b_m3



(c) v1_m3

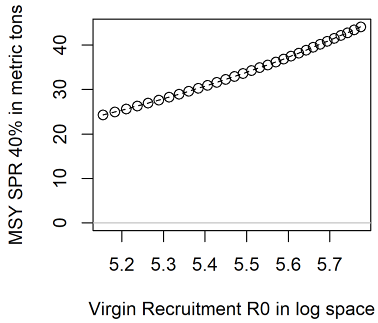


(d) v3_m3



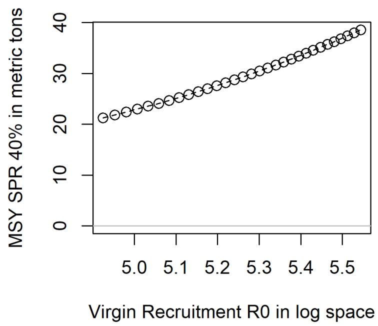
(e) v7_m3

Figure 8.13: The profile likelihood for the natural log of the unfished recruitment parameter of the Beverton – Holt stock-recruit function for St. Croix Stoplight Parrotfish across model scenarios (a_m3, b_m3, v1_m3, v3_m3, and v7_m3). Each line represents the change in negative log-likelihood value for each of the data sources fit in the model across the range of fixed unfished recruitment values tested in the profile diagnostic run.

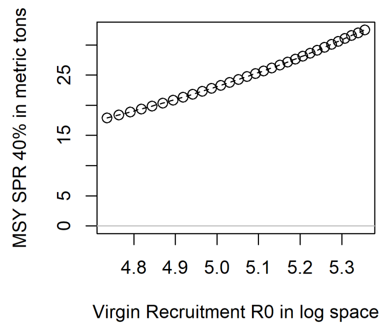


(a) a_m3

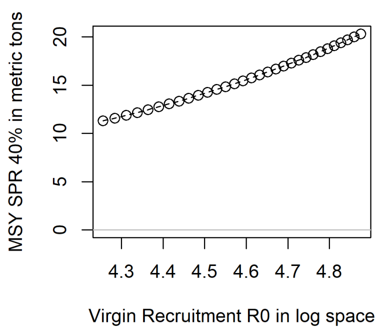
(b) b_m3



(c) v1_m3

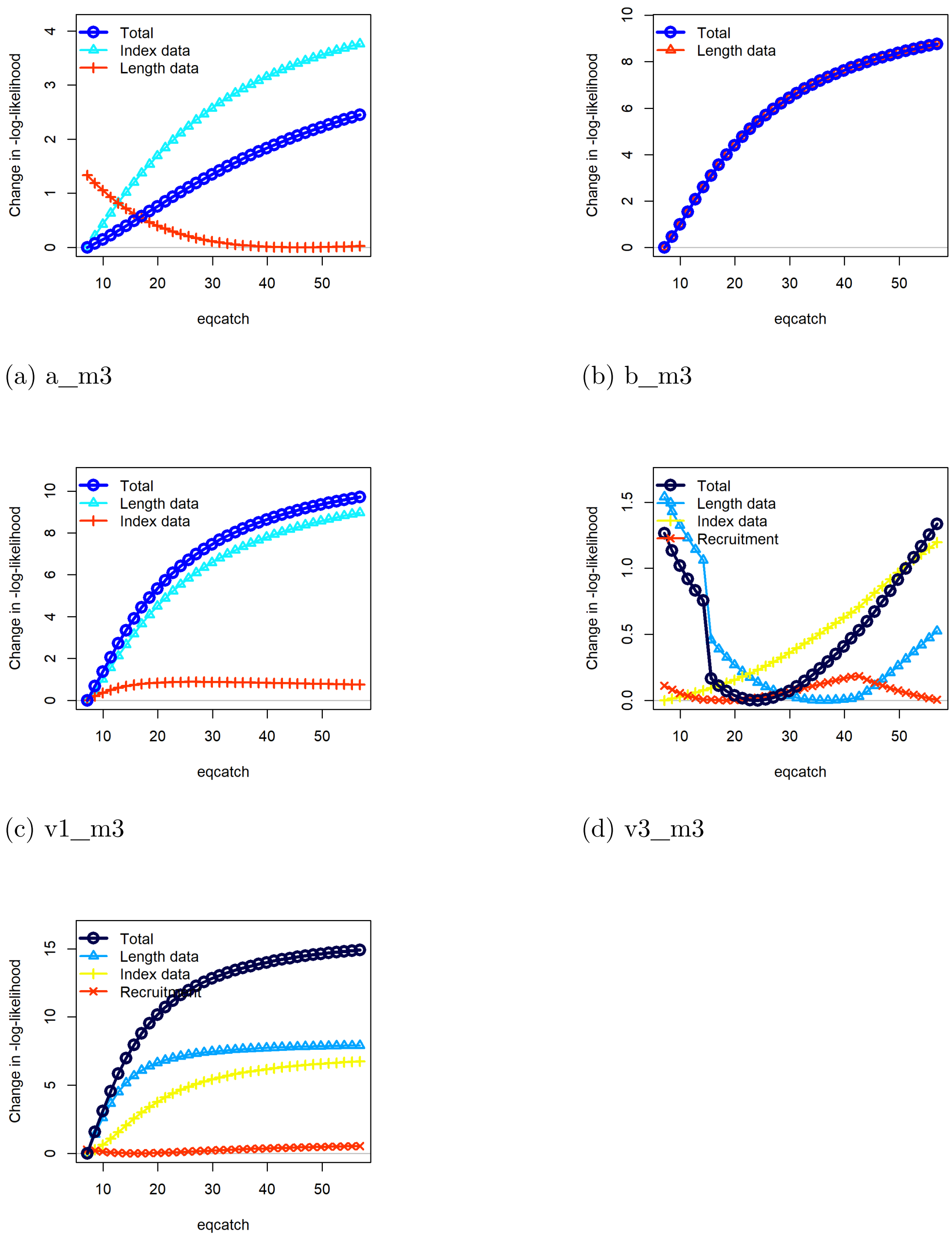


(d) v3_m3



(e) v7_m3

Figure 8.14: Estimates of the MSY proxy (based on SPR 40%) across the range of unfished recruitment values explored in the St. Croix Stoplight Parrotfish likelihood profile. These estimates, expressed in metric tons, are shown for model scenarios a_m3, b_m3, v1_m3, v3_m3, and v7_m3.



(a) a_m3

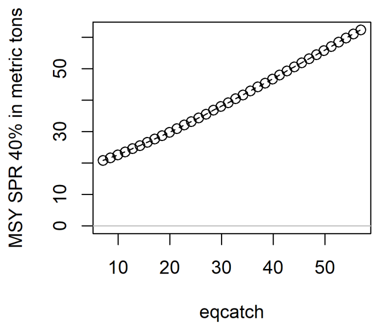
(b) b_m3

(c) v1_m3

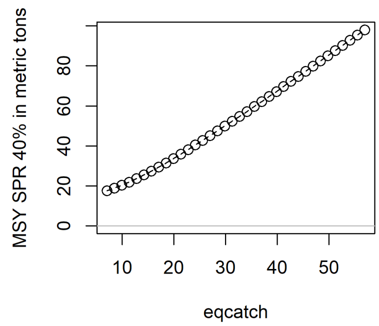
(d) v3_m3

(e) v7_m3

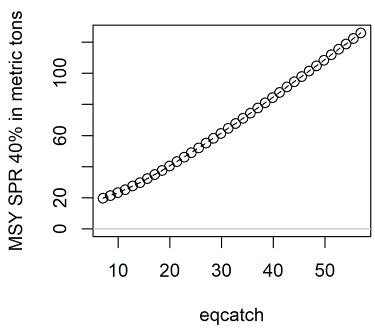
Figure 8.15: The profile likelihood for the fixed initial equilibrium catch for St. Croix Stoplight Parrotfish across model scenarios (a_m3, b_m3, v1_m3, v3_m3, and v7_m3). Each line represents the change in negative log-likelihood value for each of the data sources fit in the model across the range of fixed equilibrium catch values tested in the profile diagnostic run.



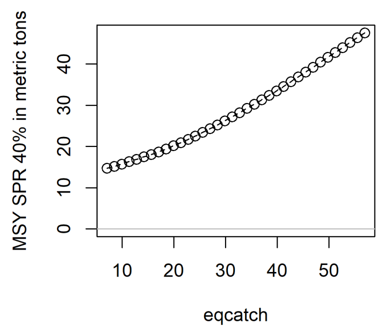
(a) a_m3



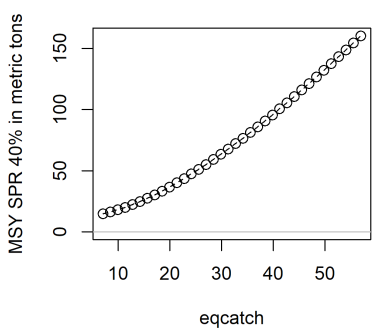
(b) b_m3



(c) v1_m3

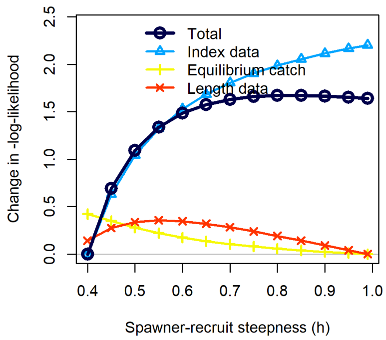


(d) v3_m3

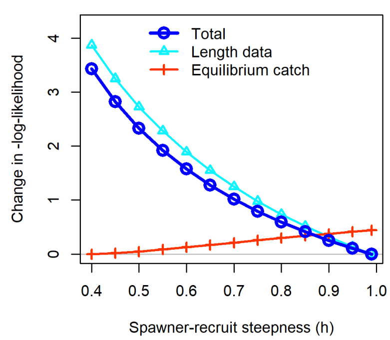


(e) v7_m3

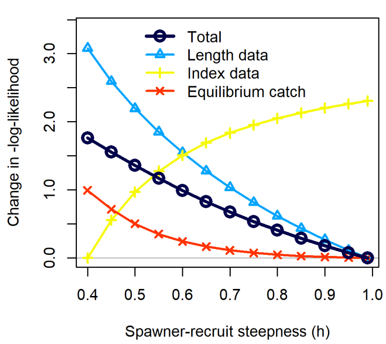
Figure 8.16: Estimates of the MSY proxy (based on SPR 40%) across the range of initial equilibrium catch values explored in the St. Croix Stoplight Parrotfish likelihood profile. These estimates, expressed in metric tons, are shown for model scenarios a_m3, b_m3, v1_m3, v3_m3, and v7_m3.



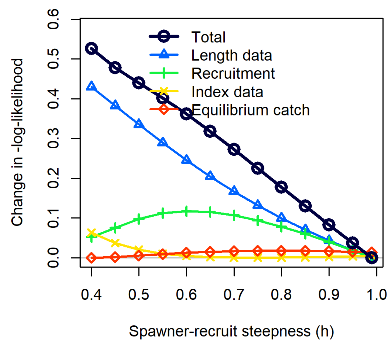
(a) a_m3



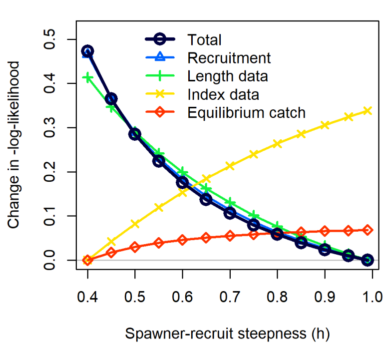
(b) b_m3



(c) v1_m3

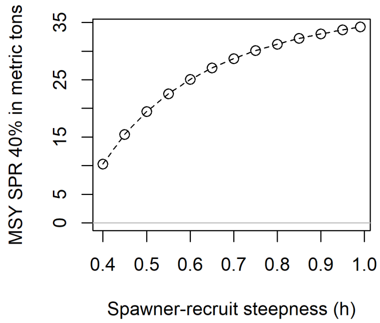


(d) v3_m3

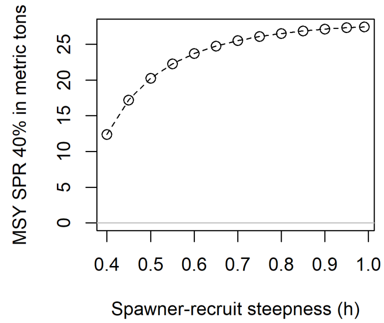


(e) v7_m3

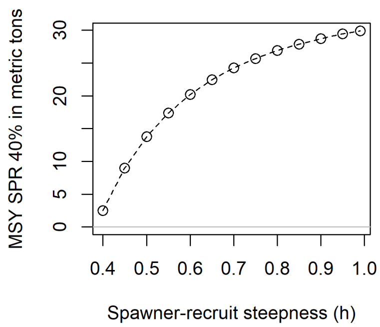
Figure 8.17: The profile likelihood for the steepness parameter of the Beverton – Holt stock-recruit function for St. Croix Stoplight Parrotfish across model scenarios (a_m3, b_m3, v1_m3, v3_m3, and v7_m3). Each line represents the change in negative log-likelihood value for each of the data sources fit in the model across the range of fixed steepness values tested in the profile diagnostic run.



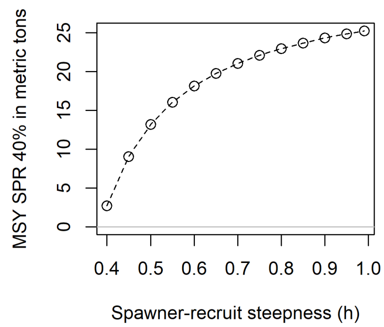
(a) a_m3



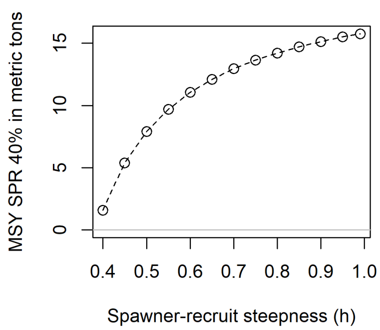
(b) b_m3



(c) v1_m3

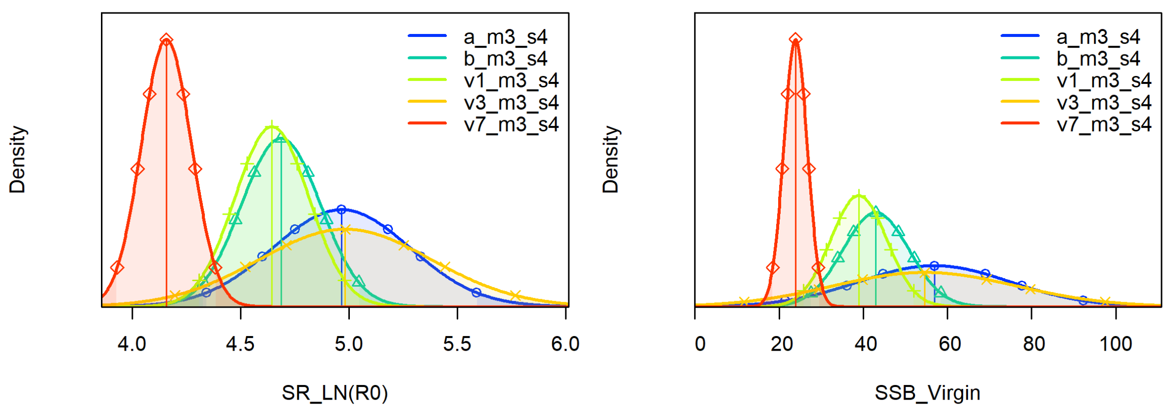


(d) v3_m3



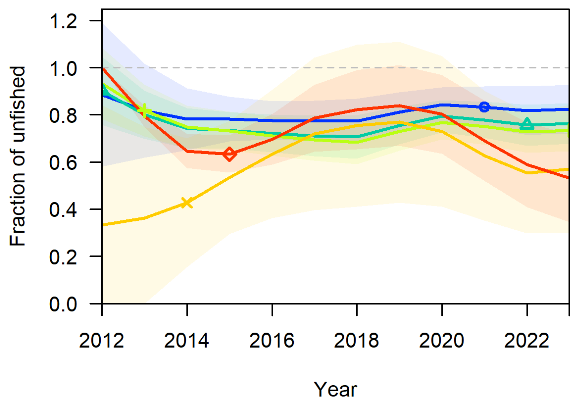
(e) v7_m3

Figure 8.18: Estimates of the MSY proxy (based on SPR 40%) across the range of steepness values explored in the St. Croix Stoplight Parrotfish likelihood profile. These estimates, expressed in metric tons, are shown for model scenarios a_m3, b_m3, v1_m3, v3_m3, and v7_m3.

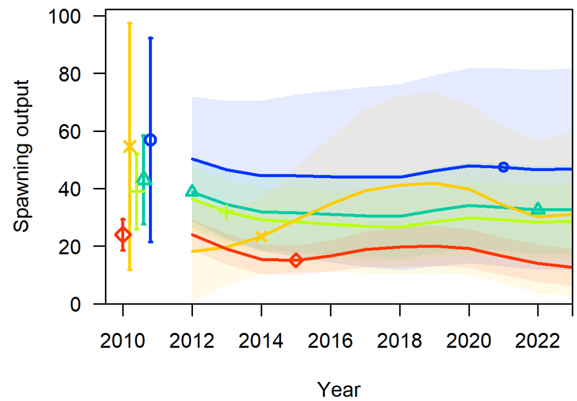


(a) Unfished recruitment (R0) (b) Virgin Spawning Stock Biomass

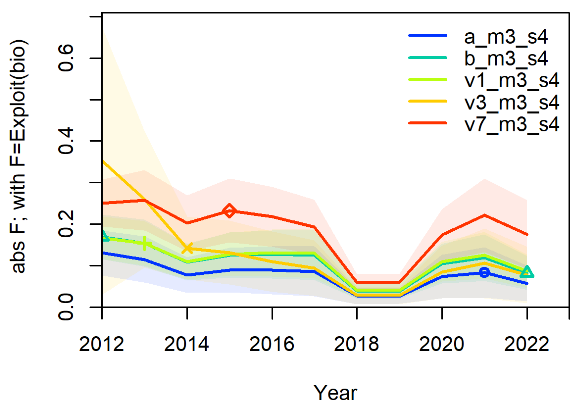
Figure 8.19: St. Croix Stoplight Parrotfish parameter distribution for (a) the natural log of the unfished recruitment parameter of the Beverton – Holt stock-recruit function and (b) virgin spawning stock biomass in metric tons across model scenarios (a_m3_s4, b_m3_s4, v1_m3_s4, v3_m3_s4, and v7_m3_s4).



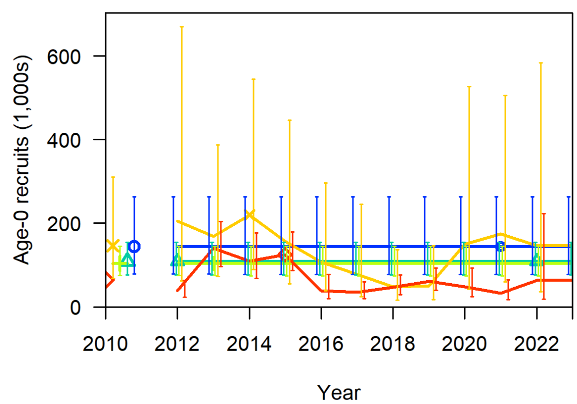
(a) Spawning Biomass Ratio



(b) Spawning Biomass

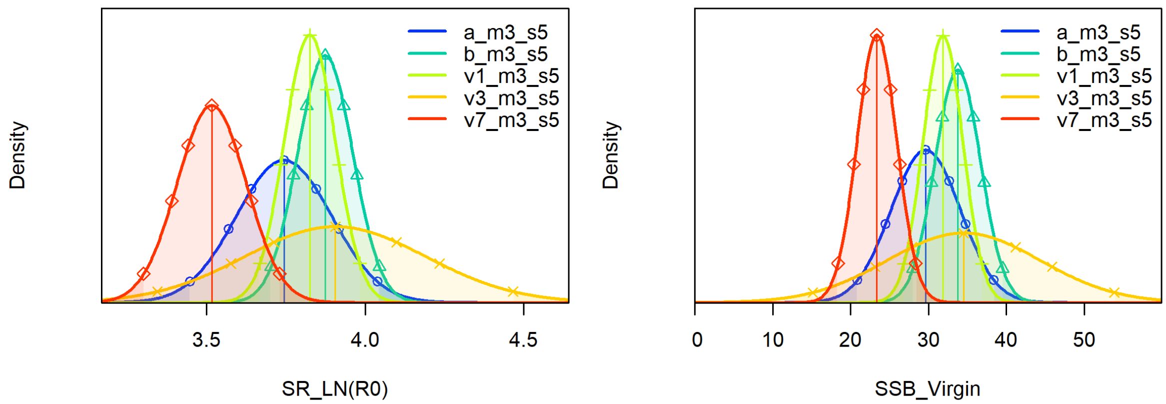


(c) Fishing Mortality



(d) Recruitment

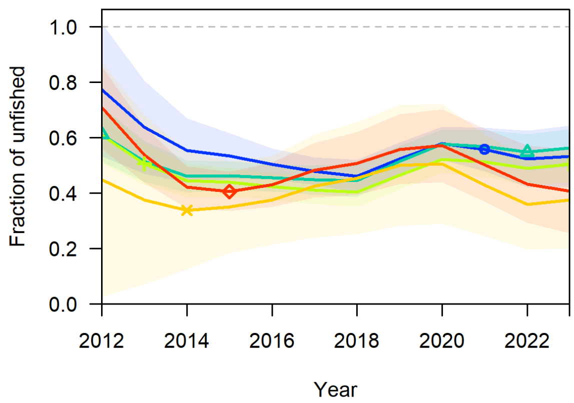
Figure 8.20: St. Croix Stoplight Parrotfish derived quantity time series across model scenarios (a_m3_s4, b_m3_s4, v1_m3_s4, v3_m3_s4, and v7_m3_s4). Derived quantities plotted over time for (a) the relative spawning stock biomass (total biomass / virgin spawning stock biomass), (b) spawning stock biomass in metric tons, (c) fishing mortality (total biomass killed / total biomass), (d) and recruitment in thousands of fish. The shaded areas and vertical bars in the derived quantities time series represent 95% confidence intervals. The values plotted prior to the model start year of 2012 reflect the unfished conditions and associated 95% confidence intervals.



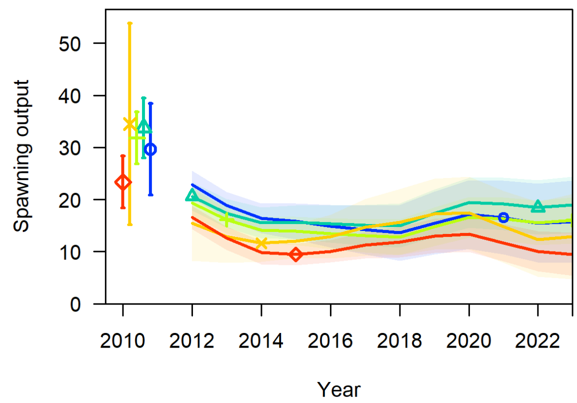
(a) Unfished recruitment (R0)

(b) Virgin Spawning Stock Biomass

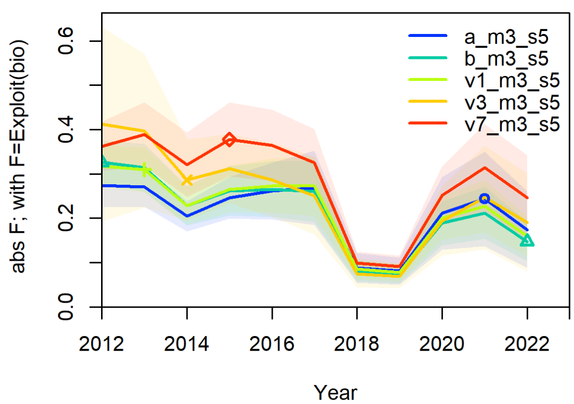
Figure 8.21: St. Croix Stoplight Parrotfish parameter distribution for (a) the natural log of the unfished recruitment parameter of the Beverton – Holt stock-recruit function and (b) virgin spawning stock biomass in metric tons across model scenarios (a_m3_s5, b_m3_s5, v1_m3_s5, v3_m3_s5, and v7_m3_s5).



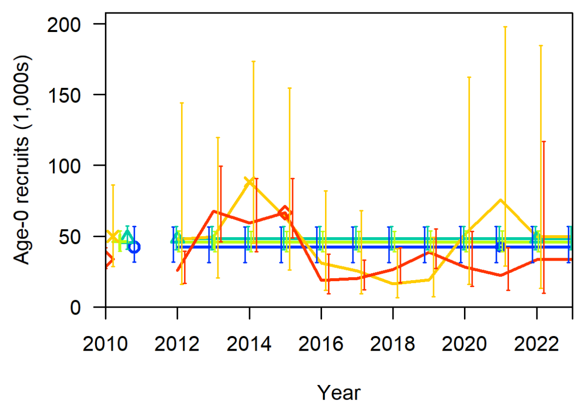
(a) Spawning Biomass Ratio



(b) Spawning Biomass



(c) Fishing Mortality



(d) Recruitment

Figure 8.22: St. Croix Stoplight Parrotfish derived quantity time series across model scenarios (a_m3_s5, b_m3_s5, v1_m3_s5, v3_m3_s5, and v7_m3_s5). Derived quantities plotted over time for (a) the relative spawning stock biomass (total biomass / virgin spawning stock biomass), (b) spawning stock biomass in metric tons, (c) fishing mortality (total biomass killed / total biomass), (d) and recruitment in thousands of fish. The shaded areas and vertical bars in the derived quantities time series represent 95% confidence intervals. The values plotted prior to the model start year of 2012 reflect the unfished conditions and associated 95% confidence intervals.

References

Carvalho, F., Winker, H., Courtney, D., Kapur, M., Kell, L., Cardinale, M., Schirripa, M., Kitakado, T., Yemane, D., Piner, K. R., Maunder, M. N., Taylor, I., Wetzel, C. R., Doering, K., Johnson, K. F., & Methot, R. D. (2021). A cookbook for using model diagnostics in integrated stock assessments. *Fisheries Research*, *240*, 105959. https://doi.org/10.1016/j.fishres.2021.105959

Choat, J. H., Robertson, D. R., Ackerman, J. L., & Posada, J. M. (2003). An age-based demographic analysis of the Caribbean stoplight parrotfish Sparisoma viride. *Marine Ecology Progress Series*, *246*, 265–277. https://doi.org/10.3354/meps246265

Cope, J. (2024). *Stock assessment continuum tool*. https://github.com/shcaba/SS-DL-tool

Cope, J., & Hamel, O. S. (2022). Upgrading from M version 0.2: An application-based method for practical estimation, evaluation and uncertainty characterization of natural mortality. *Fisheries Research*, *256*, 106493. https://doi.org/10.1016/j.fishres.2022.106493

Godwin, K., Rios, A., & Dettloff, K. (2024). *SEDAR 84 Trip Interview Program (TIP) Size Composition Analysis of Stoplight Parrotfish (Sparisoma viride) in St. Croix, U.S. Caribbean, 1983-2022* (SEDAR84-WP-11; p. 10). SEDAR. https://sedarweb.org/documents/sedar-84-dw-11-sedar-84-trip-interview-program-tip-size-composition-analysis-of-stoplight-parrotfish-sparisoma-viride-in-st-croix-u-s-caribbean-1983-2022/

Grove, L. J. W., Blondeau, J., & Ault, J. (2024). *Fishery-independent reef fish visual survey population density and length composition for stoplight parrotfish in the St. Croix*. 11. https://sedarweb.org/documents/sedar-84-dw-14-fishery-independent-reef-fish-visual-survey-population-density-and-length-composition-for-stoplight-parrotfish-in-the-st-croix/

Grove, L. J. W., Blondeau, J., & Ault, J. S. (2021). *National Coral Reef Monitoring Program's reef fish visual census metadata for the U.S. Caribbean.* 55. https://sedarweb.org/documents/sedar-80-wp-02-national-coral-reef-monitoring-programs-reef-fish-visual-census-metadata-for-the-u-s-caribbean/

Hamel, O. S. (2015). A method for calculating a meta-analytical prior for the natural mortality rate using multiple life history correlates. *ICES Journal of Marine Science*, *72*(1), 62–69. https://doi.org/10.1093/icesjms/fsu131

Hamel, O. S., & Cope, J. M. (2022). Development and considerations for application of a longevity-based prior for the natural mortality rate. *Fisheries Research*, *256*, 106477. https://doi.org/10.1016/j.fishres.2022.106477

Jensen, A. L. (1996). Beverton and holt life history invariants result from optimal trade-off of reproduction and survival. *Canadian Journal of Fisheries and Aquatic Sciences*, *53*(4), 820–822. https://doi.org/10.1139/f95-233

Jensen, A. L. (1997). Origin of relation between k and linf and synthesis of relations among life history parameters. *Canadian Journal of Fisheries and Aquatic Sciences*, *54*(5), 987–989. https://doi.org/10.1139/f97-007

Loera-Padilla, F., Piñeros, V., Baldwin, C., Simoes, N., Duarte-Ribeiro, E., Lasso-Alcalá, O., & Domínguez-Domínguez, O. (2021). Phylogeography, population connectivity and demographic history of the stoplight parrotfish, sparisoma viride (teleostei: Labridae), in the greater caribbean. *Coral Reefs*, *41*. https://doi.org/10.1007/s00338-020-02036-z

Martínez Rivera, S., Johnson, K., & Orhun, M. R. (2024). *SEDAR 84 Commercial fishery landings of Stoplight Parrotfish (Sparisoma viride) in St. Croix, U.S. Caribbean, 2012-2022*. 20. https://sedarweb.org/documents/sedar-84-dw-03-sedar-84-commercial-fishery-landings-of-stoplight-parrotfish-sparisoma-viride-in-st-croix-us-caribbean-2012-2022/

Methot, R. D., & Wetzel, C. R. (2013). Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. *Fisheries Research*, *142*, 86–99. https://doi.org/10.1016/j.fishres.2012.10.012

Methot, R. D., Wetzel, C. R., Taylor, I. G., & Doering, K. (2020). Stock synthesis user manual: Version 3.30.15. *Northwest Fisheries Science Center (U.S.)*. https://doi.org/10.25923/5WPN-QT71

Ono, K., Licandeo, R., Muradian, M. L., Cunningham, C. J., Anderson, S. C., Hurtado-Ferro, F., Johnson, K. F., McGilliard, C. R., Monnahan, C. C., Szuwalski, C. S., Valero, J. L., Vert-Pre, K. A., Whitten, A. R., & Punt, A. E. (2015). The importance of length and age composition data in statistical age-structured models for marine species. *ICES Journal of Marine Science*, *72*(1), 31–43. https://doi.org/10.1093/icesjms/fsu007

Rikhter, V. A., & Efanov, V. N. (1976). 12. https://www.nafo.int/icnaf/library/docs/1976/res-08.pdf

Rivera Hernández, J. M., & Shervette, V. (2024). *Report on the status of U.S. Caribbean stoplight parrotfish Sparisoma viride age, growth, and reproductive biology for the SEDAR 84 Stock Assessment*. 22. https://sedarweb.org/documents/sedar-84-ap-01-report-on-the-status-of-u-s-caribbean-stoplight-parrotfish-sparisoma-viride-age-growth-and-reproductive-biology-for-the-sedar84-stock-assessment

Rooij, J. M. van, & Videler, J. J. (1997). Mortality estimates from repeated visual censuses of a parrotfish (sparisoma viride) population: Demographic implications. *Marine Biology*, *128*(3), 385–396. https://doi.org/10.1007/s002270050104

Schemmel, E., Bohaboy, E. C., Kinney, M. J., & O'Malley, J. M. (2022). An assessment of sampling approaches for estimating growth from fishery-dependent biological samples. *ICES Journal of Marine Science*, *79*(5), 1497–1514. https://doi.org/10.1093/icesjms/fsac075

SEDAR. (2019). *SEDAR 57 Stock Assessment Report U.S. Caribbean Spiny Lobster*. 232. http://sedarweb.org/sedar-57

SEDAR. (2022). *SEDAR 80 U.S. Caribbean queen triggerfish Puerto Rico final stock assessment report*. https://sedarweb.org/documents/sedar-80-us-caribbean-queen-triggerfish-puerto-rico-final-stock-assessment-report/

SEDAR. (2024). *SEDAR 84 U.S. Caribbean stoplight parrotfish St. Croix data workshop report*. https://sedarweb.org/documents/sedar-84-us-caribbean-stoplight-parrotfish-st-croix-data-workshop-report/

Shertzer, K. W., Damiano, M. D., & Williams, E. H. (2024). Spawning Potential Ratio Can Provide Reference Points for Fishery Management That Are Robust to Environmental Variability. *Fishes*. https://doi.org/https://doi.org/10.3390/fishes9120497

Taylor, I. G., Doering, K. L., Johnson, K. F., Wetzel, C. R., & Stewart, I. J. (2021). Beyond visualizing catch-at-age models: Lessons learned from the r4ss package about software to support stock assessments. *Fisheries Research*, *239*, 105924. https://doi.org/10.1016/j.fishres.2021.105924

Then, A. Y., Hoenig, J. M., Hall, N. G., Hewitt, D. A., & Handling editor: Ernesto Jardim. (2015). Evaluating the predictive performance of empirical estimators of natural mortality rate using information on over 200 fish species. *ICES Journal of Marine Science*, *72*(1), 82–92. https://doi.org/10.1093/icesjms/fsu136

Thorson, J. T., Munch, S. B., Cope, J. M., & Gao, J. (2017). Predicting life history parameters for all fishes worldwide. *Ecological Applications*, *27*(8), 2262–2276. https://doi.org/10.1002/eap.1606