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ARTICLE

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Abstract
Data-limited approaches to managing fisheries are widespread in regions where insufficient data prevent traditional stock assessments from determining stock status with sufficient certainty to be useful for management. Where severe data limitations persist, a catch-only approach is commonly employed, such as in the U.S. Caribbean region. This approach, however, has not received the level of scrutiny required to determine the potential long-term risks (e.g., probability of overfishing) to fish stocks. In this study, we present a framework for comparison and implementation of data-limited methods, including the static Status Quo approach, which uses average catch landings. Candidate species for stock evaluation were identified through a data triage and included Yellowtail Snapper *Ocyurus chrysurus* (Puerto Rico), Queen Triggerfish *Balistes vetula* (St. Thomas and St. John), and Stoplight Parrotfish *Sparisoma viride* (St. Croix). Feasible data-limited methods, based on data availability and quality, included empirical indicator approaches using relative abundance (i.e., catch per unit effort) or mean length. Results from the management strategy evaluation support the use of adaptive data-limited methods, which incorporate feedback in contrast to the static Status Quo approach. The proposed framework can help guide the development of catch advice for dynamic fisheries management in data-limited regions.

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Nearly a decade ago, the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA), National Standard 1 (NS1) Guidelines required “conservation and management measures to prevent overfishing while achieving, on a continuing basis, the optimum yield from each fishery for the U.S. fishing industry (Section 301 a.1)” (NMFS 2009). By 2010, the determination of annual catch limits for all stocks in a fishery was mandatory, irrespective of the quantity or quality of information available for stock assessment. Many stocks in specific regions of the USA (e.g., Northeast, Alaska, and Northwest) are assessed using data-rich assessment methods, such as surplus production models (e.g., Atlantic Halibut *Hippoglossus hippoglossus*; NEFSC 2015), virtual population analysis (e.g., groundfish; NEFSC 2017), or statistical catch-at-age models (see Methot and Wetzel 2013 for a review). These models are feasible (i.e., can be applied) in these regions because of long-term and consistent collection of catch, abundance, size composition, and biological information (Newman et al. 2015). Contrasting the data-rich regions, the majority of stocks in the U.S. regions encompassing the Southeast, Caribbean, and Western Pacific are considered data-poor (Newman et al. 2015). Data-poor stocks have insufficient data to conduct a traditional assessment that yields meaningful and credible information on stock status and optimal yield.

The absence of sufficient information to conduct traditional stock assessments has led managers to implement catch-only procedures that use average catch during a selected time series (“Only Reliable Catch Series”; Berkson et al. 2011; Berkson and Thorson 2015). Although the adoption of catch-only approaches for setting annual catch limits has become widespread throughout the USA (Berkson and Thorson 2015), these approaches have not received the level of scrutiny required to fully evaluate the long-term sustainability of fish stocks. Importantly, the evaluation of potential management strategies should precede their implementation because some approaches may not be robust to a wide range of uncertainties (e.g., natural mortality, steepness, etc.). Catch-only approaches limiting catch landings to either the mean catch or the third highest catch, as determined over some select period, have performed poorly in simulation by exhibiting greater probabilities of overfishing and lower long-term yields across a wide range of stock types (Carruthers et al. 2014, 2015). A key limitation of these approaches is the lack of feedback between stock abundance and prescribed catch advice (i.e., total allowable catch; Geromont and Butterworth 2014, 2016). Ultimately, implementing these approaches may not lead to sustainable yields (ICES 2012; Carruthers et al. 2014; Geromont and Butterworth 2014).

The U.S. Caribbean is the only region in the USA where 100% of managed stocks are considered data-poor (Newman et al. 2015). Notable data limitations include the lack of fishery-independent surveys tracking population trends (Cass-Calay et al. 2016); inconsistent compliance by commercial fishermen and lack of enforcement (Bennett 2015); frequent modifications to and inconsistencies in fishery reporting forms, particularly in the U.S. Virgin Islands (St. Thomas, St. John, and St. Croix; CFMC 2014; SEDAR 2016a); preferential selection of “plate-sized” fish to accommodate market demands (i.e., dome-shaped fishery selectivity; Cass-Calay et al. 2016; SEDAR 2016a); recent reductions in biological sampling (Bryan 2015); and the lack of well-informed life history parameter characterizations for the region (SEDAR 2014, 2016a). Such pervasive data inadequacies have hindered the use of traditional stock assessment approaches, such as surplus production models, to inform stock status and optimize yield (e.g., SEDAR 2007a). Consequently, results from all U.S. Caribbean stock assessments to date have not been deemed useful for management purposes.

The Caribbean Fishery Management Council (CFMC) manages 179 fish stocks under four Fishery Management Plans (CFMC 2014). Subregional annual catch limits are required for two islands (Puerto Rico and St. Croix) and one island group (St. Thomas and St. John), all located in close geographical proximity (SEDAR 2016a). The U.S. Caribbean fisheries in each location are highly diverse in terms of gears, habitats, landings sites, markets, and community dependences, with artisanal commercial fisheries often competing with recreational fisheries for similar yields (Appeldoorn 2008). Overexploitation of fisheries resources has been suggested by declines in catch per unit effort (CPUE), reductions in mean size, and absences of large predatory fishes in Puerto Rico (Appeldoorn et al. 1992; Posada and Appeldoorn 1999; Causey et al. 2002) and in St. Thomas–St. John and St. Croix (Garrison et al. 1998; Rogers and Beets 2001; Beets and Rogers 2002).

The Data-Limited Methods Toolkit (DLMtool; Newman et al. 2014; Carruthers et al. 2015; Carruthers and Hordyk 2016) enables management strategy evaluation to assess the utility of management procedures (e.g., harvest strategies) for setting catch advice within R (R Development Core Team 2016). Within the context of the DLMtool, the term management procedures refers to a wide range of procedures such as stock assessments, data-limited methods (DLMs), and harvest control rules (Carruthers and Hordyk 2016; Hordyk et al. 2017). Key strengths of the DLMtool include the ability to simultaneously evaluate the performance of multiple DLMs in a simulation environment and the added flexibility to incorporate new methods, thus tailoring evaluations to geographical specificities (Hordyk et al. 2017). In this study, we present a framework for data-limited stock evaluation that moves beyond catch-only data streams with the ultimate goal of providing management advice for U.S.

Caribbean stocks. The specific objectives of the study were to (1) summarize available data for U.S. Caribbean stocks, including catch history, relative abundance, size composition, and life history, and provide baseline guidance on quality; (2) determine feasible DLMs, where feasibility was based on data availability and quality; (3) evaluate management strategies by selecting DLMs that meet the performance criteria specified by MSFCMA; (4) compare the performance of adaptive DLMs that incorporate additional data streams (e.g., relative abundance) not utilized in the catch-only Status Quo approach and test the utility of these data; and (5) provide guidance on method selection and development of catch advice for management implementation. The presented framework is intended to enable a dynamic approach to fisheries management that could streamline the development of management advice for fishery resources, particularly in the U.S. Caribbean region.

METHODS

Candidate species and data sources.— Candidate species for stock evaluation were identified from a review of primary fisheries data sets available for U.S. Caribbean marine resources in federal waters: self-reported commercial fisher logbooks; the Marine Recreational Intercept Program recreational landings, discards, and interview data (Puerto Rico only); and the National Oceanic and Atmospheric Administration Southeast Fisheries Science Center Trip Interview Program. Commercial and recreational landings were summarized by species in terms of the number of years available and the average landings per year. Length-frequency data obtained from the Trip Interview Program were summarized by the number of years available, the average number of length observations per year, and the total number of length observations. Thirty-six stocks were identified as potential candidates for evaluation given the available data, with a “stock” in the U.S. Caribbean referring to a species occurring around a single island (Puerto Rico or St. Croix) or an island group (St. Thomas and St. John) (Table 1). We focused on a single stock for each island or island group based on the species’ regional importance and the sufficiency of available data: Puerto Rico Yellowtail Snapper *Ocyurus chrysurus*, St. Thomas–St. John Queen Triggerfish *Balistes vetula*, and St. Croix Stoplight Parrotfish *Sparisoma viride*. Available data for evaluation included a time series of total removals (i.e., catch), an index of relative abundance, a measure of the mean length of the landings, and life history characteristics (e.g., maturity) (Table 2).

Data-limited methods.— Feasible DLMs, which could be applied, were identified based on data availability and quality (e.g., length of time series), required parameter inputs, and assumptions inherent to each DLM (see Table A.1.1 in Appendix 1). Candidate DLMs consisted of four categories of commonly used data-limited approaches: (1) catch only; (2) empirical index-based; (3) empirical length-based, and (4) empirical multi-indicator-based (Table 3). A static catch-only approach (i.e., the Status Quo approach) was considered for each species, where catch advice is based on mean landings during a reference period (Table 4; Figure 1). The years specified in each reference period were defined by the CFMC Scientific and Statistical Committee and were intended to reflect a period of stable catches (i.e., no trend in landings) when the fishery was no longer developing (CFMC 2011a, 2011b). Inclusion of the catch-only Status Quo approach thus allowed the comparison of performance for a set of candidate empirical DLMs to the approach currently used by the CFMC (Table A.1.1).

The DLMs included in the evaluation (detailed in Table 3 and Table A.1.1) were considered to be improvements over a catch-only approach because these adaptive approaches incorporate feedback by explicitly using trends in relative abundance or mean length to adjust the catch advice (Figure 1). This is in stark contrast to the catch-only Status Quo approach (Figure 1), where catch advice (solid line) will remain fixed at the mean landings during the specified reference period (dashed line), regardless of how the stock responds to fishing pressure. Importantly, DLMs that rely on CPUE assume proportionality between CPUE and abundance, whereas length-based DLMs assume mean length is an indirect indicator of stock abundance (See Table A.1.1 for all assumptions). For CPUE Slope, a positive slope in recent CPUE will increase the catch advice beyond the Status Quo approach and a negative slope will reduce the catch advice (Figure 1). For target-based DLMs (CPUE Target, Length Target, and Length at Maturity Target) and Stepwise Constant Catch with Mean Length, recent trends in CPUE or mean length exceeding the target or reference level will increase the catch advice beyond the Status Quo approach and trends less than the target level will reduce the catch advice (Figure 1). For the Multi-indicator approach, catch advice will increase or decrease as a function of consistency and trend across data sources (Figure 1).

Method comparison using management strategy evaluation.— Evaluating the ability of DLMs to achieve management targets was the primary objective in this study. Methods were assessed across a suite of performance metrics using management strategy evaluation. Briefly, management strategy evaluation consists of capturing system dynamics assumed to represent the “simulated reality” (i.e., truth) and “observed” system dynamics via simulation of (1) biological sampling, (2) scientific analysis (e.g., stock assessment), and (3) harvest control rule or management implementation (Sainsbury et al. 2000; Kell et al. 2007). The simulated reality is then

TABLE 1. Summary of available data for the 36 stocks identified as potential candidates for data-limited stock evaluation. Selected stocks are highlighted in bold italics. Species are ranked by average annual commercial landings for each island or island group. Empty cells indicate that no data were available.

	Commercial landings		Recreational landings		Trip Interview Program length frequency				
Species	Number of years	Mean pounds	Number of years	Mean pounds	Number of years	Mean trips	Total number of trips	Mean number of lengths	Total lengths
Puerto Rico									
Caribbean spiny lobster *Panulirus argus*	32	359,940			32	158	5,058	1,341	42,920
Silk Snapper *Lutjanus vivanus*	32	341,251	15	75,196	31	51	1,567	896	27,782
Queen conch *Lobatus gigas*	32	328,407							
***Yellowtail Snapper* Ocyurus chrysurus**	***32***	***287,164***	***15***	***21,285***	***31***	***144***	***4,478***	***3,039***	***94,218***
Lane Snapper *Lutjanus synagris*	32	212,214	15	22,707	31	110	3,416	1,368	42,402
White Grunt *Haemulon plumierii*	32	197,815	15	2,821	31	133	4,135	1,642	50,894
King Mackerel *Scomberomorus cavalla*	32	145,351	15	93,939	30	38	1,149	300	8,997
Dolphinfish *Coryphaena hippurus*	32	139,961	15	1,078,815	28	16	448	128	3,571
Queen Snapper *Etelis oculatus*	28	121,935	15	23,097	30	17	522	220	6,602
Mutton Snapper *Lutjanus analis*	32	75,974	15	30,723	31	69	2,131	251	7,780
Queen Triggerfish *Balistes vetula*	32	71,428	15	10,258	31	62	1,921	288	8,924
Hogfish *Lachnolaimus maximus*	32	68,132	15	5,338	31	58	1,801	184	5,695
Red Hind *Epinephelus guttatus*	29	62,585	15	30,053	31	120	3,733	802	24,864
Cero *Scomberomorus regalis*	28	50,913	15	29,468	31	24	743	168	5,223
Blackfin Tuna *Thunnus atlanticus*	28	25,134	15	3,207	28	15	411	94	2,639
Vermilion Snapper *Rhomboplites aurorubens*	28	17,108	15	8,465	31	32	996	420	13,008
Coney *Cephalopholis fulva*	28	11,638	15	12,533	31	83	2,577	579	17,958
Wahoo *Acanthocybium solandri*	28	6,289	15	139,627	24	6	151	28	675
Great Barracuda *Sphyraena barracuda*	7	683	15	80,969	11	2	25	3	34
Atlantic Tripletail *Lobotes surinamensis*	6	317	15	30,301	12	2	25	22	263
Stoplight Parrotfish *Sparisoma viride*	5	144	15	9,053	28	53	1,475	601	16,828
Crevalle Jack *Caranx hippos*			15	39,127	18	3	56	13	242
St. Thomas and St. John									
Caribbean spiny lobster	15	107,534			24	21	509	467	11,205
Queen Triggerfish	***4***	***44,235***			***23***	***31***	***721***	***365***	***8,394***
Red Hind	4	33,494			23	31	712	309	7,104
Yellowtail Snapper	4	29,263			23	30	679	490	11,277
White Grunt	4	11,152			22	20	449	168	3,700
Blue Tang *Acanthurus coeruleus*	3	965			22	19	414	139	3,054
St. Croix									
Caribbean spiny lobster	16	110,978			31	47	1,468	598	18,531
Queen conch	16	96,498							
Dolphinfish	16	55,381			17	12	206	55	930
Stoplight Parrotfish	***4***	***32,464***			***27***	***33***	***899***	***1,009***	***27,231***
Queen Parrotfish *Scarus vetula*	4	14,894			25	8	200	32	807

TABLE 1. Continued.

Species	Commercial landings		Recreational landings		Trip Interview Program length frequency				
	Number of years	Mean pounds	Number of years	Mean pounds	Number of years	Mean trips	Total number of trips	Mean number of lengths	Total lengths
Queen Triggerfish	4	14,858			28	34	965	314	8,790
Redtail Parrotfish *Sparisoma chrysopterum*	4	12,488			27	37	999	1,365	36,845
White Grunt	4	7,297			29	35	1,006	751	21,788

TABLE 2. Summary of data recommended for assessment of select U.S. Caribbean fisheries stocks. Maturity references are provided in Tables A.1.3–A.1.5.

Available data	Fisheries stock		
	Yellowtail Snapper	Queen Triggerfish	Stoplight Parrotfish
Island or island group	Puerto Rico	St. Thomas–St. John	St. Croix
Start year	1983	1998	1996
End year	2014	2014	2014
Fishery			
Predominant fleet	Commercial handline	Commercial trap	Commercial diving
Length composition (range of sample sizes, i.e., number of length observations)	70−9,058	2−1,521	1−798
Abundance			
Index of relative abundance (units)	Commercial handline (pounds per hour fished)	Commercial trap (pounds per trap fished)	Commercial diving (pounds per dive)
Life history			
Length at 50% maturity (fork length)	248 mm	215 mm	205 mm
Length at 95% maturity (fork length)	315 mm	275 mm	235 mm

projected forward in time and updated according to the harvest control rule (i.e., setting of the catch advice) generated by a particular management strategy (Carruthers et al. 2014).

Operating model.— In management strategy evaluation, the operating model represents the biological components of the system to be managed and the fisher behavior in response to management actions (Carruthers et al. 2014; Punt et al. 2014). For each stock considered, an operating model was developed using the best available information to reflect the stock dynamics (e.g., growth, etc.) and fleet dynamics (e.g., effort, selectivity, etc.). Stock and fleet dynamics for the three U.S. Caribbean stocks are summarized in Table 5, with data inputs and justifications provided in Tables A.1.2–A.1.5. The operating models were populated using inputs assimilated from fishery biologists, stock assessment scientists, academic researchers, commercial and recreational fishers, and other stakeholders from each island or island group as part of the Southeast Data Assessment and Review (SEDAR) 46: U.S. Caribbean Data-Limited Species Data and Assessment Workshop (SEDAR 2016a). Within the DLMtool, the operating model is defined as an age-structured, spatial model and has been detailed thoroughly in Carruthers et al. (2014, 2015), SEDAR (2016b), and Harford and Carruthers (2017).

Simulated stock dynamics.— Between-simulation variability in many of the biological parameters (e.g., natural mortality) was accounted for by allowing the parameters to change over a specified range (Table 5). For each simulation, values for each stock and fleet parameter were randomly drawn from a uniform distribution between an upper and lower bound. Correlations between growth parameters were accounted for in the operating model and were based on a review of available literature, which borrowed largely from temperate species due to a paucity of

TABLE 3. Summary of candidate data-limited methods and data input requirements (shaded). Data inputs include lengths at 50% and 95% maturity (L50 and L95, respectively) and total removals in pounds whole weight (Catch). Method assumptions, equations, and references are provided in Table A.1.1. Reference refers to the specified reference period for each species used to reflect stable catches.

				Reference			Recent		
Method	Description	L50	L95	Catch	Mean length	Index	Catch	Mean length	Index
	Catch-only method								
Status Quo	Catch advice set using mean catch during reference period (Table 4); assume removals equal annual catch limit each year			■					
	Index-based methods								
CPUE Slope	Mean catch and trend in slope based on last 5 (2010–2014) or 10 (2005–2014) years; method adjusts the catch advice based on the slope of CPUE						■		■
CPUE Target	Mean catch and target CPUE based on reference years; method adjusts the catch advice to maintain a target index level			■		■			■
	Length-based methods								
Stepwise Constant Catch with Mean Length	Mean catch and target length based on reference years; method adjusts the catch advice by a fixed amount based on the ratio of recent mean length to reference			■	■			■	
Length Target	Mean catch and target length based on reference years; method adjusts the catch advice to maintain a target length level			■	■			■	
Length at Maturity Target	Mean catch based on reference years, target based on length at 95% maturity rather than an arbitrary multiplicative of mean length; method adjusts the catch advice to maintain a target length level	■	■	■				■	
	Multi-indicator-based method								
Multi-indicator	Indicator reference conditions based on reference years, trends in catch, mean length in catch, and CPUE based on terminal year of data collection; method adjusts catch advice based on trends in recent data compared with reference data			■	■	■	■	■	■

TABLE 4. Reference periods specified for each stock by the Caribbean Fishery Management Council (CFMC 2011a, 2011b). Abbreviations are as follows: OFL = overfishing limit and ABC = acceptable biological catch.

Island or island group	Species	Reference years	OFL	ABC	Annual catch limit
Puerto Rico	Yellowtail Snapper	1999–2005	Mean landings	OFL	ABC × 0.85
St. Thomas and St. John	Queen Triggerfish	2000–2008	Mean landings	OFL	ABC × 0.90
St. Croix	Parrotfish (Scaridae) complex (includes Stoplight Parrotfish)	1999–2005	Mean landings	300,000 pounds	ABC × 0.85 (plus 5.8822% reduction)

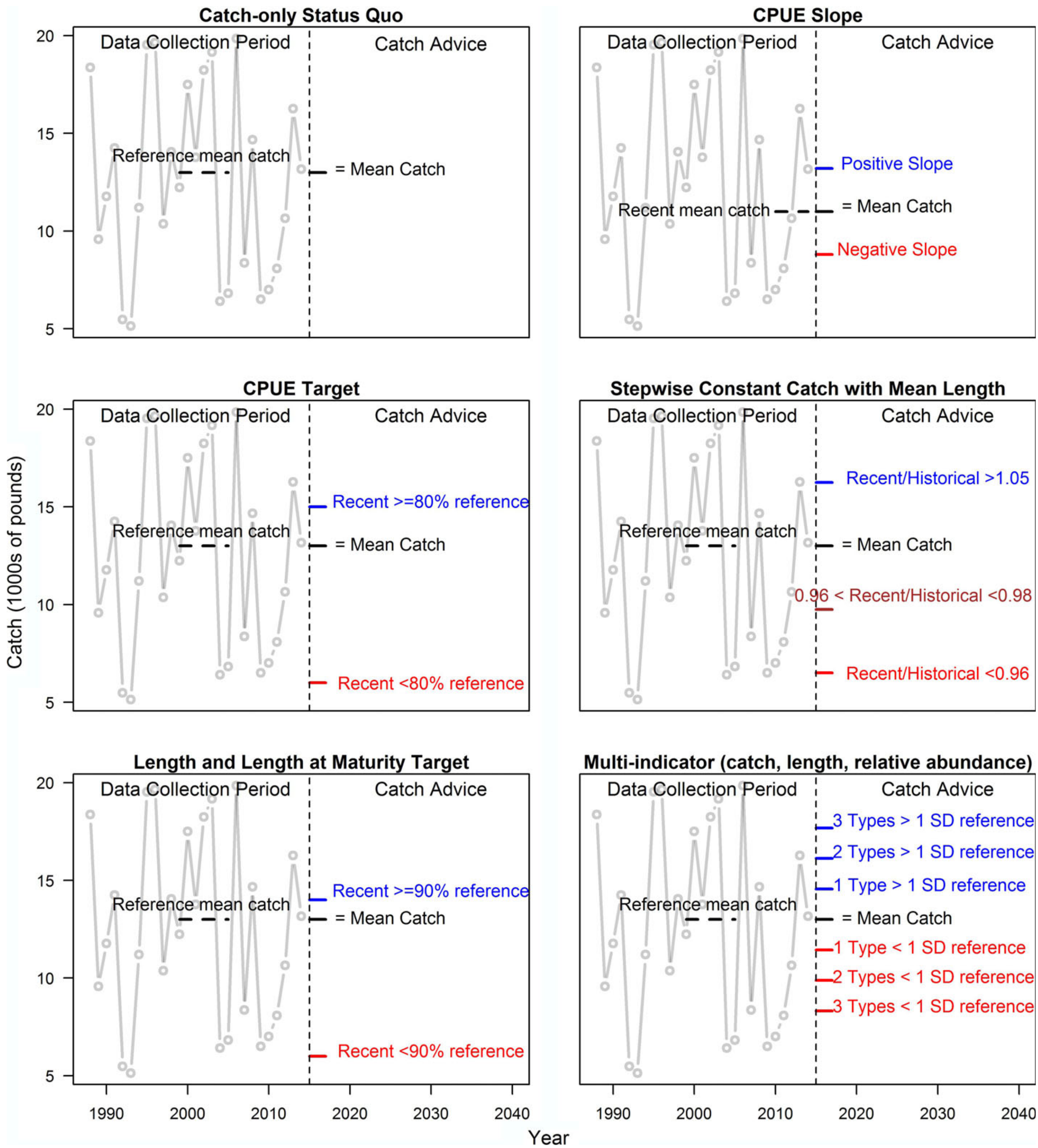

FIGURE 1. Demonstration of catch advice derived from each data-limited method considered. Gray lines and dots represent a hypothetical time series of catches, dashed horizontal lines reflect mean catch, and solid horizontal lines reflect derived catch advice (under various scenarios, where applicable; blue and red text identify derived catch advice above or below the Status Quo, respectively). Method configurations are detailed in Table A.1.1.

TABLE 5. Parameter estimates and ranges used to characterize stock and fleet dynamics in the management strategy evaluations. Operating model data inputs and justifications are detailed in Tables A.1.2–A.1.5.

Data input	Puerto Rico Yellowtail Snapper	St. Thomas–St. John Queen Triggerfish	St. Croix Stoplight Parrotfish
Life history			
Maximum age (years)	19	14	12
Natural mortality rate (per year)	0.21–0.33	0.30–0.47	0.35–0.55
Steepness	0.70–0.90	0.35–0.84	0.35–0.95
Type of stock–recruitment relationship	Beverton–Holt	Beverton–Holt	Beverton–Holt
von Bertalanffy asymptotic length (mm FL)	484–545	415–605	275–632
von Bertalanffy growth rate (per year)	0.10–0.17	0.14–0.40	0.25–0.71
von Bertalanffy theoretical age at length 0 (years)	−1.87 to −0.96	−1.80 to −0.60	−0.06 to 0.00
Length–weight parameter *a*	3.46×10^{-5}	8.64×10^{-5}	3.70×10^{-5}
Length–weight parameter *b*	2.859	2.784	2.905
Current level of stock depletion	0.36–0.59	0.10–0.54	0.05–0.60
Length at 50% maturity (mm FL)	199–250	215–235	163–205
Length increment from 50% to 95% maturity (mm FL)	50–101	45–65	35–77
Process error in recruitment deviations	0.20–0.50	0.20–0.50	0.20–0.50
Autocorrelation in recruitment deviations	0.10–0.90	0.10–0.90	0.10–0.90
Fleet			
Number of years for historical simulation	116	85	45
Length at full selection (fraction of length at 50% maturity)	1.12–1.41	1.28–1.40	1.32–1.66
Length at 5% selectivity (fraction of length at 50% maturity)	0.76–0.95	0.96–1.05	1.10–1.38
Vulnerability of oldest age-class	1.0–1.0	0.0–0.5	1.0–1.0
Interannual variability in fishing mortality	0.10–0.23	0.10–0.40	0.10–0.40
Index of effort (units)	Commercial handline (total hours fishing)	Commercial traps (total number of traps)	Commercial diving (total number of dives)

information available for tropical species (Cummings et al. 2016a). Several biological parameters were fixed across simulations, including the weight–length parameters, maximum age, and initial recruitment.

Populations were simulated for a historical time period based on the exploitation history of each stock. The exploitation history was assumed to be of sufficient length to reasonably characterize the historical pattern for U.S. Caribbean fisheries. Commercial fishing was first documented in 1899 for Puerto Rico (350 vessels, 800 fishers; Cummings and Matos-Caraballo 2003) and in 1980 for the U.S. Virgin Islands (405 fishers, 1,880 estimated traps; Kojis and Quinn 2006). The simulated population was initiated in an unfished equilibrium condition and then subjected to a series of annual fishing mortality rates (F) that were proportional to a user-specified time series of fishing effort. These F rates were rescaled to achieve a user-specified level of stock depletion at the end of the historical time period, where depletion was defined in the simulation as the ratio of current biomass (i.e., terminal year, 2014) to unfished biomass. A simulation period of 40 years with stock evaluations conducted every 3 years was specified because at least 40 years was required to ensure the reference yield (maximum yield at the end of the time period from a fixed F strategy) did not reach a high level and "mine" the stock. A replication level of 1,000 simulation runs was chosen after observing stable performance metrics with additional simulations (Carruthers and Hordyk 2016).

Data inputs to the DLMs were simulated through an observation model that introduced error and bias to reflect user-specified levels of imperfect knowledge. Both bias and error parameters were parameterized using available data to reflect the actual data quality in the U.S. Caribbean (Table 6). Imperfect knowledge was introduced in terms of imprecision, or the random interannual variation in observable quantities around respective "true" simulated values, and bias, or the inaccuracy in a given quantity that occurs for the duration of a simulation. Simulating bias and imprecision allowed for the measurement of the effects of imperfect information on method performance (Carruthers et al. 2014).

Robustness testing of operating model specifications.— Factors that could potentially affect method performance were considered, including assumptions, biases, and uncertainties in data inputs. For each stock, fleet dynamics were parameterized for the single fishing fleet that accounted for the largest percentage of commercial fishing trips reporting landings of each species (Table 2). Fleet dynamics characterizations included considerations of selectivity. Based on available landings, size composition data, and fisher testimony, fleets were parameterized to exhibit either dome-shaped selectivity (St. Thomas–St. John Queen Triggerfish) or asymptotic selectivity (Puerto Rico Yellowtail Snapper and St. Croix Stoplight Parrotfish). Two varieties of dome-shaped selectivity were tested, including a moderate dome (i.e., final selectivity between 0.6 and 0.9) and a high dome (final selectivity between 0.3 and 0.6 for Puerto Rico Yellowtail Snapper and St. Croix Stoplight Parrotfish and between 0.0 and 0.5 for St. Thomas–St. John Queen Triggerfish). Alternative configurations (e.g., asymptotic for St. Thomas–St. John Queen Triggerfish) were also tested to address uncertainties in selectivity.

Robustness testing was also carried out on operating model specifications to address assumptions made regarding current stock depletion (i.e., depletion in the terminal year of the historical period). Assumed base depletion ranges for Puerto Rico Yellowtail Snapper (36–59%) and St. Thomas–St. John Queen Triggerfish (10–54%) were based on a catch-at-size reduction analysis ("ML2D" function in DLMtool; Carruthers and Hordyk 2016), which determines the resultant depletion level and corresponding equilibrium F that would arise from recent mean length from current catches, fishery selectivity, and stock dynamics. Limited data prevented this analysis for St. Croix Stoplight Parrotfish and therefore a wide range of 5–60% stock depletion was assumed in the base case. Due to considerable uncertainty concerning current stock depletion for each stock, robustness testing was conducted assuming various current depletion ranges: 5–20% (i.e., severely overexploited), 20–40%, 40–60%, 60–80%, and 80–99% (i.e., highly underexploited).

TABLE 6. Bias and error parameters controlling the accuracy and precision of knowledge within the simulated system for each U.S. Caribbean stock based on available data. Operating model inputs and justifications are detailed in Tables A.1.2–A.1.5.

Management strategy evaluation attribute	Puerto Rico Yellowtail Snapper	St. Thomas–St. John Queen Triggerfish	St. Croix Stoplight Parrotfish
Data inputs			
Observation error in annual catches	0.46–0.92	0.28–0.56	0.51–1.02
Bias in annual catches	0.46	0.28	0.51
Observation error in relative abundance index	0.08–0.25	0.02–0.03	0.05–0.10
Bias in recruitment	0.10–0.30	0.10–0.30	0.10–0.30
Bias in absolute biomass			
Bias in ratio of B_{MSY} to virgin biomass	0.14	0.14	0.14
Bias in absolute biomass	0.20–5.00	0.20–5.00	0.20–5.00
Observation error in absolute biomass	0.20–0.50	0.20–0.50	0.20–0.50
Bias in length at 50% maturity	0.20	0.20	0.20
Bias in natural mortality	0.32	0.32	0.32
Bias in von Bertalanffy asymptotic size	0.05	0.12	0.12
Bias in von Bertalanffy maximum growth rate	0.16	0.35	0.30
Bias in von Bertalanffy theoretical age at length 0	0.45	0.50	0.50
Bias in length at first capture	0.50	0.50	0.50
Bias in length at full selection	0.50	0.50	0.50
Bias in current stock depletion	1.00	1.00	1.00
Observation error in current stock depletion	0.05–0.20	0.05–0.20	0.05–0.20
Bias in steepness	0.14	0.46	0.58
Lognormal variability in length at age	0.15–0.26	0.13–0.25	0.09–0.13
Number of annual length–age observations	150–200	150–200	50–100
Other control rule inputs			
Bias in ratio of F_{MSY} to natural mortality	0.11	0.11	0.11
Bias in target CPUE	0.30	0.30	0.30
Bias in target catch (MSY)	0.30	0.30	0.30
Bias in target biomass level (B_{MSY})	0.50	0.50	0.50

Performance metrics.— As this study focused on a set of U.S. Caribbean stocks, performance metrics were developed around management objectives defined for conservation criteria in concordance with the MSFCMA NS1 Guidelines. Two conservation performance metrics were specified: (1) the probability of not overfishing (PNOF), calculated as the fraction of simulation years where F was below the F at maximum sustainable yield (MSY; F_{MSY}), and (2) B50, the probability of not being overfished, calculated as the fraction of simulation years where the ratio of current biomass to biomass at maximum sustainable yield (B_{MSY}) exceeded 0.5. For the final metrics, PNOF and B50 were averaged across all 1,000 simulations and thresholds of greater than 50% were specified to meet NS1 Guidelines (NMFS 2009).

A third performance metric relating to the average annual variability in yield (AAVY) characterized economic stability in DLM advice. This metric is the mean difference in the yield of adjacent simulation years (starting from the last historical year) divided by the mean yield over the same time period:

$$\text{AAVY} = \frac{(n_p + 1)\sum_{y=n_h}^{n_h+n_{p-1}} |\text{Cat}_{y+1} - \text{Cat}_y|}{n_p \sum_{y=n_h}^{n_h+n_p} \text{Cat}_y} \tag{1}$$

where n_p is the number of simulation years, n_h is the number of historical years, and Cat is the true simulated total removals in year y or y + *1* (Carruthers et al. 2015). A cutoff of 15% allowable variation in interannual yield was specified by the SEDAR 46 Data and Assessment Workshop Panel (SEDAR 2016a) as follows:

$$\text{AAVY15}(\%) = \frac{\sum_{y=t_1}^{t_2} \text{simulations where AAVY} < 0.15}{\text{total simulations}} \times 100 \tag{2}$$

where t_1 is the start year of the simulation period and t_2 is the end year of the simulation period. A specified threshold of at least 50% was chosen to reflect at least a 50% chance of the AAVY remaining within 15%.

Three additional metrics were provided to assist in comparing DLM performance: (1) long-term yield, defined as the fraction of simulations achieving over 50% F_{MSY} yield over the final 5 years of the simulation period; (2) short-term yield, defined as the fraction of simulations achieving over 50% F_{MSY} yield over the first 5 years of the simulation period; and (3) B20, the probability of the biomass being above 20% B_{MSY} over the entire simulation period (i.e., related to stock collapse).

Guidance on implementation of catch advice for management.— Candidate DLMs from the management strategy evaluation were applied to actual data to illustrate how catch advice could be developed for consideration by managers. Catch advice was derived for the subset of DLMs that met the performance criteria (i.e., PNOF, B50, and AAVY15 > 50%) and was estimated using existing biology (e.g., maturity), landings, CPUE, and mean length data for each stock (Table 2; Figure 2). For each DLM, 10,000 random draws from parameter distributions defined by the input mean and coefficient of variation provided a stochastic sample of the plausible catch advice. For each DLM, the derived median catch advice was compared to the Status Quo approach (as a percentage) to illustrate changes in the catch advice, with values above 100 indicative of higher DLM catch advice compared with that of the Status Quo approach and values less than 100 indicating lower DLM catch advice.

Implementation of target-based methods required target indicator values of either relative abundance (CPUE Target) or mean length (Length Target) based on assumed stock status during the reference period. Given the considerable uncertainty in terms of assumed stock status during the reference period and its potential influence on derived catch advice, four assumptions of stock status (and therefore model configurations) were tested: (1) severely overexploited (set indicator target much higher than reference level), (2) overexploited (set indicator target higher than reference level), (3) near optimum (set indicator target equal to reference level), and (4) underexploited (set indicator target below the reference level).

RESULTS

Management Strategy Evaluation of DLMs: Identifying Candidate DLMs (i.e., Meeting Performance Criteria)

The catch-only Status Quo approach often resulted in moderate to high probabilities of long-term yield and short-term yield achieving 50% yield relative to F_{MSY} (Figure 3). However, for both St. Thomas–St. John Queen Triggerfish and St. Croix Stoplight Parrotfish, this approach fell below the 50% threshold for interannual variability in yield (AAVY15), suggesting instability in interannual catches (Figure 3). Although the catch-only Status Quo approach produces a static value in reality and should not vary between evaluation cycles, simulated catches (and therefore derived mean catch advice) were variable because they included both observation error and bias. For Puerto Rico Yellowtail Snapper, the catch-only Status Quo approach met all performance criteria, possibly owing to the more moderate depletion range (current biomass between 36% and 59% of unfished biomass) assumed in the base simulation when compared with the other species (St. Thomas–St. John Queen Triggerfish: 10−54%, St. Croix Stoplight Parrotfish: 5−60%).

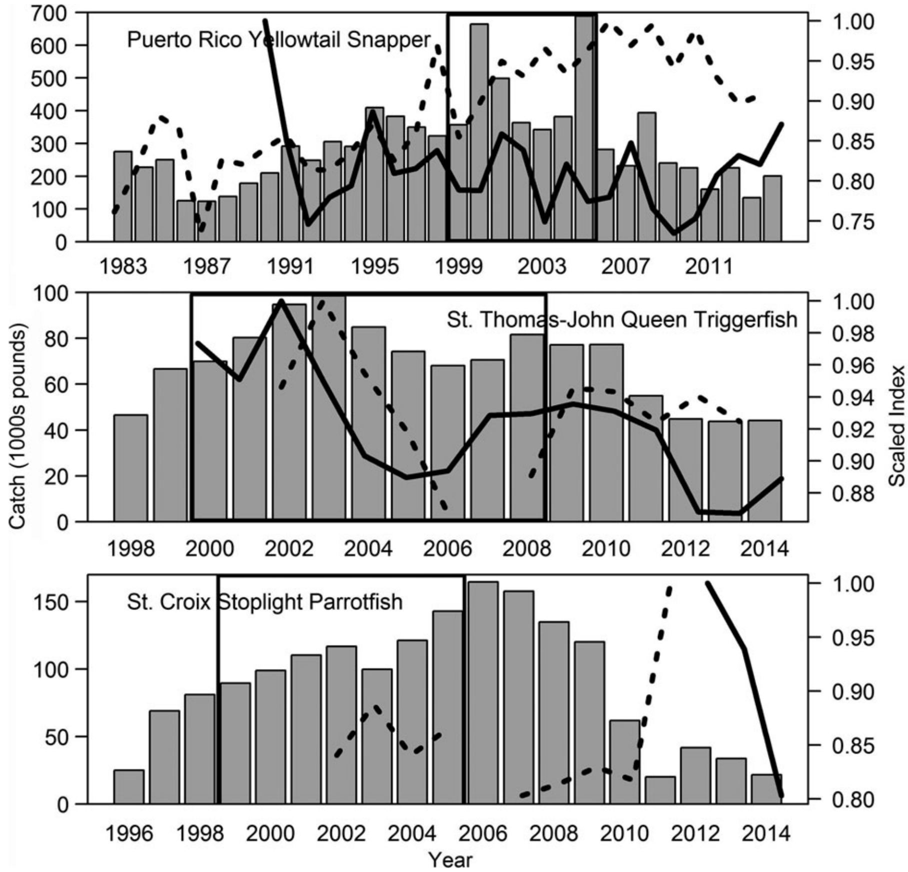

FIGURE 2. Time series of total removals (bars), an index of relative abundance (CPUE from the most representative fishing fleet; solid line), an index of mean length (derived from the most representative fishing fleet; dashed line), and a reference period (box) for the three U.S. Caribbean stocks. Species-specific data collection began in July 2011 for St. Thomas–St. John and St. Croix (data compilation prior to 2011 based on assumed proportion of landings).

Data-limited methods based on empirical indicators consistently met performance criteria (Figure 3). These approaches included CPUE Target, which assumed relative stock abundance (CPUE) during the reference period was near optimum and therefore an appropriate target CPUE level (method hereafter referred to as CPUE Target [near optimum]); CPUE Slope, which used recent catch and CPUE during the most recent 5 (CPUE Slope [5 years]) or 10 years (CPUE Slope [10 years]); and Stepwise Constant Catch with Mean Length. The CPUE Target was not feasible for St. Croix Stoplight Parrotfish because the CPUE time series began in 2012 (Figure 2). Clear evidence of trade-offs between conservation metrics (e.g., PNOF) and yield metrics (e.g., long-term yield) were noted for these empirical DLMs (Figure 3). For example, CPUE Target (near optimum) resulted in lower PNOF but higher probabilities of long-term yield achieving 50% yield relative to F_{MSY} for Puerto Rico Yellowtail Snapper. In contrast, CPUE Slope (5 or 10 years) and Stepwise Constant Catch with Mean Length often exhibited lower probabilities of long-term yield and short-term yield achieving 50% yield relative to F_{MSY} but more conservative PNOF, B50, B20, and AAVY15. Between these three DLMs, CPUE Slope (10 years) generally resulted in higher probabilities of long-term yield achieving 50% yield relative to F_{MSY} (Figure 3). Other approaches including the Multi-indicator, Length Target (assuming mean length during reference period was near optimum, hereafter referred to as Length Target [near optimum]), and Length at Maturity Target met the performance criteria for Puerto Rico Yellowtail Snapper but not St. Thomas–St. John Queen Triggerfish or St. Croix Stoplight Parrotfish (AAVY15 $<$ 50%; Figure 3).

Management Strategy Evaluation of DLMs: Robustness Testing of Operating Model Specifications

Fleet selectivity.— In general, the selectivity pattern exhibited by the fishery in the simulation did not affect the performance criteria of candidate DLMs for any of the stocks considered (Figure 4). Performance metrics were generally similar across selectivity scenarios, with differences ranging from 2.8% to 5.7% for PNOF, from 2.5%

Method	PNOF	B50	AAVY15	B20	LTY	STY
Puerto Rico Yellowtail Snapper (D = 0.36-0.59)						
CPUE Target (near optimum)	61	72	56	89	40	50
Multi-indicator	73	81	71	94	38	42
Length at Maturity Target	69	79	66	92	38	44
Length Target (near optimum)	72	80	68	93	37	43
Status Quo	78	84	76	95	34	38
CPUE Slope (10 years)	88	90	88	98	21	30
CPUE Slope (5 years)	88	90	86	98	20	30
Stepwise Constant Catch with Mean Length	88	90	88	98	16	30
St. Thomas-St. John Queen Triggerfish (D = 0.10-0.54)						
Length at Maturity Target	50	63	31	81	49	64
Multi-indicator	58	69	41	84	49	60
Status Quo	62	70	48	85	47	58
Length Target (near optimum)	60	70	45	85	46	57
CPUE Target (near optimum)	71	76	59	90	41	48
CPUE Slope (10 years)	86	83	83	94	28	36
CPUE Slope (5 years)	86	83	78	94	26	37
Stepwise Constant Catch with Mean Length	88	85	85	95	19	35
St. Croix Stoplight Parrotfish (D = 0.05-0.60)						
Length at Maturity Target	55	68	15	86	54	65
Multi-indicator (no index)	65	74	33	89	49	56
Length Target (near optimum)	68	76	38	90	47	54
Status Quo	68	76	40	90	47	53
CPUE Slope (10 years)	90	88	83	97	20	26
CPUE Slope (5 years)	90	88	79	97	18	27
Stepwise Constant Catch with Mean Length	92	89	85	97	8	25

Performance Metric (%)

FIGURE 3. Performance metrics (%) for candidate data-limited methods identified for the three U.S. Caribbean stocks. Base depletion levels (*D*; ratio of current to unfished biomass) are specified in parentheses for each species. Methods are as defined in Table 3 and detailed in Table A.1.1. Performance metrics (defined in the text, LTY = long-term yield, STY = short-term yield) that must exceed the 50% threshold fall to the left of the thick vertical line. A gradation color scheme from dark (i.e., low metric, red online) to light (high metric, green online) is used to highlight differences within metrics for each species.

to 4.6% for B50, and from 5.8% to 6.9% for AAVY15. The DLM most affected by selectivity changes was Length at Maturity Target, the only DLM tested that relied upon maturity estimates, emphasizing the requirement for accurate inputs for this life history parameter.

Stock depletion.— The stock depletion level assumed at the end of the historical period (i.e., terminal year = 2014) had a strong impact on which DLMs met the performance criteria. Overall, all strategies met the criteria for each stock when depletion was above 40%, with the exception of Length at Maturity Target for Queen Triggerfish and Stoplight Parrotfish (Figure 5). For Puerto Rico Yellowtail Snapper, CPUE Target did not meet all performance criteria under an overexploited scenario at the end of the historical period in the simulation (i.e., current biomass from 5% to 40% of unfished biomass). Under overexploited scenarios for St. Thomas–St. John Queen Triggerfish and St. Croix Stoplight Parrotfish, Length Target, Length at Maturity Target, Multi-indicator, and the catch-only Status Quo approach failed to meet all performance criteria. For these two stocks, large gradients in performance were noted across the lowest to highest depletion levels for these strategies. Although these results stress the importance of information content needed for initial conditions, empirical indicator DLMs such as CPUE Slope (5 or 10 years) and Stepwise Constant Catch with Mean Length remained relevant management options across depletion ranges considered for each simulated stock (Figure 5).

Guidance on Implementation of Catch Advice for Management and Stakeholders

The suite of DLMs that met the performance criteria resulted in highly variable distributions of catch advice within each stock, with large differences evident between DLMs and the catch-only Status Quo approach (Figure 6). The greatest number of candidate DLMs was identified for Puerto Rico Yellowtail Snapper and resulted in the most variability in catch advice, ranging from the lowest catch advice for Length at Maturity Target to the highest catch advice for CPUE Target (near optimum). Although fewer candidate DLMs were identified for the remaining stocks, catch advice remained variable (Figure 6). Of the DLMs considered for St. Thomas–St. John Queen Triggerfish and St. Croix Stoplight Parrotfish, catch advice ranged from lowest for CPUE Slope (5 years) to highest for Stepwise Constant Catch with Mean Length. Estimates of uncertainty in derived catch advice were similar across stocks, with coefficients of variation highest for the Multi-indicator approach (range = 0.28–0.49) and lowest for CPUE Slope (10 years) (range = 0.09–0.16).

Given a paucity of data indicating that the Puerto Rico Yellowtail Snapper stock could be severely overexploited, CPUE Target (near optimum) could be a suitable candidate approach for providing catch advice for management based on simulation results (i.e., meeting MSFCMA NS1 Guidelines criteria and robustness to assumptions) and data quality (Table 7). Based on similar criteria, CPUE Target (near optimum) could be a candidate approach for St. Thomas–St. John Queen Triggerfish (Table 7), which made up the majority (~95%) of landings of “triggerfish” (family Balistidae) since July 2011 (SEDAR 2016a). However, for species such as St. Croix Stoplight Parrotfish, where species-specific data are limited to recent years (Figure 2), CPUE Slope (5 and 10 years) could be a candidate approach based on data availability and quality combined with simulation results (Figure 3–5).

Fishery Selectivity Pattern

Method	Yellowtail Snapper			Queen Triggerfish			Stoplight Parrotfish		
	Asymptotic*	Dome	High dome	Asymptotic	Dome	High dome*	Asymptotic*	Dome	High dome
PNOF									
CPUE Slope (10 years)	88	87	88	84	85	86	90	90	91
CPUE Slope (5 years)	88	87	88	84	85	86	90	90	91
CPUE Target (near optimum)	61	58	61	66	67	71			
Stepwise Constant Catch with Mean Length	88	89	88	85	86	88	92	92	92
Length Target (near optimum)	72	72	74	56	54	60	68	68	66
Length at Maturity Target	69	67	73	47	47	50	55	55	56
Multi-indicator	73	72	73	56	57	58	65	65	67
Status Quo	78	77	78	59	60	62	68	69	71
B50									
CPUE Slope (10 years)	90	89	90	81	82	83	88	88	90
CPUE Slope (5 years)	90	90	90	82	82	83	88	88	90
CPUE Target (near optimum)	72	70	73	72	72	76			
Stepwise Constant Catch with Mean Length	90	90	90	82	83	85	89	89	90
Length Target (near optimum)	80	80	82	66	65	70	76	75	75
Length at Maturity Target	79	77	81	59	59	63	68	67	70
Multi-indicator	81	80	82	66	66	69	74	74	76
Status Quo	84	84	84	68	68	70	76	76	78
AAVY15									
CPUE Slope (10 years)	88	86	89	79	82	83	83	81	83
CPUE Slope (5 years)	86	83	87	75	78	78	79	79	80
CPUE Target (near optimum)	56	51	54	53	56	59			
Stepwise Constant Catch with Mean Length	88	87	90	81	82	85	85	84	85
Length Target (near optimum)	68	70	71	41	39	45	38	39	33
Length at Maturity Target	66	64	70	28	30	31	15	17	18
Multi-indicator	71	69	71	41	41	41	33	34	37
Status Quo	76	77	78	44	47	48	40	40	44

FIGURE 4. Method performance (%) across fleet selectivity patterns for the three U.S. Caribbean stocks. Fleet selectivity patterns include asymptotic, dome-shaped (final selectivity between 0.6 and 0.9), and highly dome-shaped (final selectivity between 0.0 and 0.5 [St. Thomas–St. John Queen Triggerfish] or between 0.3 and 0.6). An asterisk identifies the base configurations. Additional details are provided in the caption for Figure 3.

Depletion (current biomass / unfished biomass) (%)

Method	Yellowtail Snapper Base	5-20	20-40	40-60	60-80	80-99	Queen Triggerfish Base	5-20	20-40	40-60	60-80	80-99	Stoplight Parrotfish Base	5-20	20-40	40-60	60-80	80-99
PNOF																		
CPUE Slope (10 years)	88	84	85	88	91	92	86	83	85	88	91	94	90		89	91	93	94
CPUE Slope (5 years)	88	83	85	88	91	92	86	83	85	88	91	94	90		89	92	93	94
CPUE Target (near optimum)	61	49	52	61	72	75	71	70	68	73	79	85						
Stepwise Constant Catch with Mean Length	88	86	86	89	92	93	88	85	87	91	92	94	92		90	92	94	95
Length Target (near optimum)	72	66	68	73	83	84	60	47	61	67	75	86	68		64	73	79	84
Length at Maturity Target	69	62	66	68	79	81	50	42	51	60	69	80	55		54	62	69	77
Multi-indicator	73	64	67	74	82	84	58	51	58	68	76	86	65		65	72	79	84
Status Quo	78	69	72	78	85	87	62	55	60	71	78	87	68		68	76	81	85
B50																		
CPUE Slope (10 years)	90	82	87	90	92	93	83	77	83	88	90	92	88		87	90	91	93
CPUE Slope (5 years)	90	82	87	90	92	93	83	77	83	88	90	92	88		87	90	91	93
CPUE Target (near optimum)	72	57	65	73	79	82	76	70	74	80	84	88						
Stepwise Constant Catch with Mean Length	90	83	88	90	92	94	85	78	84	89	90	92	89		88	91	91	93
Length Target (near optimum)	80	70	76	81	87	88	70	54	70	76	82	88	76		73	80	83	87
Length at Maturity Target	79	68	75	78	84	86	63	51	63	72	78	84	68		67	74	78	84
Multi-indicator	81	69	76	81	86	88	69	57	68	77	83	88	74		74	80	83	87
Status Quo	84	72	80	84	88	90	70	60	70	79	84	88	76		76	82	85	88
AAVY15																		
CPUE Slope (10 years)	88	77	82	87	94	93	83	77	82	88	92	96	83		79	87	91	95
CPUE Slope (5 years)	86	70	78	85	93	92	78	72	79	86	91	94	79		76	85	90	94
CPUE Target (near optimum)	56	34	43	57	69	75	59	57	59	67	77	84						
Stepwise Constant Catch with Mean Length	88	79	84	87	94	93	85	79	84	89	92	96	85		81	88	92	95
Length Target (near optimum)	68	58	64	71	83	84	45	25	51	60	71	85	38		32	51	68	79
Length at Maturity Target	66	53	61	65	78	82	31	18	36	49	63	78	15		14	33	55	67
Multi-indicator	71	55	62	71	82	86	41	30	46	60	74	86	33		34	51	68	78
Status Quo	76	60	68	78	86	90	48	34	48	66	76	88	40		39	56	72	81

FIGURE 5. Method performance (%) across current stock depletion (i.e., ratio of current to unfished biomass) levels for the three U.S. Caribbean stocks. Depletion levels range from severely overexploited (5–20%) to highly underexploited (80–99%). Base stock depletion levels and additional details are provided in Figure 3. St. Croix Stoplight Parrotfish results are not shown for the severely overexploited scenario (current depletion between 5% and 20% could not be reached at the end of the historical time period) or for CPUE Target (no reference index).

Target levels based on assumed stock status during the reference period strongly determined the magnitude of catch advice derived for CPUE Target and Length Target (Figure 7). An underexploited or near optimum stock during the reference period could lead to higher derived catch advice, dependent upon recent data (Figure 7). In contrast, catch advice would decrease as a function of declining stock condition. This trend was evident for both Puerto Rico Yellowtail Snapper and St. Thomas–St. John Queen Triggerfish, although it is important to note that some stock conditions (e.g., underexploited CPUE Target configuration) did not meet the performance metrics in simulation (Figure A.2.1 in Appendix 2) and therefore would not be considered suitable management options.

DISCUSSION

A Proposed Framework for Providing Catch Advice for Data-Limited Stocks

This study examined the potential for improved fisheries management advice through the use of adaptive DLMs compared with the static advice available from the catch-only Status Quo approach. Simulation analysis for three U.S. Caribbean stocks revealed performance criteria meeting NS1 Guidelines for empirical index-based and length-based approaches tested. Poor performance was noted (e.g., AAVY15 < 50%) for the catch-only Status Quo approach, ultimately suggesting a need for caution when implementing static catch-only approaches. Similar results were reported in other studies (Carruthers et al.

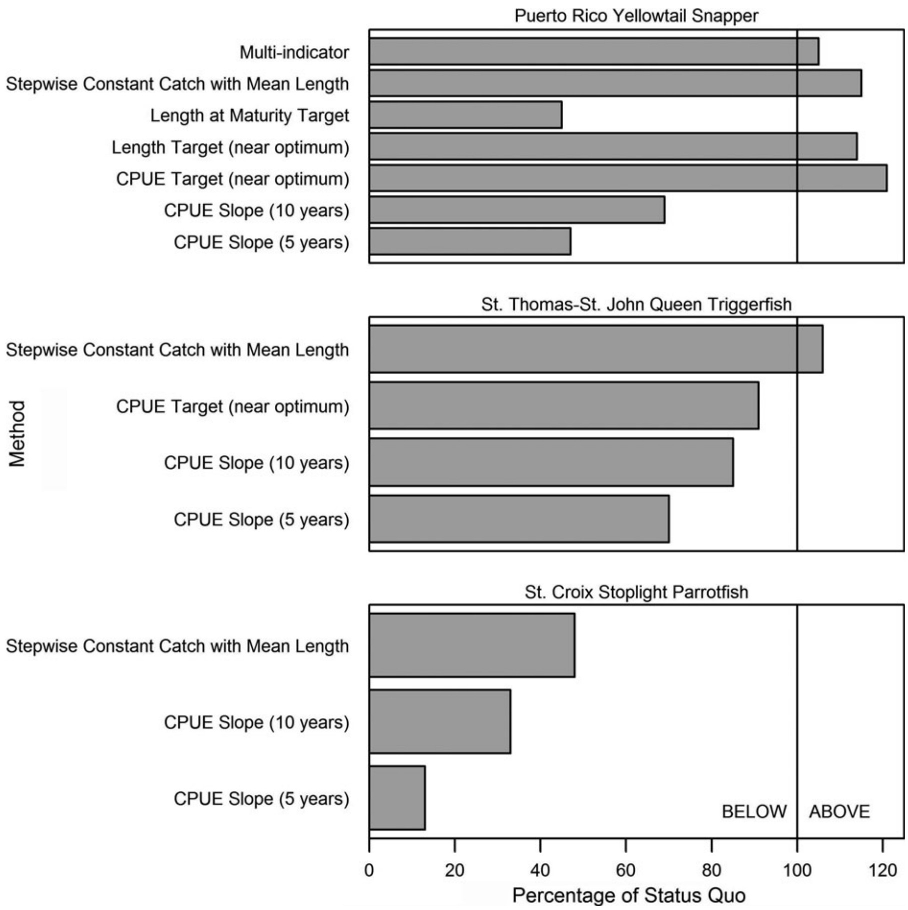

FIGURE 6. Comparison of catch advice derived from candidate data-limited methods as a percentage of the Status Quo catch advice for the three U.S. Caribbean stocks. The vertical lines depict where catch advice would equal the Status Quo catch advice, with bars to the left indicative of catch advice below the Status Quo catch advice. Note that the Status Quo catch advice for Stoplight Parrotfish is for the entire parrotfish (Scaridae) complex.

2014, 2015). Catch-only approaches that provide fixed catch are frequently implemented by managers; however, such approaches are not robust to a variety of conditions, such as environmental variability, initial depletion level, and unstable (nonequilibrium) stock status when constant catch was initially established. Further, static catch-only approaches do not possess a feedback mechanism to adjust catch advice based on trends in the resource's abundance.

The DLMs considered in the present study represent only a small subset of available DLMs (Chrysafi and Kuparinen 2015; Geromont and Butterworth 2016). However, these approaches reflect improved procedures for generating catch advice when compared with the catch-only Status Quo approach currently implemented by the CFMC (CFMC 2011a, 2011b). The tested DLMs are well suited for application in the U.S. Caribbean based on current data availability (Table 1). In addition, management strategy evaluation results for these DLMs provide important input relating to trade-offs in management improvements from future enhancements in data collection. Importantly, these adaptive DLMs will guard against stock collapse by incorporating feedback into the management process. In contrast to the static catch-only Status Quo approach, catch advice from adaptive DLMs would vary with changes in the abundance of the resource—if indices of abundance or mean length increased, catch advice would be increased, and if they decreased, catch advice would decrease (Geromont and Butterworth 2014; Carruthers et al. 2015). Such stock evaluations considering adaptive DLMs could therefore produce higher catch advice than the static catch-only Status Quo approach if indicated by the data, allowing increased opportunities for harvest if market demands allow.

Less data-intensive empirical DLMs, using either trends in relative abundance or mean length, were generally robust to changes in simulated dynamics, including current stock depletion and fleet selectivity. The CPUE

TABLE 7. Guidance and rationale used to select candidate data-limited methods for each stock under evaluation.

	Stock and candidate approach		
Selection criteria	Puerto Rico Yellowtail Snapper, CPUE Target (near optimum)	St. Thomas–St. John Queen Triggerfish, CPUE Target (near optimum)	St. Croix Stoplight Parrotfish, CPUE Slope (10 years)
Justification from management strategy evaluation			
Performance criteria and NS1 Guidelines satisfied?	• Yes, exhibits greatest probabilities of long-term and short-term yield achieving 50% yield relative to F_{MSY}	• Yes, exhibits greatest probabilities of long-term and short-term yield achieving 50% yield relative to F_{MSY}	• Yes, exhibits greatest probability of long-term yield achieving 50% yield relative to F_{MSY}
Robust to uncertainty in depletion level?	• Yes, except at severely exploited condition	• Yes	• Yes
Robust to uncertainty in fleet selectivity?	• Yes	• Yes	• Yes
Justification from data quality			
Data quality	• Good	• Good	• Good
Other concerns	• None	• Mean length less reliable due to dome-shaped selectivity of fishery and relatively small sample sizes	• Short time series • Mean length less reliable due to very small sample sizes

Target method often outperformed other adaptive DLMs in the simulation, for example by exhibiting relatively higher probabilities of long-term and short-term yields achieving 50% relative to F_{MSY} compared with other adaptive DLMs. Where reference data and associated assumptions cannot be supported due to limited data collection or species rarity, CPUE Slope could produce catch advice to guide the stock to a stable catch level. Both CPUE Slope and Stepwise Constant Catch with Mean Length met the performance criteria for each of the three simulated stocks across assumed stock depletion ranges. This result suggests that these approaches are appropriate options in situations where current stock depletion is highly uncertain or unknown, with the caveat that the probabilities of long-term and short-term yields achieving 50% yield relative to F_{MSY} are lower when compared with CPUE Target. Current stock depletion in the U.S. Caribbean is difficult to quantify and therefore remains unknown for managed species; for this reason, depletion-based DLMs such as Depletion-Corrected Average Catch (MacCall 2009) were not evaluated because of their reliance on both the depletion estimate and historical catches (Harford and Carruthers 2017).

The DLMs meeting performance criteria in the management strategy evaluation were generally robust to assumptions regarding current stock depletion and fishing fleet behavior, particularly for St. Thomas–St. John Queen Triggerfish and St. Croix Stoplight Parrotfish. In contrast, method performance varied for Puerto Rico Yellowtail Snapper across assumed stock depletion ranges. For example, if Puerto Rico Yellowtail Snapper were more severely depleted (i.e., current biomass between 5% and 20% unfished biomass) than initially parameterized (36−59%), CPUE Target assuming a near optimum stock condition during the reference period would no longer meet the performance criteria. In this situation, the Multi-indicator approach would be suited to balancing performance metrics while also achieving management objectives (Harford et al. 2016), as evident by slightly higher long-term and short-term yield when compared with the other candidate DLMs.

In the present study, we tested one variant of a multi-indicator approach that integrated catch, relative abundance, and mean length (Harford et al. 2016). Notable benefits of a multi-indicator approach can include performance gains found in certain multi-indicator data, the

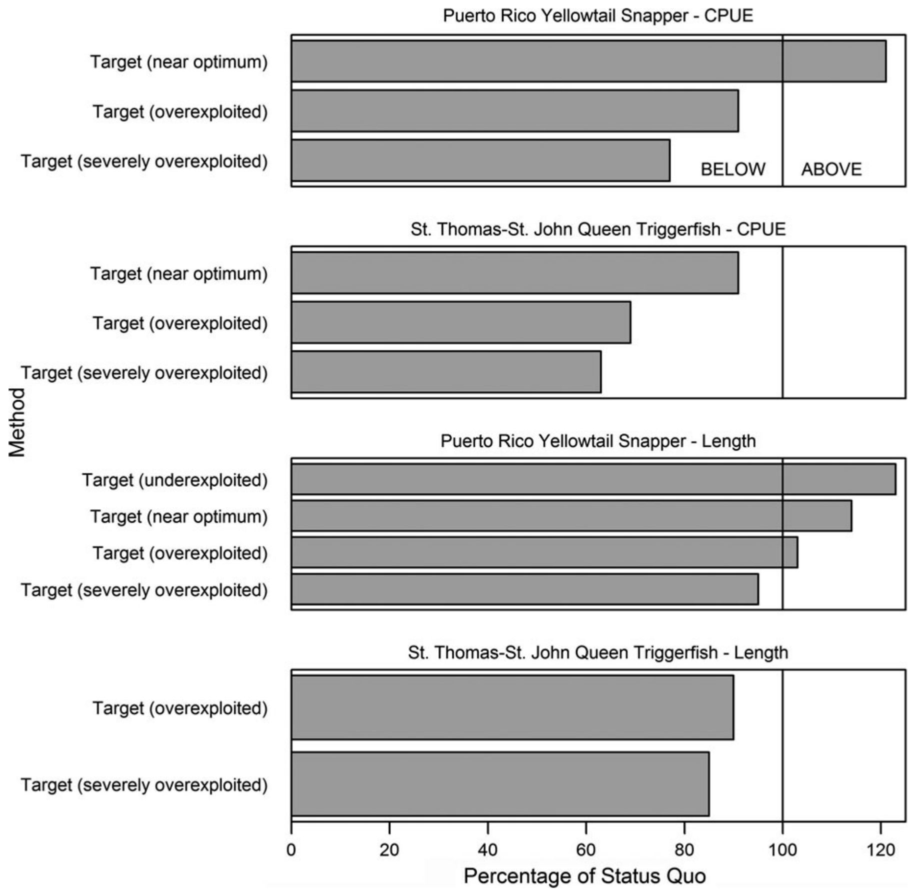

FIGURE 7. Demonstration of the influence of assumed target levels on the derived catch advice for empirical CPUE Target and Length Target approaches as a percentage of the Status Quo catch advice. These methods were not feasible for St. Croix Stoplight Parrotfish due to a lack of species-specific data during the reference period. Additional details are provided in Figure 6.

cancelling out of conflicting trends in data, and the flexibility to include environmental effects. The use of multi-indicator approaches can be implemented via harvest control rules that reflect disparate concepts related to structured decision-making. For example, multi-indicator approaches sometimes utilize degree of agreement among indicators to determine management response strength (Punt et al. 2001; Caddy 2004; Harford et al. 2016). Alternatively, decision trees can be used to parse information from each indicator into a sequence of decision-making steps, which allows management responses to reflect a variety of different circumstances (Dowling et al. 2015). The potential use of multi-indicator approaches points to the need for management and stakeholders to explicitly define management goals well before undertaking such investigations. However, careful consideration during development must be given to ensure reproducibility (e.g., of decisions) for simulation testing (Carruthers et al. 2014).

The derived catch advice was highly variable across DLMs for each stock, likely due to the various types of data required, the often-conflicting trends in the data, and the method assumptions (e.g., target levels). Catch advice from CPUE Slope was consistently lower compared to almost all other DLMs for each stock, particularly when the last 5 years were used. This finding relates to the magnitude of recent reported catches, which are hypothesized to be artificially low due to reduced effort as a result of economic hardship and potential underreporting rather than changes in stock abundance (SEDAR 2016a). Although artificially low catches would initially lead to low catch advice at the onset of implementation, the feedback aspect of CPUE Slope would systematically scale the catch advice from subsequent assessments up or down as a function of the slope of the index of abundance. Approaches such as CPUE Slope, which only rely on recent information, could be particularly useful for species in the U.S. Virgin Islands, where species-specific reporting began in July 2011 (SEDAR 2016a). However, the required indices necessitate that informed data collection practices be implemented that assure stock representativeness, preferably from fishery-independent sources, to adhere to the strict assumption of proportionality between CPUE and abundance. Fishery-dependent data can be confounded by changes in the fishery (e.g., regulations, selectivity, and market demands) that cannot be separated from stock dynamics.

Current Impediments to Using DLMtool to Set Catch Limits in the U.S. Caribbean

Considerable effort is required to design and test the performance of DLMs within the U.S. fisheries management framework (Hordyk et al. 2017). During the benchmark SEDAR 46 U.S. Caribbean Data-limited Species Assessment (SEDAR 2016a), it became clear that there is a need to specify management objectives early in the process based on consensus from stakeholders, fisheries managers, fishermen, and scientists (Punt et al. 2014). In addition, stakeholders must be educated on how DLMs are designed (i.e., assumptions) and their operational nature. For example, implementation of CPUE Target requires one to characterize the mean relative abundance during the reference period relative to an appropriate index target (e.g., $I^{\text{target}} = I^{R\text{EF}}$). This decision should be based on the best available scientific information as it drives the magnitude of the derived catch advice (Figure 7); a lower target requires a lower recent index to produce catch advice above the reference mean catch (Geromont and Butterworth 2014). Different stock status assumptions during the reference period were tested when configuring both CPUE Target and Length Target to demonstrate the impact of this decision. The flexibility of DLMs facilitates modifications as new information is presented or discovered. If a consensus regarding stock status cannot be reached, or target reference levels cannot be determined, best practice would be to either exclude such DLMs or assume higher target values to accommodate high uncertainty (Geromont and Butterworth 2014).

Through development of the DLMtool, the potential for streamlined data-limited evaluations of fishery resources has been enhanced (Newman et al. 2014). However, there is confusion regarding the implementation of DLMs in the context of the U.S. fisheries management framework, particularly how catch advice fits into operational harvest control rules (e.g., catch advice terminology, such as total allowable catch versus overfishing limit versus acceptable biological catch; Miller et al. 2015). For multiple DLMs included in DLMtool, many alternatives are available that differ only in their level of precaution (Carruthers et al. 2015; Carruthers and Hordyk 2016; Miller 2016). For example, two default CPUE Slope methods (Islope1 and Islope4; Carruthers and Hordyk 2016) produce catch advice using 80% or 60% of the average catch, respectively, resulting in increasingly precautionary catch advice (Geromont and Butterworth 2014). Although the issue of terminology may be more problematic to U.S. fisheries management than to others, these issues highlight the critical thinking that should accompany any DLMtool analysis with the intent of providing catch advice. If the perceived stock status does not warrant concern, naively setting an annual catch limit using the recommended catch advice from a precautionary method such as Islope4 will result in annual catch limits lower than what could be safely extracted from the fishery and will result in frequent overages if reduced effort cannot be enforced (e.g., annual catch limits on nontarget fisheries or bycatch species).

Given the variety of DLMs available in DLMtool, the question remains how to select a single approach or identify and combine a subset of DLMs to provide catch advice (Cummings et al. 2016b; SEDAR 2016a, 2016b). The Mid-Atlantic Fishery Management Council Scientific and Statistical Committee developed interim management advice using DLMtool that was accepted for use in 2017 for Black Sea Bass *Centropristis striata* (Cadrin et al. 2016; McNamee et al. 2016) and Blueline Tilefish *Caulolatilus microps* (Miller 2016; MAFMC 2017). These determinations are discussed here in the context of U.S. Caribbean fisheries. For each species, catch advice was computed as a weighted average across candidate DLMs (Boreman 2015; Miller 2016). The DLMtool developers and reviewers of DLMtool stock evaluations generally, however, support the selection of a single DLM based on specified performance criteria (e.g., greatest probability of achieving relatively high yield [long- or short-term] for target species). If multiple DLMs are combined, the joint approach should be simulation tested to ensure it continues to meet the performance criteria.

Future Improvements Envisioned for Data-Limited Stocks

Within the modeling framework presented herein, many limitations are acknowledged within management strategy evaluation. Pragmatically, results are a product of the specific conditions of the simulation, which are as simplistic as possible while retaining sufficient complexity to represent the dynamics of the stock and fishery. Additional efforts could greatly streamline data-limited investigations, particularly through data recovery exercises and operating model refinements. For example, a critical first step in any data-limited evaluation is a workshop of regional experts to review important demographic and fishery data needed to accurately specify operating models, and thus feed directly into simulation analysis. More certain life history characteristics could also enable more advanced DLMs that provide information on stock status and optimum yield, such as yield per recruit analysis and the nonequilibrium mean length-based mortality estimator (Gedamke and Hoenig 2006; Huynh et al. 2017). In addition, considerations will likely be needed for nontarget species or bycatch species, which are often of low economic value. For example, care must be taken when defining and selecting performance metrics because certain objectives, such as avoiding overexploitation, could be more important or relevant than achieving maximum sustainable yield for such species, as noted during review of the Gulf of Mexico Data-Limited Species Assessment (SEDAR 2016b).

A technical review of potential DLMs by an expert panel could greatly benefit future data-limited stock evaluations, such as the review of methods conducted by the Pacific Fishery Management Council (NMFS 2011). In particular, it is desirable to develop through consensus specific decision rules to inform method selection (e.g., selection of a single model versus application of a joint model) and DLMtool output (e.g., weighting of model outputs based on relative data quality when more than one is recommended). Specific issues to address could include the types of models to consider (e.g., candidate DLMs must provide stock status and optimum yield), model assumptions, robustness of models to departures in assumptions (biases), model uncertainty and identification of scenarios where models fail or are inappropriate, consideration of the frequency of assessment, and the fate of DLM output in a U.S. context (i.e., catch advice = overfishing limit or acceptable biological catch). Modifications to acceptable biological catch control rules in current U.S. management frameworks (as well as the creation of such rules in the U.S. Caribbean) will be required to accommodate DLM output and appropriately account for scientific uncertainty. In addition, a methodological review of DLMtool as planned by the Pacific Fishery Management Council (T. Carruthers, University of British Columbia, personal communication) could increase confidence in its application.

These results and the proposed framework support the use of adaptive DLMs to set catch advice in the U.S. Caribbean, which could have broad implications for fisheries stocks and the fishing communities. Stock evaluations considering adaptive DLMs could produce catch advice exceeding the static catch-only Status Quo approach if indicated by the data, allowing increased opportunities for harvest if market demands allow. The adoption of adaptive DLMs would move management beyond a static catch-only approach (Berkson and Thorson 2015; Newman et al. 2015), which performed poorly for two of the three stocks tested and in previous evaluations (Carruthers et al. 2014, 2015; SEDAR 2016b). The stock evaluation framework provided transparency of method performance, with comparisons of trade-offs across both conservation (e.g., probability of not overfishing) and economic management objectives (e.g., yields), greatly aiding in method selection. The selection of DLMs for providing catch advice for data-limited stocks must include considerations of the following: management objectives and inherent trade-offs (e.g., stable catches versus long-term or short-term yield for target species), data sufficiency and quality, method assumptions and limitations, incorporation of uncertainty, method performance, and identification of DLMs that do not perform acceptably.

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Appendix 1: Details on Data-Limited Methods

TABLE A.1.1. Data-limited method equations and assumptions for developing catch advice.

Method	Catch advice equation	Assumptions	References
	Catch-only method		
Status Quo	$\text{Catch Rec}_{y+1} = \frac{\Sigma_{y=t_1}^{t_2} \text{Cat}_y}{1+t_2-t_1} = C^{\text{REF}}$, where Catch Rec = catch advice, y = year, t_2 = end year of reference period, t_1 = start year of reference period, and Cat = total removals (landings). The annual catch limit was tested in the management strategy evaluation (defined in Table 4). Note that mean catch will vary across simulations due to inclusion of observation error in simulated catches	• Reference year selection based on expert evaluation of best available scientific information for reliable landings	CFMC (2011a, 2011b)
	Index-based methods		
CPUE Slope (5 years)	$\text{Catch Rec}_{y+1} = \frac{\Sigma_{y=t_{y-4}}^{t_y} \text{Cat}_y}{1+t_y-t_{y-4}} \times (1+\lambda \times S_y)$, where t_y is the terminal year, lambda (λ) controls the adjustment to the catch advice, and S_y = CPUE Slope (regression) for the most recent 5 years	• Trend in the index is a reliable indicator of the trend in resource biomass • λ = 0.4 (allows a moderate adjustment to catch level)	Geromont and Butterworth (2014)
CPUE Slope (10 years)	Same as CPUE Slope (5 years) except last 10 years (t_{y-9}:t_y) are used to calculate the mean catch and index slope	• Same as CPUE Slope (5 years)	Geromont and Butterworth (2014)
CPUE Target	If $I_y^{\text{recent}} \geq I^0$, $\text{Catch Rec}_{y+1} = C^{\text{REF}}\left[w + (1-w)\frac{I^{\text{recent}} - I^0}{I^{\text{target}} - I^0}\right]$ If $I_y^{\text{recent}} < I^0$, $\text{Catch Rec}_{y+1} = wC^{\text{REF}}\left[\frac{I_y^{\text{recent}}}{I^0}\right]^2$, where I_y^{recent} = mean CPUE for recent time period (2010–2014), I^{REF} = mean CPUE for reference period, $I^0 = 0.8\ I^{\text{REF}}$, C^{REF} = as defined in Status Quo, w = smoothing parameter, and index targets based on assumed stock status during reference period Underexploited: $I^{\text{target}} = 0.8\ I^{\text{REF}}$ (reference CPUE high) Near optimum: $I^{\text{target}} = 1.0\ I^{\text{REF}}$ (reference CPUE near optimum) Overexploited: $I^{\text{target}} = 1.2\ I^{\text{REF}}$ (reference CPUE low) Severely overexploited: $I^{\text{target}} = 1.5\ I^{\text{REF}}$ (reference CPUE very low)	• Same as reference catch for Status Quo • Trend in the index is a reliable indicator of the trend in resource biomass • Relative stock status during reference period is known to determine an appropriate target index • w = 0.5 allows for relatively higher rate of change when catch advice exceeds I^0	Geromont and Butterworth (2014)
	Length-based methods		
Stepwise Constant Catch with Mean Length	If $L_y^{\text{recent}}/L^{\text{REF}} < 0.96$, $\text{Catch Rec}_{y+1} = C^{\text{REF}} - 2\times(0.05\times C^{\text{REF}})$ If $0.96 \leq L_y^{\text{recent}}/L^{\text{REF}} < 0.98$, $\text{Catch Rec}_{y+1} = C^{\text{REF}} - (0.05\times C^{\text{REF}})$ If $0.98 \leq L_y^{\text{recent}}/L^{\text{REF}} \leq 1.05$, $\text{Catch Rec}_{y+1} = C^{\text{REF}}$ If $L_y^{\text{recent}}/L^{\text{REF}} > 1.05$, $\text{Catch Rec}_{y+1} = C^{\text{REF}} + (0.05\times C^{\text{REF}})$, where L_y^{recent} = mean length for the recent time period (2010–2014), L^{REF} = mean length for the reference period, and C^{REF} as defined in Status Quo	• Same as reference catch for Status Quo • Mean length of fish caught assumed an indirect index of abundance • 5% step size is a fixed input to control for random fluctuations in average size • Status of the fishery judged to be healthy	Geromont and Butterworth (2014)

TABLE A.1.1. Continued.

Method	Catch advice equation	Assumptions	References
Length Target (near optimum)	If $L_y^{recent} \geq L^0$, $\text{Catch Rec}_{y+1} = C^{REF}\left[w + (1-w)\frac{(L_y^{recent} - L^0)}{(L^{target} - L^0)}\right]$ If $L_y^{recent} < L^0$, $\text{Catch Rec}_{y+1} = wC^{REF}\left[\frac{(L_y^{recent})}{L^0}\right]^2$, where L_y^{recent}, L^{REF}, and C^{REF} are as specified above, w = smoothing parameter, $L^0 = 0.9\ L^{REF}$, and length targets based on assumed stock status during reference period Underexploited: $L^{target} = 0.95\ L^{REF}$ (reference mean length large) Near optimum: $L^{target} = 1.0\ L^{REF}$ (reference mean length near optimum) Overexploited: $L^{target} = 1.025\ L^{REF}$ (reference mean length small) Severely overexploited: $L^{target} = 1.05\ L^{REF}$ (reference mean length very small)	• Same as reference catch for Status Quo • Mean length of fish caught assumed an indirect index of abundance • Relative stock status is known to determine an appropriate target mean length • w = 0.5 allows for relatively higher rate of change when catch advice goes above L^0	Geromont and Butterworth (2014)
Length at Maturity Target	Same as Length Target except L^0 = 0.9 L50 (length at 50% maturity), and L^{target} = L95 (length at 95% maturity)	• Same as reference catch for Status Quo • Mean length of fish caught assumed an indirect index of abundance	Geromont and Butterworth (2014), Carruthers and Hordyk (2016)
	Multi-indicator method		
Multi-indicator	$\text{Catch Rec}_{y+1} = C^{REF} \times (1 + (\text{AddCat+AddML+AddInd}) \times 0.1)$, where $\text{AddCat} = +1/3 \text{ if } \text{Cat}_y > (C^{REF} + C^{SD})$ $= -1/3 \text{ if } \text{Cat}_y < (C^{REF} - C^{SD})$ $= 0 \text{ otherwise}$ $\text{AddML} = +1/3 \text{ if } L_y > (L^{REF} + L^{SD})$ $= -1/3 \text{ if } L_y < (L^{REF} - L^{SD})$ $= 0 \text{ otherwise}$ $\text{AddInd} = +1/3 \text{ if } \text{Ind}_y > (I^{REF} + I^{SD})$ $= -1/3 \text{ if } \text{Ind}_y < (I^{REF} - I^{SD})$ $= 0 \text{ otherwise}$, where Cat_y, L_y, and Ind_y represent terminal year's catch, mean length, and index, respectively, REF refers to conditions during the reference period, and SD refers to the standard deviation	• Same as reference catch for Status Quo • Trend in the index is a reliable indicator of the trend in resource biomass • Mean length of fish caught assumed an indirect index of abundance	Harford et al. (2016)

TABLE A.1.2. Data inputs required for management strategy evaluation. An asterisk indicates that the parameter was sampled from a lognormal distribution with a coefficient of variation.

Input	Description
	Life history
MaxAge	Maximum age (no plus group)
R0	Magnitude of unfished recruitment (scaling factor)
M	Natural mortality rate
*M*sd	Interannual variability in *M* (as coefficient of variation [CV])
*M*grad	Mean temporal trend in *M* (percent change per year)
h	Recruitment compensation (steepness)
SRrel	Type of stock–recruitment relationship (1 = Beverton–Holt, 2 = Ricker)
Linf	Asymptotic length (von Bertalanffy)
Linfsd	Interannual variability in Linf (as CV)
Linfgrad	Mean temporal trend in Linf (percent change per year)
K	Maximum growth rate (von Bertalanffy)
*K*sd	Interannual variability in *K* (as CV)
*K*grad	Mean temporal trend in *K* (percent change per year)
vbt0	Theoretical age at length zero (von Bertalanffy)
a	Length–weight parameter *a*
b	Length–weight parameter *b*
D	Current level of stock depletion (ratio of current to unfished biomass); estimated using “ML2D” function in DLMtool, where possible
L50	Length at which 50% of individuals are mature
L50_95	Length increment from 50% to 95% maturity (L95 – upper L50, L95 – lower L50)
Perr	Process error in recruitment deviations
AC	Autocorrelation in recruitment deviations
Frac_area_1	Fraction of unfished biomass in area 1 at start of simulation
Prob_ staying	Probability that individuals in area 1 stay there in year
	Fleet
nyears	Number of years for historical simulation, set as close as possible to the length of time that the fishery has been exploited
Spat_targ	Distribution of fishing in relation to spatial biomass; 1 = fishers are indiscriminate in where they fish (e.g., bycatch species), >1 indicates targeting areas of higher biomass
LFS	Length at full selection (LFS/L50) for representative fleet
L5	Length at 5% selectivity (length at first capture [LFC]/L50) for representative fleet
Vmaxlen	Vulnerability of oldest age-class to representative fleet (controls extent of dome-shaped selectivity)
Fsd	Interannual variability in *F*, determines how much *F* fluctuates from year to year
Eff	Index of relative fishing effort
	Observation
LenMcv	Bias in length at 50% maturity
Cbiascv	Bias in observed catch
Cobs	Lognormal catch observation error
CAA_nsamp	Number of catch-at-age observations per time step
CAA_ESS	Effective sample size
CAL_nsamp	Number of catch-at-length observations per time step
CAL_ESS	Effective sample size
CALcv	Lognormal variability in length at age
Iobs	Observation error in relative abundance index (as a CV)
Mcv	Bias in *M**
Linfcv	Bias in Linf*
Kcv	Bias in *K**

TABLE A.1.2. Continued.

Input	Description
t0cv	Bias in t0*
LFCcv	Bias in length at first capture*
LFScv	Bias in length at full selection*
B0cv	Bias in unfished biomass*
FMSYcv	Bias in FMSY*
FMSY_Mcv	Bias in FMSY/*M**
BMSY_B0cv	Bias in BMSY/B0*
rcv	Bias in intrinsic rate of increase*
Dbiascv	Bias in stock depletion*
Dcv	Imprecision in stock depletion among years (as a CV)
Btbias	Bias in current stock biomass*
Btcv	Imprecision in current stock biomass (as a CV)
Fcurbiascv	Bias in current *F* sampled from a lognormal distribution with a CV
Fcurcv	Imprecision in current *F* among years (as a CV)
hcv	Bias in knowledge of steepness
Reccv	Bias in recent recruitment strength
Irefcv	Bias in relative abundance index at BMSY
Crefcv	Bias in MSY
Brefcv	Bias in BMSY
beta	Parameter controlling hyperstability (<1) or hyperdepletion (>1)

TABLE A.1.3. Management strategy evaluation inputs for Puerto Rico Yellowtail Snapper. Parameters are as defined in Table A.1.2.

Input (value)	Source
	Life history
MaxAge	Maximum age observed (Brazil, commercial gear; Araújo et al. 2002)
R0 (1,000)	Normally fixed to some arbitrary value since it simply scales the simulated numbers (Carruthers and Hordyk 2016)
M	*Lower bound*: 25th percentile of *M* estimates from various methods available; *upper bound*: *M* estimate from the updated Hoenig equation (note: 75th percentile would be 0.32)
*M*sd (0–5%)	Range for South Atlantic Red Snapper *Lutjanus campechanus* (Carruthers et al. 2014)
*M*grad (±25%)	Range for South Atlantic Red Snapper (Carruthers et al. 2014)
h	Range in past Yellowtail Snapper assessments in the southeastern USA (Muller et al. 2003; O'Hop et al. 2012) and U.S. Caribbean (SEDAR 2005). See Table 3.2.9 in SEDAR (2016a)
SRrel	Relationship assumed in past assessments (Muller et al. 2003; SEDAR 2005; O'Hop et al. 2012)
Linf	*Lower bound*: derived from fishery-dependent (commercial, recreational) and fishery-independent (reef fish visual census) gears in Puerto Rico (Ault et al. 2008); *upper bound*: derived from commercial gears in Puerto Rico (SEDAR 2005)
Linfsd (15−20%)	Level of plasticity in growth that can be commonly expected in wild populations (Lorenzen 2016)
Linfgrad (±25%)	Range for South Atlantic Red Snapper (Carruthers et al. 2014)
K	*Lower bound*: derived from commercial gears in Puerto Rico (SEDAR 2005); *upper bound*: derived from fishery-dependent (commercial, recreational) and fishery-independent (reef fish visual census) gears in Puerto Rico (Ault et al. 2008)
*K*sd (0–2.5%)	Range for South Atlantic Red Snapper (Carruthers et al. 2014)
*K*grad (±25%)	Range for South Atlantic Red Snapper (Carruthers et al. 2014)

TABLE A.1.3. Continued.

Input (value)	Source
vbt0	*Lower bound*: derived from fishery-dependent (commercial, recreational) and fishery-independent (reef fish visual census) gears in Puerto Rico (Ault et al. 2008); *upper bound*: derived from hook-and-line and trap gears in U.S. Caribbean (Manooch and Drennon 1987); range encompasses Puerto Rico estimate of –1.83 obtained from commercial gears (SEDAR 2005)
a	SEAMAP hook-and-line survey data from Puerto Rico (SEDAR 2016a; N. Pena, Puerto Rico Department of Natural and Environmental Resources, unpublished)
b	SEAMAP hook-and-line survey data from Puerto Rico (SEDAR 2016a; Pena, unpublished)
D	Estimate using current mean length and catch-at-size reduction analysis
L50	*Lower and upper bounds*: commercial and research survey collections in Puerto Rico (Figuerola et al. 1997; SEDAR 2005)
L50_95	L95 = ~300 mm FL from commercial and research survey collections in Puerto Rico (Figuerola et al. 1997; SEDAR 2005)
Perr	Range for South Atlantic Red Snapper (Carruthers et al. 2014)
AC	Typical range (Carruthers and Hordyk 2016; McNamee et al. 2016; Miller 2016)
Frac_area_1 (0.095–0.105)	Maintain biomass in area 2, mimic single unit stock
Prob_staying (0.5–0.6)	Range for South Atlantic Red Snapper (Carruthers et al. 2014)
	Fleet
nyears	Commercial fishing first documented in 1899 (350 vessels, 800 fishers), although it was not carried out to any large extent (Cummings and Matos-Caraballo 2003)
Spat_targ (1.0–1.5)	>1 to account for active targeting behavior
LFS (280 mm)	Addenda in SEDAR (2016a)
L5 (190 mm)	Section 2.6 in SEDAR (2016a)
Vmaxlen	Asymptotic based on consensus among fishers and SEDAR 46 panelists (SEDAR 2016a)
Fsd	Range of interannual variability in annual *F* for the dominant fleet (“representative”) based on SEDAR 46 (SEDAR 2016a) mean length estimator analysis (*Z* range = 0.26–0.56, *M* point estimate = 0.33/year)
Eff	Section 2.1.2.2 in SEDAR (2016a)
	Observation
LenMcv	No information available; using default for imprecise, biased (Carruthers and Hordyk 2016), also used for Blueline Tilefish *Caulolatilus microps* (Miller 2016)
Cbiascv	No CV provided by SEDAR 46 (SEDAR 2016a) data providers for the catch series; CV calculated as the SD/mean for the catch time series and *assumed* an accurate proxy
Cobs	Range of CV to two times the CV assumed appropriate to account for large uncertainty
CAA_nsamp (150–200)	Based on annual age composition observations desired (up to 200) for assessment of Yellowtail Snapper in the southeastern USA (O’Hop et al. 2012)
CAA_ESS (10–25)	Based on estimated effective sample size for age-based assessment of Yellowtail Snapper in the southeastern USA (O’Hop et al. 2012)
CAL_nsamp (150–200)	Range assumed similar to CAA_nsamp range
CAL_ESS (10–25)	Range assumed similar to CAA_ESS range
CALcv	Derived from length data for the representative fleet (range of annual SD/mean estimates)
Iobs	Range of annual CV estimates from the handline index in Puerto Rico; Section 2.4.2.2 in SEDAR (2016a)
Mcv	Cross validation prediction error of the updated Hoenig equation using nonlinear least squares estimation (Then et al. 2014)
Linfcv	SE reported in Manooch and Drennon (1987)

TABLE A.1.3. Continued.

Input (value)	Source
Kcv	SE reported in Manooch and Drennon (1987)
t0cv	SE reported in Manooch and Drennon (1987)
LFCcv	Used for South Atlantic Red Snapper to reflect the difficulty in determining an appropriate value from patchy length composition data that might be available for data-limited stocks (Carruthers et al. 2014)
LFScv	Assumed similar to bias in LFC due to lack of information
B0cv (4.0)	No information available; using default for imprecise, biased (Carruthers and Hordyk 2016), also used for Blueline Tilefish (Miller 2016)
FMSYcv (0.20)	No information available; using default for imprecise, biased (Carruthers and Hordyk 2016), also used for Black Sea Bass *Centropristis striata* (McNamee et al. 2016) and Blueline Tilefish (Miller 2016)
FMSY_Mcv	From meta-analysis (Zhou et al. 2012)
BMSY_B0cv	From meta-analysis (Thorson et al. 2012)
Rcv (0.5)	Used for South Atlantic Red Snapper (Carruthers et al. 2014) and Blueline Tilefish (Miller 2016)
Dbiascv	Used for South Atlantic Red Snapper to reflect large uncertainty in stock depletion (Carruthers et al. 2014)
Dcv	No information available; using default for imprecise, biased (Carruthers and Hordyk 2016), also used for Blueline Tilefish (Miller 2016)
Btbias	No information available; using default for imprecise, biased (Carruthers and Hordyk 2016), also used for Blueline Tilefish (Miller 2016)
Btcv	No information available; using default for imprecise, biased (Carruthers and Hordyk 2016), also used for Blueline Tilefish (Miller 2016)
Fcurbiascv (0.75)	No information available; using default for imprecise, biased (Carruthers and Hordyk 2016), also used for Blueline Tilefish (Miller 2016)
Fcurcv (0.5–1.0)	No information available; using default for imprecise, biased (Carruthers and Hordyk 2016), also used for Blueline Tilefish (Miller 2016)
hcv	Determined from maximum value of absolute value of [(lower or upper range estimate–point estimate)/point estimate]
Reccv	No information available; using default for imprecise, biased (Carruthers and Hordyk 2016), also used for Blueline Tilefish (Miller 2016)
Irefcv	No information available; using default for imprecise, biased (Carruthers and Hordyk 2016), also used for Blueline Tilefish (Miller 2016)
Crefcv	No information available; using default for imprecise, biased (Carruthers and Hordyk 2016), also used for Blueline Tilefish (Miller 2016)
Brefcv	No information available; using default for imprecise, biased (Carruthers and Hordyk 2016), also used for Blueline Tilefish (Miller 2016)
beta 1–1	Fixed at 1 to remove influence of hyperstability or hyperdepletion (Carruthers and Hordyk 2016)

TABLE A.1.4. Management strategy evaluation inputs for St. Thomas–St. John Queen Triggerfish. Parameters are as defined in Table A.1.2. Parameters not shown are as reported in Table A.1.3.

Input (value)	Source
	Life history
MaxAge	Maximum age observed (Brazil; de Albuquerque et al. 2011)
M	*Lower and upper bounds*: 25th and 75th percentiles of *M* estimates from various methods available; range includes the *M* estimate from the updated Hoenig equation (0.44)
h	Range considered in past Gray Triggerfish *Balistes capriscus* assessments (South Atlantic = 0.46–0.84 [SEDAR 2016c], Gulf of Mexico = 0.35–0.80 [SEDAR 2015])

TABLE A.1.4. Continued.

Input (value)	Source
SRrel	Relationship assumed in past assessments for Gray Triggerfish (SEDAR 2015, 2016c)
Linf	*Lower bound*: trap and hook-and-line fisheries in U.S. Caribbean (Manooch and Drennon 1987); *upper bound*: SEDAR 46 (SEDAR 2016a) analysis of Trip Interview Program data from the Virgin Islands
K	*Lower bound*: bottom longline scientific survey and commercial handline in Brazil (de Albuquerque et al. 2011); *upper bound*: trap and hook-and-line fisheries in U.S. Caribbean (Manooch and Drennon 1987); range encompasses SEDAR 46 (SEDAR 2016a) point estimate of *K* (0.214), which was calculated using Rothschild et al. (1994) equation
vbt0	*Lower bound*: bottom longline scientific survey and commercial handline in Brazil (de Albuquerque 2011); *upper bound*: trap and hook-and-line fisheries in U.S. Caribbean (Manooch and Drennon 1987)
a	Caribbean and southeastern United States data (Bohnsack and Harper 1988)
b	Caribbean and southeastern United States data (Bohnsack and Harper 1988)
D	Based on current mean length and catch-at-size reduction analysis
L50	*Lower and upper bounds*: trap and handline survey in Jamaica (Aiken 1975)
L50_95	L95 = 280 mm FL from trap and handline survey in Jamaica (Aiken 1975)
AC	Typical range (Carruthers and Hordyk 2016; McNamee et al. 2016; Miller 2016)
	Fleet
nyears	Commercial fishing in U.S. Virgin Islands first documented in 1930 (405 fishers, 1,880 estimated traps; Kojis and Quinn 2006)
LFS (300 mm)	Addenda in SEDAR (2016a)
L5 (225 mm)	Section 2.6 in SEDAR (2016a)
Vmaxlen	Dome-shaped based on consensus among fishers and SEDAR 46 panelists (SEDAR 2016a)
Fsd	Typical range (Carruthers and Hordyk 2016); range of interannual variability in annual *F* for the dominant fleet ("representative") based on SEDAR 46 (SEDAR 2016a) mean length estimator analysis (*Z* range = 1.34, *M* point estimate = 0.44/year) not used to due concerns over analysis
Eff	Section 2.1.2.3 in SEDAR (2016a)
	Observation
Cbiascv	No CV provided by SEDAR 46 (SEDAR 2016a) data providers for the catch series; CV calculated as the SD/mean for the catch time series and *assumed* an accurate proxy
Cobs	Range of CV to two times the CV assumed appropriate to account for large uncertainty
CAA_nsamp (150–200)	Range based on annual age composition observations desired (up to 200) for assessment of Gray Triggerfish in the Gulf of Mexico (SEDAR 2015)
CAA_ESS (10–20)	Range based on estimated effective sample size for age-based assessment of Gray Triggerfish in the southeastern USA (SEDAR 2015)
CAL_nsamp (150–200)	Range assumed similar to CAA_nsamp range
CAL_ESS (10–20)	Range assumed similar to CAA_ESS range
CALcv	Derived from length data for the representative fleet (range of annual SD/mean estimates)
Iobs	Range of annual CV estimates from the trap index in St. Thomas; Section 2.4.2.3 in SEDAR (2016a)
Linfcv	Imputed by SEDAR 46 Life History Working Group (LHWG) (SEDAR 2016a)
Kcv	Imputed by SEDAR 46 LHWG (SEDAR 2016a)
t0cv	Imputed by SEDAR 46 LHWG (SEDAR 2016a)
hcv	Determined from maximum value of absolute value of [(lower or upper range estimate − point estimate)/point estimate]

TABLE A.1.5. Management strategy evaluation inputs for St. Croix Stoplight Parrotfish. Parameters are as defined in Table A.1.2. Parameters not shown are as reported in Table A.1.3.

Input (value)	Source
	Life history
MaxAge	Assigned by SEDAR 46 Life History Working Group (LHWG) based on expert opinion (SEDAR 2016a)
M	*Lower and upper bounds*: 25th and 75th percentiles of *M* estimates from various methods available; range includes the *M* estimate from the updated Hoenig equation (0.50)
h	No family level information available, using range from Rose et al. (2001) and Myers et al. (1999)
SRrel	No information available, assume more common relationship
Linf	*Lower bound*: spear and fence net survey collections in Barbados (Choat et al. 2003); *upper bound*: estimated using size at maximum age from Puerto Rico Trip Interview Program and South Florida Reef Visual Census (Lmax = 0.95 Linf) by LHWG
K	*Lower bound*: Estimated using Rothschild et al. (1994) equation; *upper bound*: spear and net survey collections in Barbados (Paddack et al. 2009)
vbt0	*Lower bound*: spear and fence net survey collections in Panama (Choat and Robserton 2002), in Bahamas (Choat et al. 2003), in Venezuela (Choat et al. 2003), and spear and net survey collections in the Florida Keys (Paddack et al. 2009); *upper bound*: LHWG point estimate
a	Caribbean and southeastern United States data (Bohnsack and Harper 1988)
b	Caribbean and southeastern United States data (Bohnsack and Harper 1988)
D	No estimates available, assume broad range
L50	*Lower bound*: unspecified collection type in Bermuda (Reeson 1975); *upper bound*: commercial and research survey collections in Puerto Rico (Figuerola et al. 1997)
L50_95	L95 = ~240 mm FL from commercial and research survey collections in Puerto Rico (Figuerola et al. 1997)
AC	Typical range (Carruthers and Hordyk 2016; McNamee et al. 2016; Miller 2016)
	Fleet
nyears	Commercial fishing using diving gear not documented in U.S. Virgin Islands during 1930 or 1967 (Kojis and Quinn 2006); assume fishing for parrotfish (Scaridae) began after decline of snappers (Lutjanidae) and groupers (Epinephelidae) in the 1970s (Jackson et al. 2014)
LFS (270 mm)	Addenda in SEDAR (2016a)
L5 (225 mm)	Section 2.6 in SEDAR (2016a)
Vmaxlen	Asymptotic based on consensus among fishers and SEDAR 46 panelists (SEDAR 2016a)
Fsd	Typical range (Carruthers and Hordyk 2016)
Eff	Section 2.1.2.6 in SEDAR (2016a)
	Observation
Cbiascv	No CV provided by SEDAR 46 (SEDAR 2016a) data providers for the catch series; CV calculated as the SD/mean for the catch time series and *assumed* an accurate proxy
Cobs	Range of CV to two times the CV assumed appropriate to account for large uncertainty
CAA_nsamp (50–100)	No information available; using default for imprecise, biased (Carruthers and Hordyk 2016), also used for Blueline Tilefish (Miller 2016)
CAA_ESS (10–20)	No information available; using default for imprecise, biased (Carruthers and Hordyk 2016), also used for Blueline Tilefish (Miller 2016)
CAL_nsamp (50–100)	No information available; using default for imprecise, biased (Carruthers and Hordyk 2016), also used for Blueline Tilefish (Miller 2016)
CAL_ESS (10–20)	No information available; using default for imprecise, biased (Carruthers and Hordyk 2016), also used for Blueline Tilefish (Miller 2016)
CALcv	Derived from length data for the representative fleet (range of annual SD/mean estimates)
Iobs	Range of annual CV estimates from the diving index in St. Croix; Section 2.4.2.6 in SEDAR (2016a)
Linfcv	Recommendation of LHWG (SEDAR 2016a)
Kcv	Recommendation of LHWG (SEDAR 2016a)
t0cv	Recommendation of LHWG (SEDAR 2016a)
hcv	Determined from maximum value of absolute value of [(lower or upper range estimate − point estimate)/point estimate]

Appendix 2: Management Strategy Evaluation Results for Different Configurations of CPUE Target and Length Target Based on Assumed Stock Status during the Reference Period

Method	PNOF	B50	AAVY15	B20	LTY	STY
	Performance Metric (%)					
Puerto Rico Yellowtail Snapper						
CPUE Target (severely overexploited)	76	83	76	95	34	37
CPUE Target (overexploited)	68	78	65	92	37	43
CPUE Target (near optimum)	61	72	56	89	40	50
CPUE Target (underexploited)	55	68	48	87	42	54
Length Target (severely overexploited)	75	82	73	94	32	37
Length Target (overexploited)	73	80	70	93	34	40
Length Target (near optimum)	72	80	68	93	37	43
Length Target (underexploited)	70	79	67	93	39	45
St. Thomas-St. John Queen Triggerfish						
CPUE Target (severely overexploited)	82	82	76	94	34	37
CPUE Target (overexploited)	78	80	71	92	36	40
CPUE Target (near optimum)	71	76	59	90	41	48
CPUE Target (underexploited)	58	69	43	86	49	60
Length Target (severely overexploited)	67	73	55	87	43	52
Length Target (overexploited)	65	72	54	87	42	52
Length Target (near optimum)	60	70	45	85	46	57
Length Target (underexploited)	56	67	39	84	48	61

FIGURE A.2.1. Performance metrics for different configurations of CPUE Target and Length Target based on assumed stock status during the reference period. Note that these methods were not feasible for St. Croix Stoplight Parrotfish due to data limitations. Methods are as defined in Table 3 and detailed in Table A.1.1. Performance metrics (defined in the text) to the left of the vertical line must exceed the 50% threshold. A gradation color scheme from dark (i.e., low metric, red online) to light (high metric, green online) is used to highlight differences within metrics for each species.