Fishery-Independent Reef Fish Visual Survey Population Density and Length Composition for Queen Triggerfish in the U.S. Caribbean

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SEDAR80-WP-08

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Fishery-Independent Reef Fish Visual Survey Population Density and Length Composition for Queen Triggerfish in the U.S. Caribbean

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Fishery-independent size-structure and density estimates for Queen Triggerfish are compiled from the following data:

1. National Coral Reef Monitoring Program's (NCRMP) Reef fish Visual Census Metadata for the U.S. Caribbean (SEDAR80-WP-02)
    a. Historic belt-transect (BT) estimates (2001–2015)
    b. Present reef visual census stationary point count (RVC-SPC) estimates (2016–2019)

Parameters for data prepared for SEDAR80 fishery-independent reef fish visual survey data:

Species: Queen Triggerfish
Year Range: 2001 to 2019
Geographic Range: U.S. Caribbean including Puerto Rico, St. Thomas/St. John, and St. Croix.
Survey Design: Stratified-random sampling on hard-bottom coral reef habitats from 0 to 30 m.
Sampling Mode: Fishery-independent reef fish visual surveys.

Survey Methodology: Fully calibrated estimates that take into account the change in sampling methodology from Belt Transects (BT) to RVC Stationary Points Counts (RVC-SPC) to allow for multi-decadal evaluations.
Survey Dataset Names:
Caribbean_QTrigger_Abundance_at_Length.xlsx
Caribbean_QT_Density_AllStages.xlsx
Caribbean_QT_Density_AdultJuvenile.xlsx
Caribbean_QT_Density_Strat_AllStages.xlsx
Caribbean_QT_Density_Strat_AdultJuvenile.xlsx

Overview
This document outlines the data and methodologies used to estimate density and abundance-at-length compositions for the SEDAR80 Caribbean Queen Triggerfish Assessment for Puerto Rico, St. Thomas/St. John, and St. Croix.

For more background details about the reef visual survey program (historic and NCRMP), methodology, data, and sampling coverage including maps of all survey sites completed by year (2001–2019) in each U.S. Caribbean sampling domain (Puerto Rico, St. Thomas/St. John, and St. Croix) see SEDAR80-WP-02 (Grove et al. 2021).

Calibration
Two levels of calibration were needed to incorporate historical transect data. First, we analyzed the regionally restricted transect data from 2001 to 2013 in La Parguera in Puerto Rico and National Parks in St. Thomas/John and St. Croix and the more recent island-wide data from 2015 to 2019. We determined that similar density distributions existed within strata between the regional data and whole island-wide data, and that each strata was represented in the sampling for proper area weighting. Secondly, a robust method calibration was conducted to convert belt transect (BT) densities (2001–2015) to RVC stationary point count (RVC-SPC) densities (2017–2019). In short, paired BT and RVC-SPC sampling was conducted a number of times within each survey strata. Density and occurrence were modeled in a two-stage GLM regression using a "delta" framework for estimation of the gear correction (method calibration) factors. The method calibration factor was then applied to the BT dataset prior to any domain level estimations (Ault et al. 2020). For more details, see Appendix I.

Analyses
Domain-wide density and variance estimates were calculated using standard stratified random design-based principles (Smith et al. 2011). Metric estimates and associated variance were computed in each strata and multiplied by the stratum weighting factor. Area weighted stratum density and variance was then summed across all strata for the final domain wide estimate. All density data are presented as reef visual census stationary point count (RVC-SPC) estimates (number per 178 m^2, ±1). For more details, see Appendix II.

U.S. Caribbean

Table 1A.- Hard-bottom habitat code abbreviations and habitat names where reef fish visual surveys were collected in the U.S. Caribbean coral reef ecosystem. Shaded habitats (rows) were combined for analyses: AGRF & BDRK (dark gray) and PVMT & SCR (light gray).

Habitat Code	Habitat Name
AGRF	Aggregate Reef
BDRK	Bedrock
PTRF	Patch Reef (Aggregate and Individual)
PVMT	Pavement
SCR	Scattered Coral and Rock

Table 1B.- Depth code abbreviations, depth name, and depth range (m) where reef fish visual surveys were collected in the U.S. Caribbean coral reef ecosystem.

Depth Code	Depth Name	Range (m)
SHLW	Shallow	0 to < 12m
DEEP	Deep	≥ 12 to 30m

Table 2.- Percent of U.S. Caribbean sampling domain area (i.e., Puerto Rico, St. Thomas/St. John, and St. Croix) within each analysis strata (strata code).

Strata Code	Puerto Rico	St. Thomas/John	St. Croix
AGRFSHLW	8.4	11.8	4.3
AGRFDEEP	9.3	25.2	3.8
PTRFSHLW	7.3	0.9	1.9
PTRFDEEP	4.4	3.4	1.2
PVMTSHLW	24.6	13.2	25.4
PVMTDEEP	46	45.5	63.4

Puerto Rico

Table 3.- Number of reef fish visual survey sites (left column) and number of queen triggerfish (*Balistes vetulus*) length observations (right column) by hard-bottom strata from the reef fish visual surveys in the Puerto Rico coral reef ecosystem (2001–2019). Empty cells indicate zero samples (left column) or no observations (right column).

Year	AGRFSHLW		BDRKSHLW		PTRFSHLW		PVMTSHLW		SCRSHLW		AGRFDEEP		BDRKDEEP		PTRFDEEP		PVMTDEEP		SCRDEEP		Site Total	Length Total
2001	15				6		5				2				5		3	2			36	2
2002	21	1			11		10	2			5				8		16	5			71	8
2003	18				16		5				8				15		20	3			82	3
2004	16				12		12	2			17				13		13	1			83	3
2005	17	1			7		6				20	1			14		31	3			95	5
2006	10	2			5		10	2			42	6			9	1	24	7			100	18
2007	21	2			18	3	29	12			46	10			14		45	11			173	38
2008	7				4		8	1			30	5			7	1	30	12			86	19
2009	18	4			12		8	2			42	15			5	1	31	10			116	32
2010	13				1	1	14	5			12	1			10	5	24	7			74	19
2011	6				3		10	3			3				5		24	12			51	15
2012	1				1		8	3			11	3			2	1	12	4			35	11
2014	45	4			19	9	42	5			46				20	13	51	18			223	49
2016	24	10	7		14	5	38	12	8		48	16	2	3	27	15	57	64	15	14	240	139
2019	38	20	10	3	16		28	25	9	2	42	47	1	2	16	13	27	48	16	7	203	167

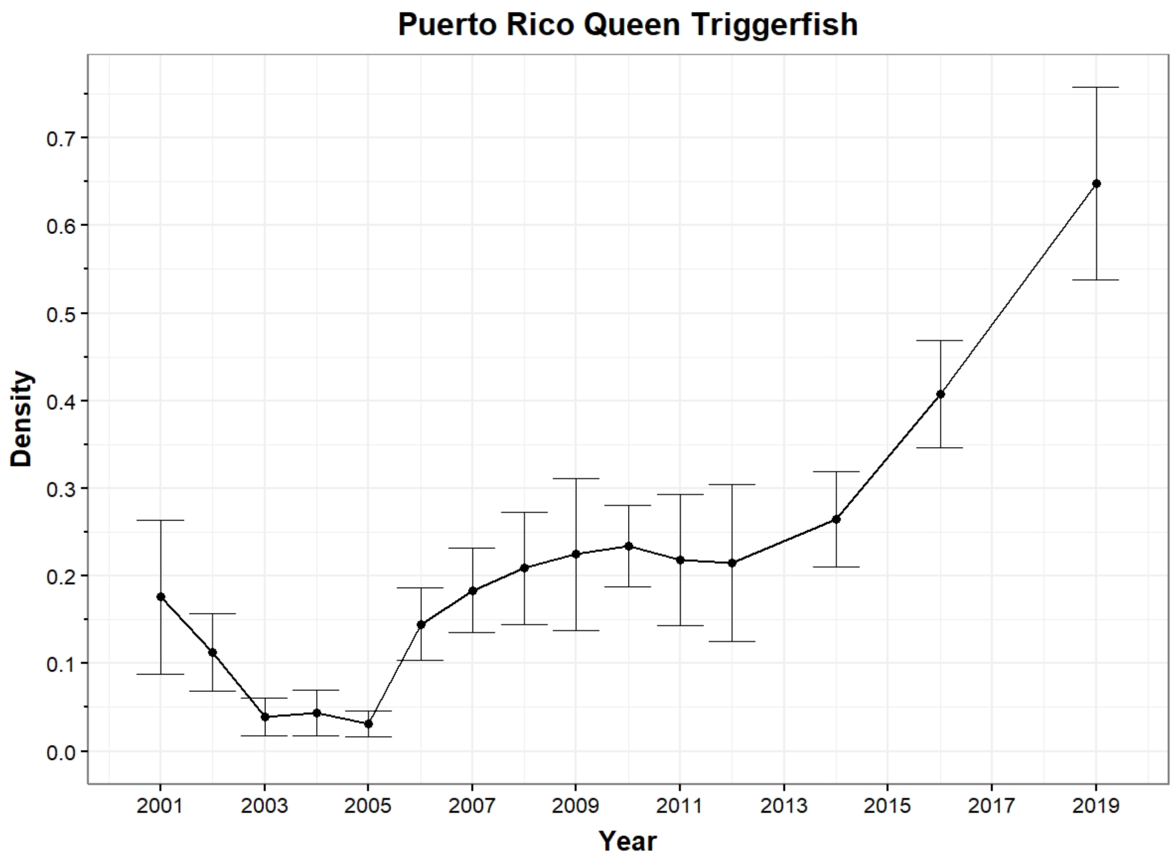

Figure 1.- Time series (2001–2019) of queen triggerfish (*Balistes vetulus*) mean population density (number per 178 m^2, ±1 *se*) from the reef fish visual surveys in the Puerto Rico coral reef ecosystem.

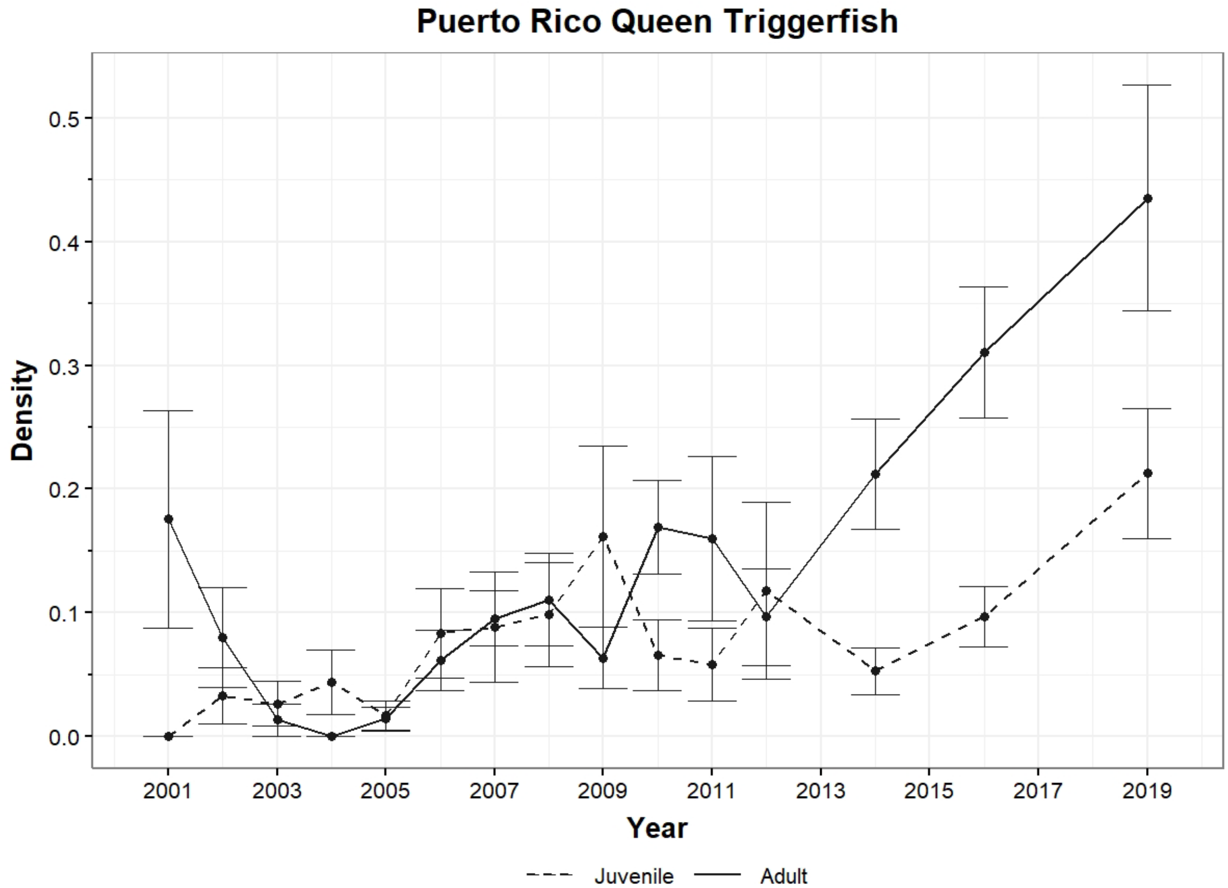

Figure 2.- Time series (2001–2019) of juvenile (dashed line, < 21.4 cm) and adult (solid line, ≥ 21.4 cm) queen triggerfish mean population density (number per 178 m^2, ±1 *se*) from the reef fish visual surveys in the Puerto Rico coral reef ecosystem. Length at first maturity (21.4 cm fork length) from SEDAR80 working paper by Shervette and Rivera-Hernandez (2022).

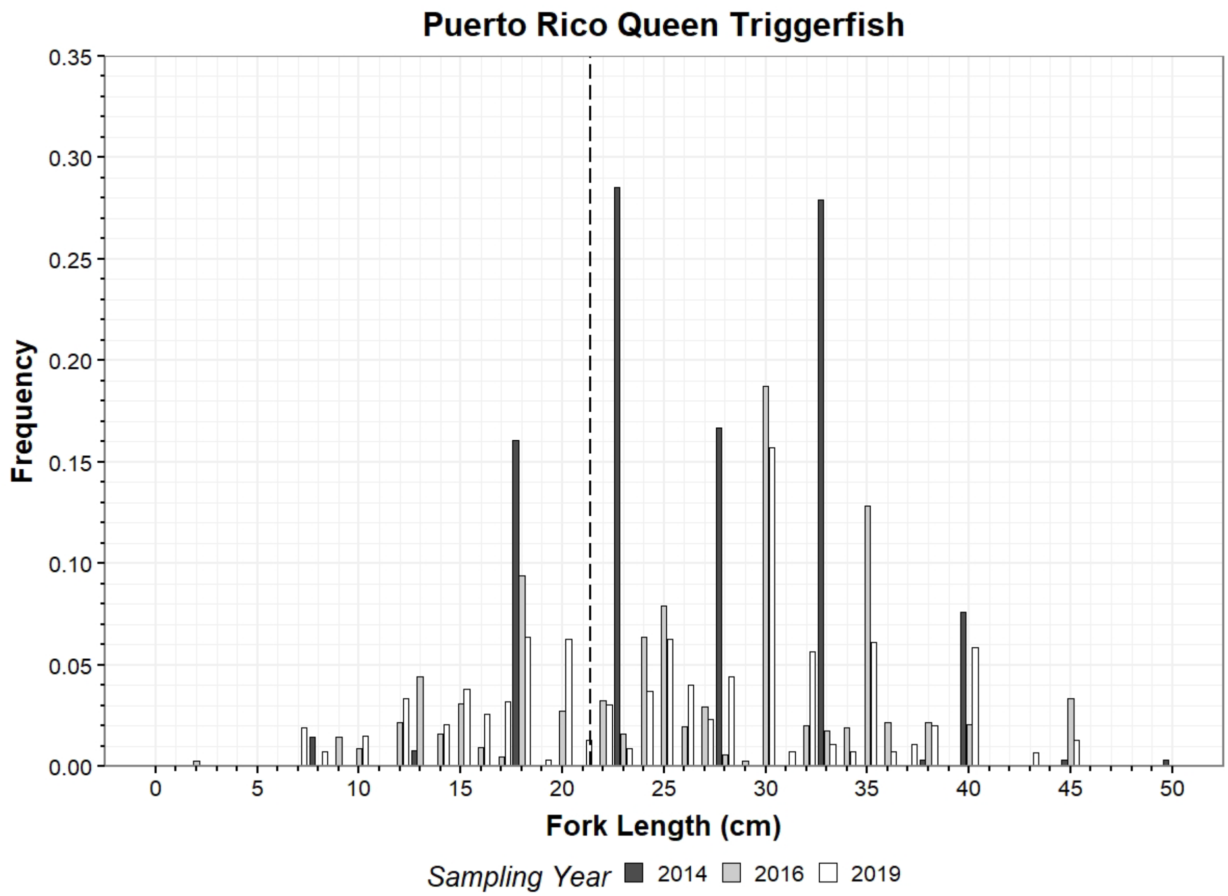

Figure 3.- Queen triggerfish population size-frequency distribution at 1-cm bins from the NCRMP RVC-SPC for the 2014 (n = 49), 2016 (n = 139), and 2019 (n = 167) Puerto Rico surveys. Vertical dashed line is length at first maturity (21.4 cm fork length).

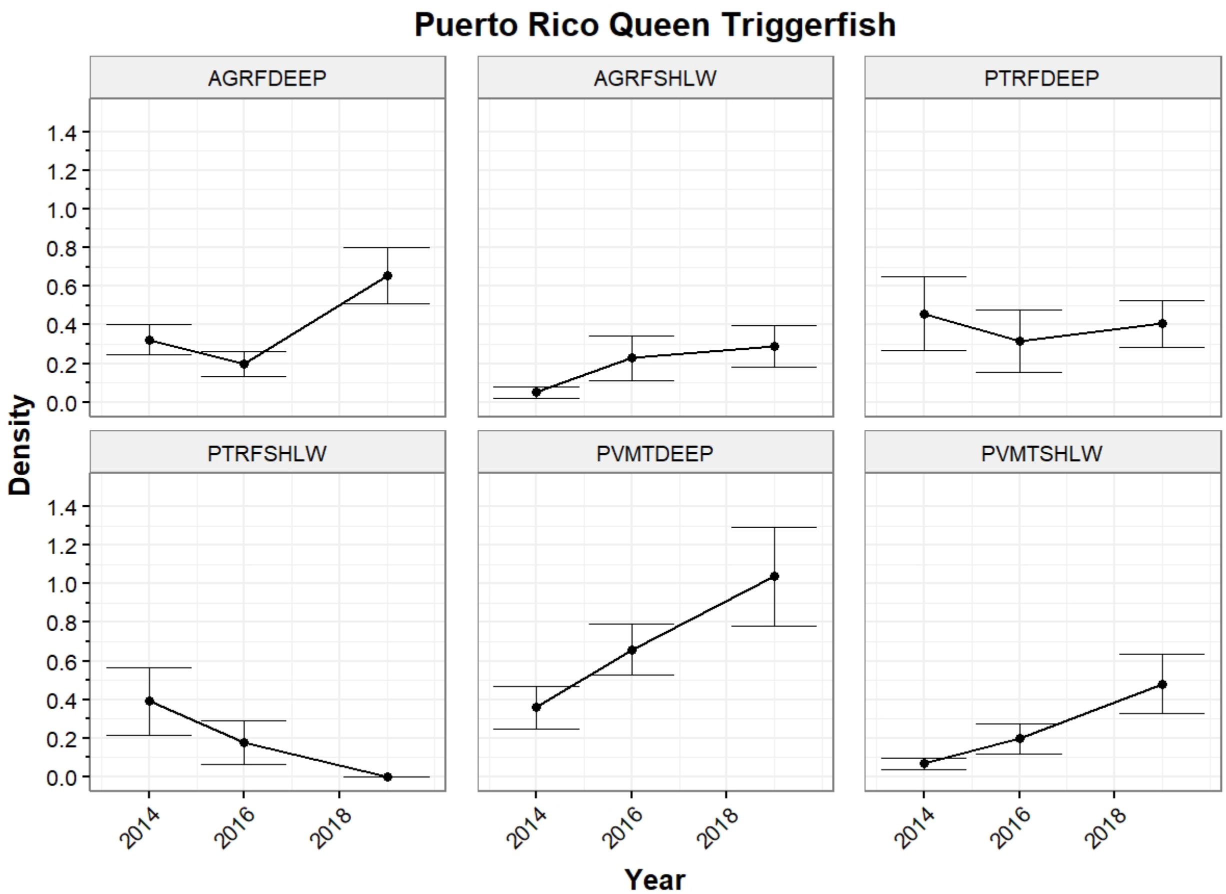

Figure 4.- Habitat stratum specific queen triggerfish population density (number per 178 m^2, ± 1 *se*) from the NCRMP for the 2014, 2016, and 2019 Puerto Rico coral reef ecosystem surveys.

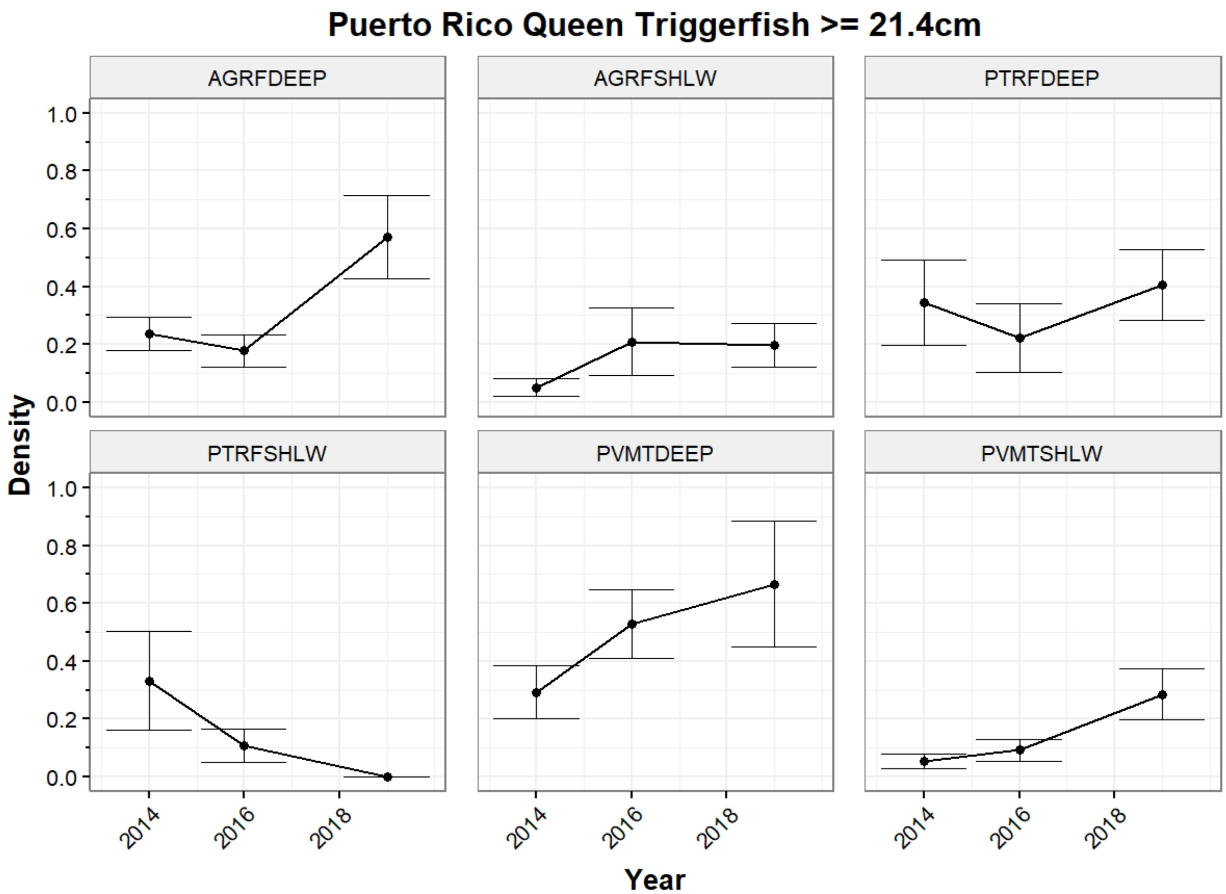

Figure 5.- Habitat stratum specific mature queen triggerfish population density (number per 178 m^2, ±1 *se*) for fish ≥ 21.4 cm from the NCRMP RVC-SPC for the 2014, 2016, and 2019 Puerto Rico coral reef ecosystem surveys.

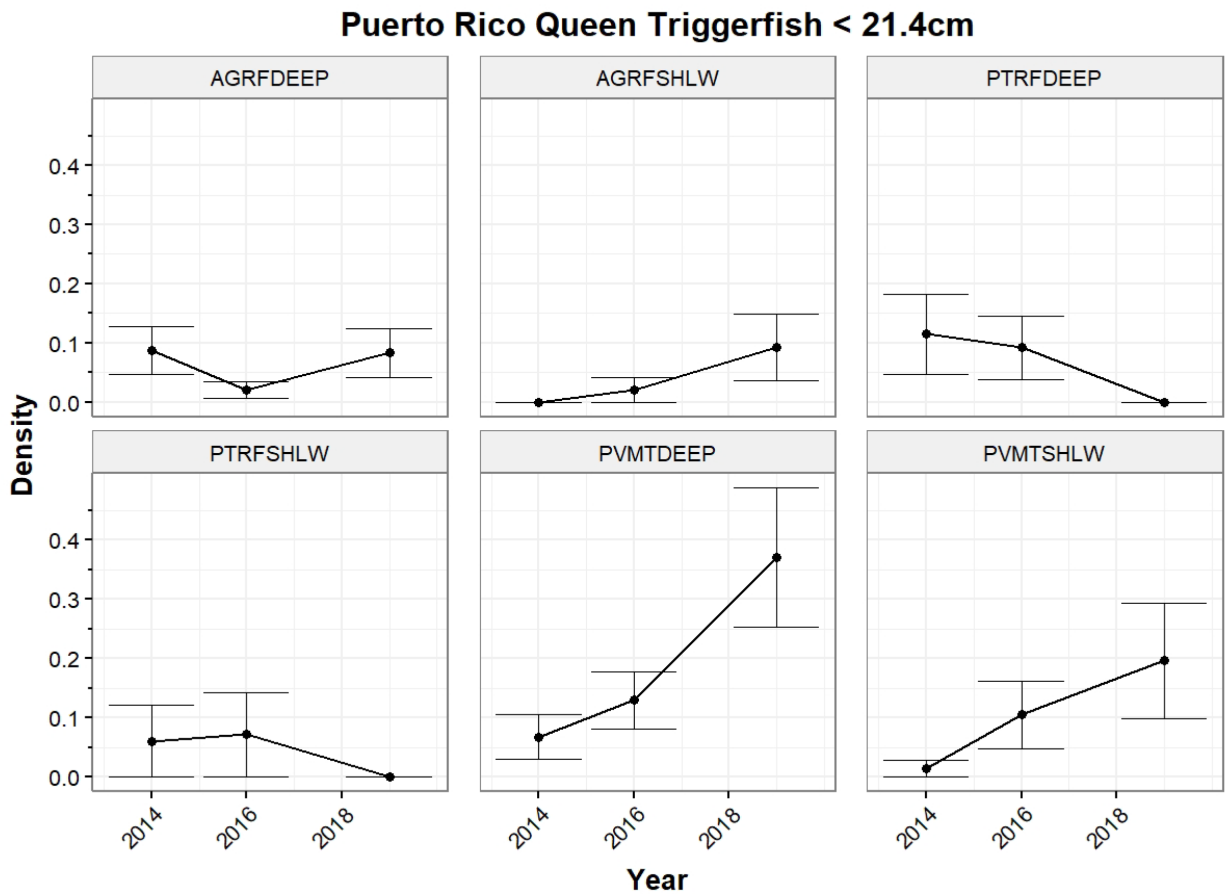

Figure 6.- Habitat stratum specific immature queen triggerfish population density (number per 178 m^2, ± 1 *se*) for fish < 21.4 cm from the NCRMP RVC-SPC for the 2014, 2016, and 2019 Puerto Rico coral reef ecosystem surveys.

St. Thomas/St. John

Table 4.- Number of reef fish visual survey sites (left column) and number of queen triggerfish (*Balistes vetulus*) length observations (right column) by hard-bottom strata from the reef fish visual surveys in the St. Thomas/St. John coral reef ecosystem (2001–2019). Empty cells indicate zero samples (left column) or no observations (right column).

Year	AGRFSHLW		BDRKSHLW		PTRFSHLW		PVMTSHLW		SCRSHLW		AGRFDEEP		BDRKDEEP		PTRFDEEP		PVMTDEEP		SCRDEEP		Site Total	Length Total
2001	6				1		9				2				1		6				25	0
2002	20	2			4		20	1			2						26	17			72	20
2003	22	2			8	1	28	5			22	15			3		26	25			109	48
2004	26	3			4		24	1			35	14			5		34	20			128	38
2005	32				9		19				30	14			6		32	16			128	30
2006	36	1			2		12				43	16			14	2	20	11			127	30
2007	39	2			5		16				41	23			9	2	19	2			129	29
2008	18				9		19	1			43	20			15	2	30	4			134	27
2009	33	1			13		11	1			46	30			9		20	11			132	43
2010	26	1			6		29	1			28	10			12	1	33	12			134	25
2011	32	1			9		20				43	46			11	13	18				133	60
2013	59	1			13		46				77	24			20	7	60	9			275	41
2015	34	1			17		40	6			63	25			29	9	72	18			255	59
2017	36	1	22	1	13	1	7		5		68	42	3	1	19	19	38	21	26	8	237	94
2019	49	12	39	10	13		19	1	14		88	143	4	2	32	49	36	24	28	10	322	251

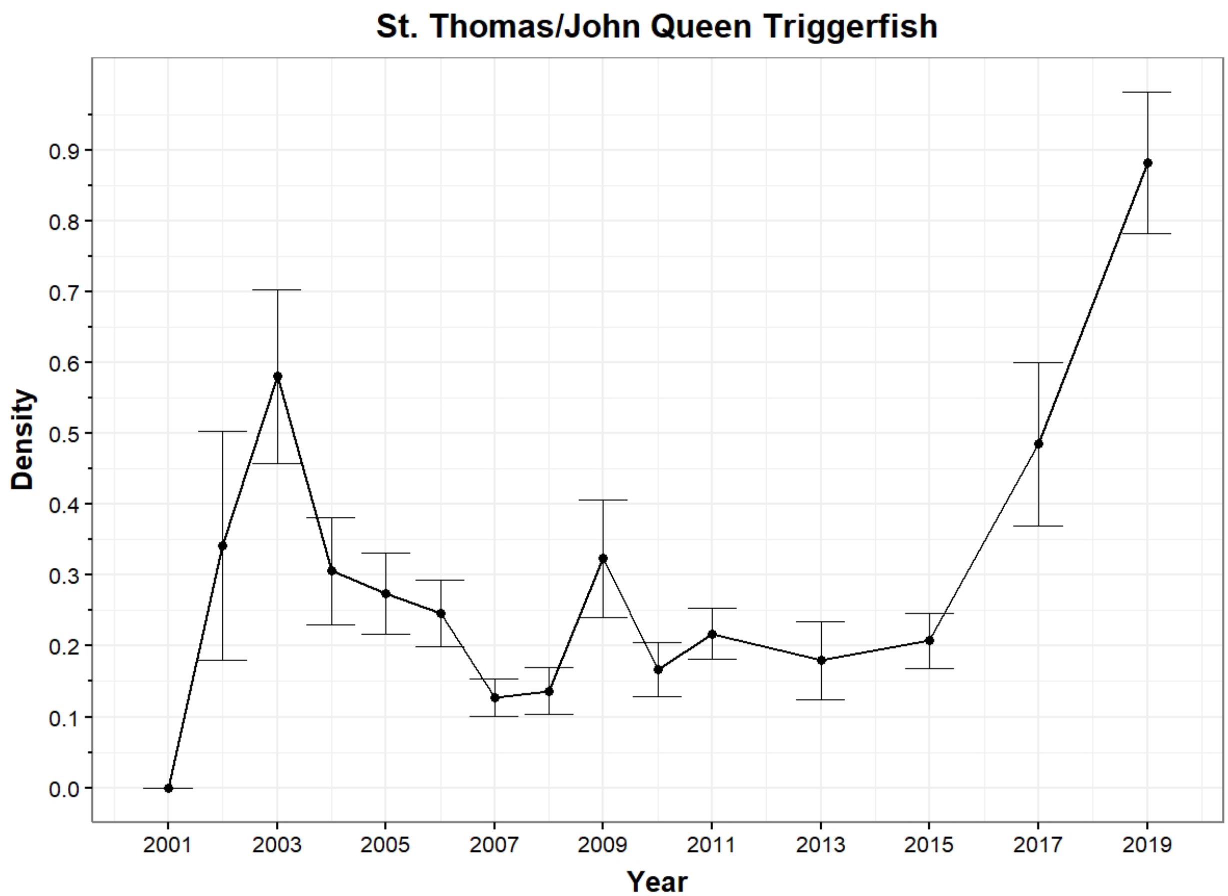

Figure 7.- Time series (2001–2019) of queen triggerfish (*Balistes vetulus*) mean population density (number per 178 m^2) and error (± 1 *se*) from the reef fish visual survey in the St. Thomas/St. John coral reef ecosystem.

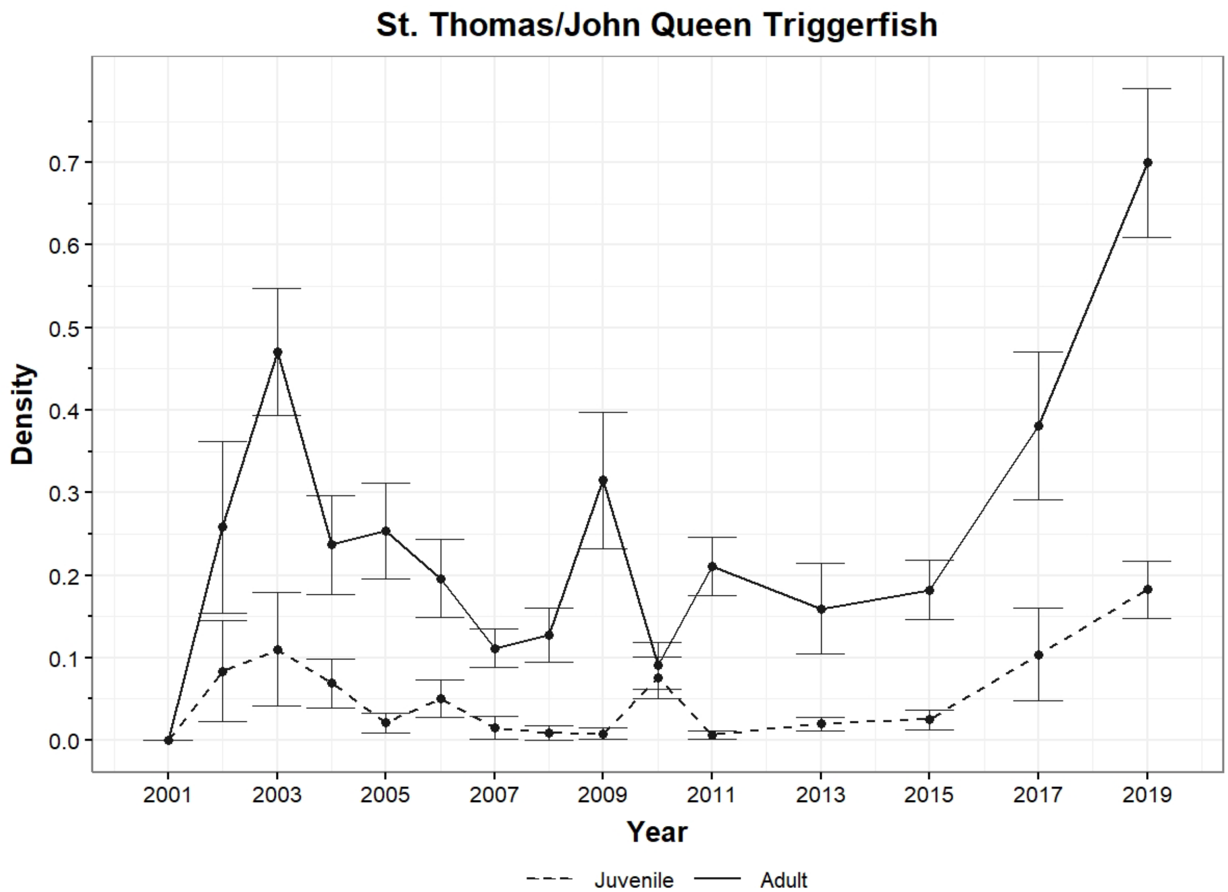

Figure 8.- Time series (2001–2019) of juvenile (dashed line) and adult (solid line) queen triggerfish mean population density (number per 178 m², ±1 *se*) from the reef fish visual survey in the St. Thomas/St. John coral reef ecosystem. Length at first maturity (21.4 cm fork length) from SEDAR80 working paper by Shervette and Rivera-Hernandez (2022).

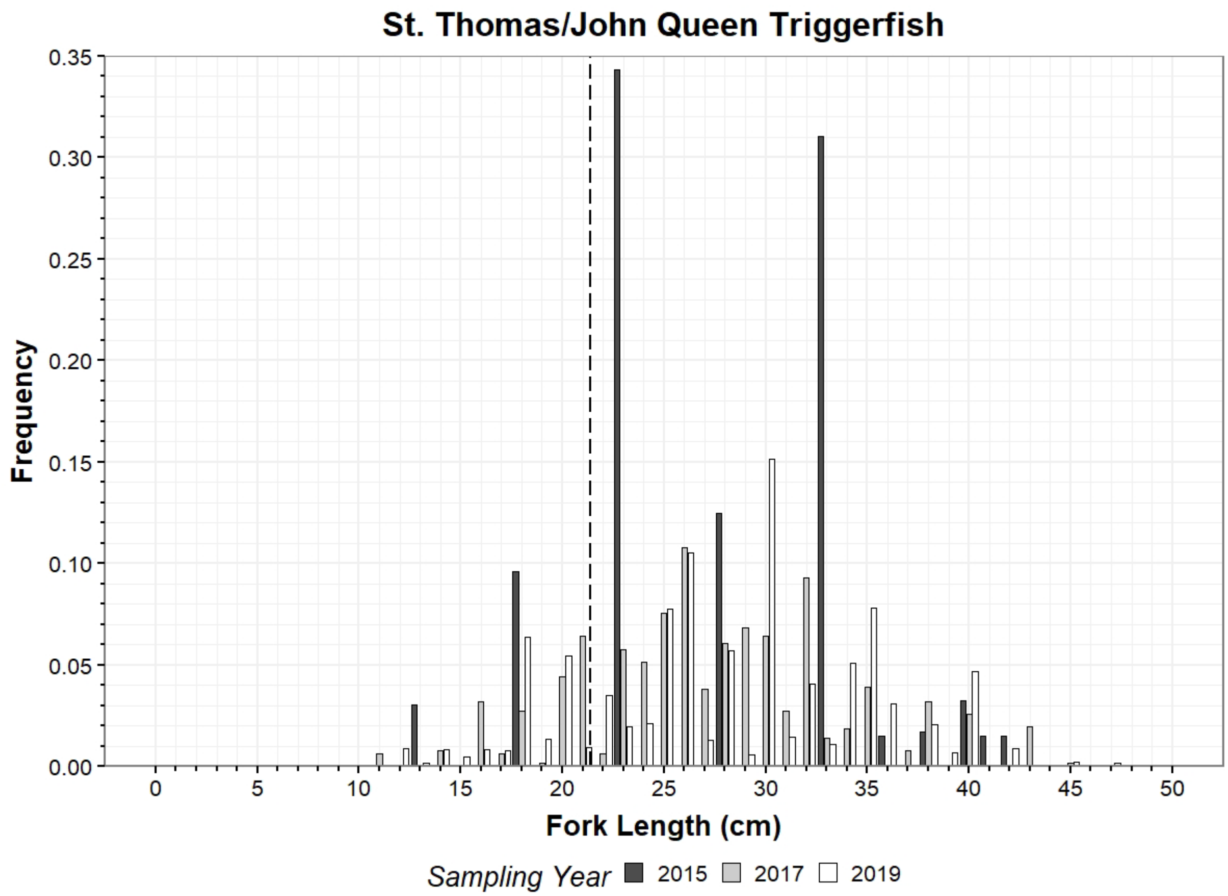

Figure 9.- Queen triggerfish population size-frequency distribution at 1-cm bins from the NCRMP RVC-SPC for the 2015 (n = 59), 2017 (n = 94), and 2019 (n = 251) St. Thomas/St. John coral reef ecosystem surveys. Vertical dashed line is length at first maturity (21.4 cm fork length).

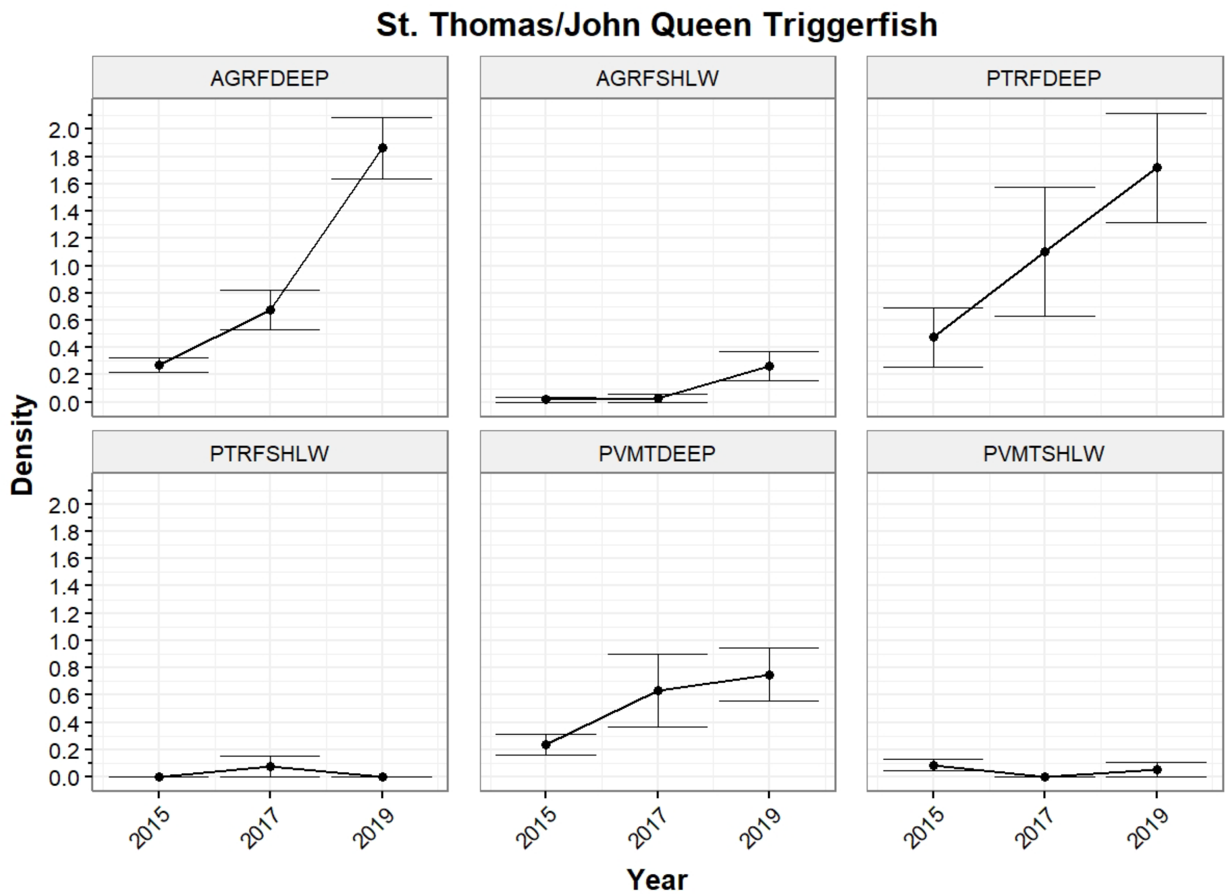

Figure 10.- Habitat stratum specific queen triggerfish population density (number per 178 m^2, ± 1 *se*) from the NCRMP RVC-SPC for the 2015, 2017, and 2019 St. Thomas/St. John coral reef ecosystem surveys.

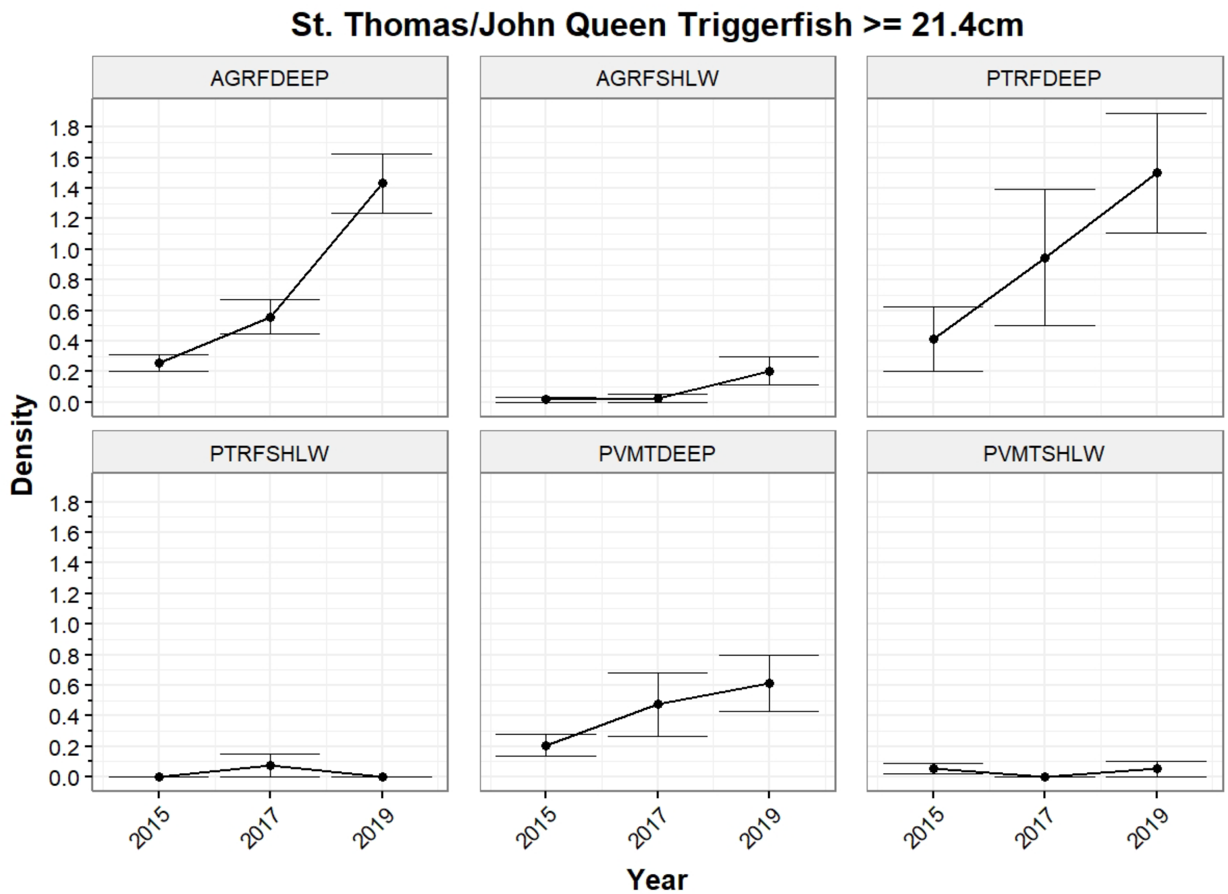

Figure 11.- Habitat stratum specific mature queen triggerfish population density (number per 178 m^2, ±1 *se*) for fish ≥ 21.4 cm from the NCRMP RVC-SPC for the 2015, 2017, and 2019 St. Thomas/St. John coral reef ecosystem surveys.

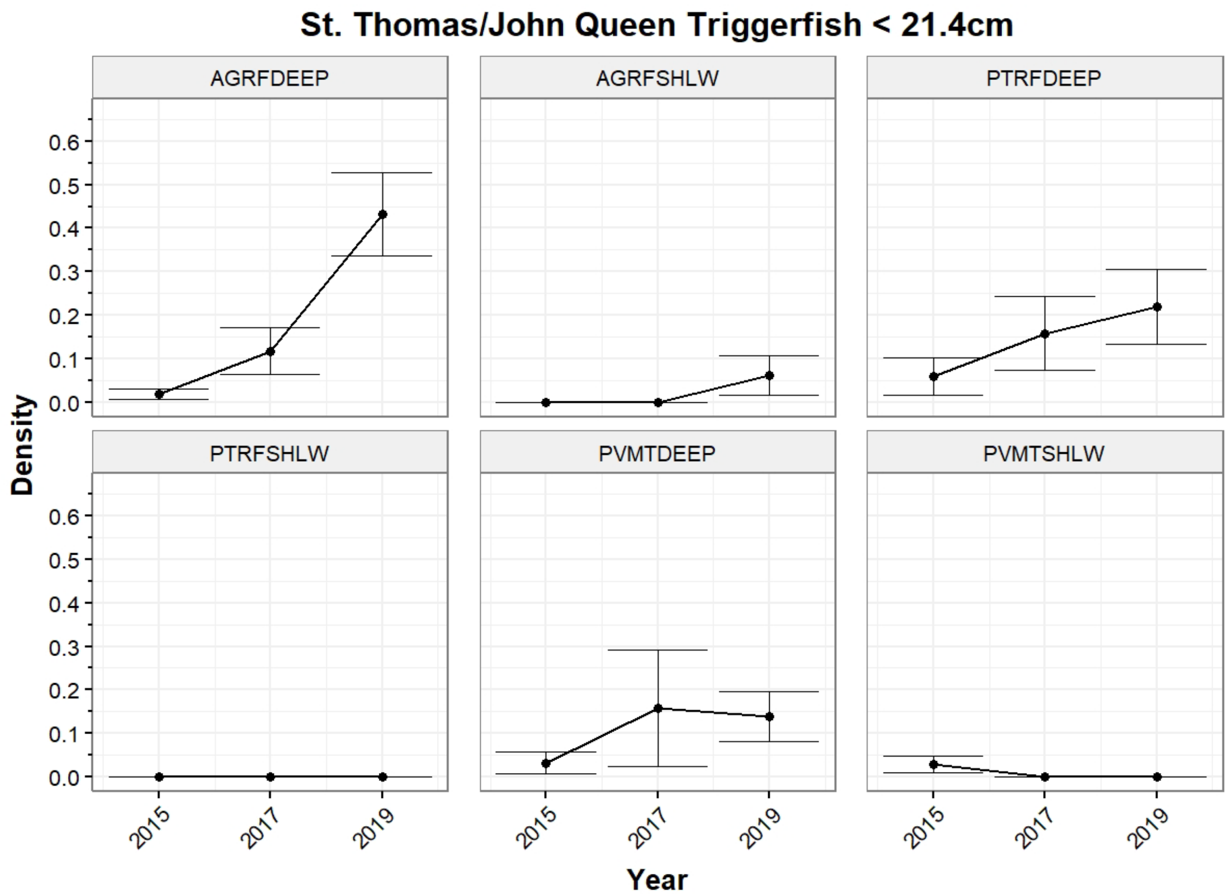

Figure 12.- Habitat stratum specific immature queen triggerfish population density (number per 178 m^2, ± 1 *se*) for fish < 21.4 cm from the NCRMP RVC-SPC for the 2015, 2017, and 2019 St. Thomas/St. John coral reef ecosystem surveys.

St. Croix

Table 5.- Number of reef fish visual survey sites (left column) and number of queen triggerfish (*Balistes vetulus*) length observations (right column) by hard-bottom strata from the reef fish visual surveys in the St. Croix coral reef ecosystem (2001–2019). Empty cells indicate zero samples (left column) or no observations (right column).

Year	AGRFSHLW		BDRKSHLW		PTRFSHLW		PVMTSHLW		SCRSHLW		AGRFDEEP		BDRKDEEP		PTRFDEEP		PVMTDEEP		SCRDEEP		Site Total	Length Total
2001	12				14		47	2							9		4	2			86	4
2002	8	1			15	1	31	2							7		15	10			76	14
2003	44				13	1	79	4							3	2	23	13			162	20
2004	27				14		55	7			2				4		12	4			114	11
2005	47	9			17	1	57	4			10	1			7	2	32	12			170	29
2006	36	7			18	1	68	14			6	1			13	1	44	29			185	53
2007	14				14		28	4			1				7	2	26	14			90	20
2008	16	1			27	2	65	12			5	1			12	2	42	29			167	47
2009	15				23	2	70	11			4	3			8	3	37	19			157	38
2010	17	1			15		43	14			3				2		38	28			118	43
2011	3						19	1									19	14			41	15
2012	23	3			20	5	70	18			71	27			29	25	49	29			262	107
2015	19	3			14	2	64	12			33	11			19	6	90	44			239	78
2017	11	1	1		14	3	33	16	5	1	46	41			19	6	47	66	5	3	181	137
2019	29	7	8		32	1	46	35	10		74	51			35	21	72	120	8	6	314	241

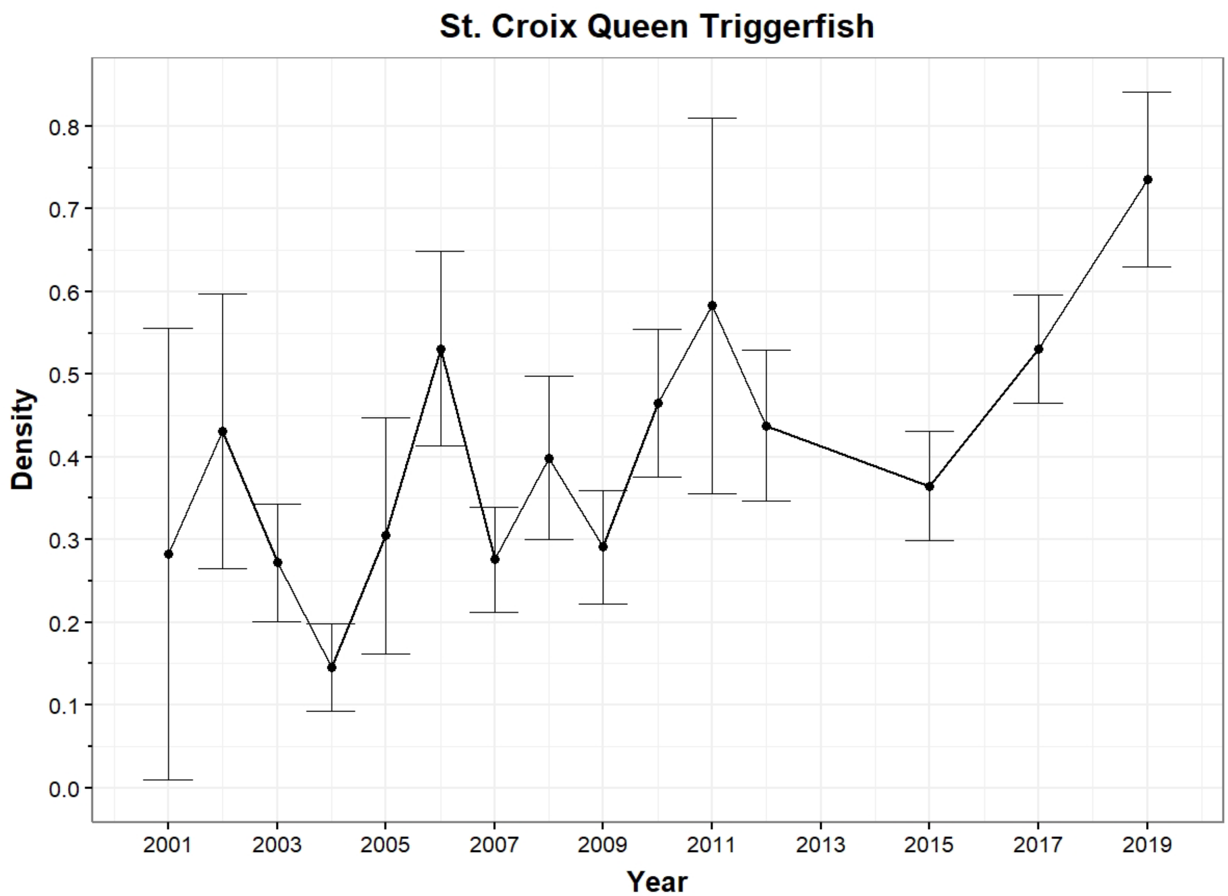

Figure 19.- Time series (2001–2019) of queen triggerfish (*Balistes vetulus*) mean population density (number per 178 m^2) and error (±1 *se*) from the reef fish visual survey in the St. Croix coral reef ecosystem.

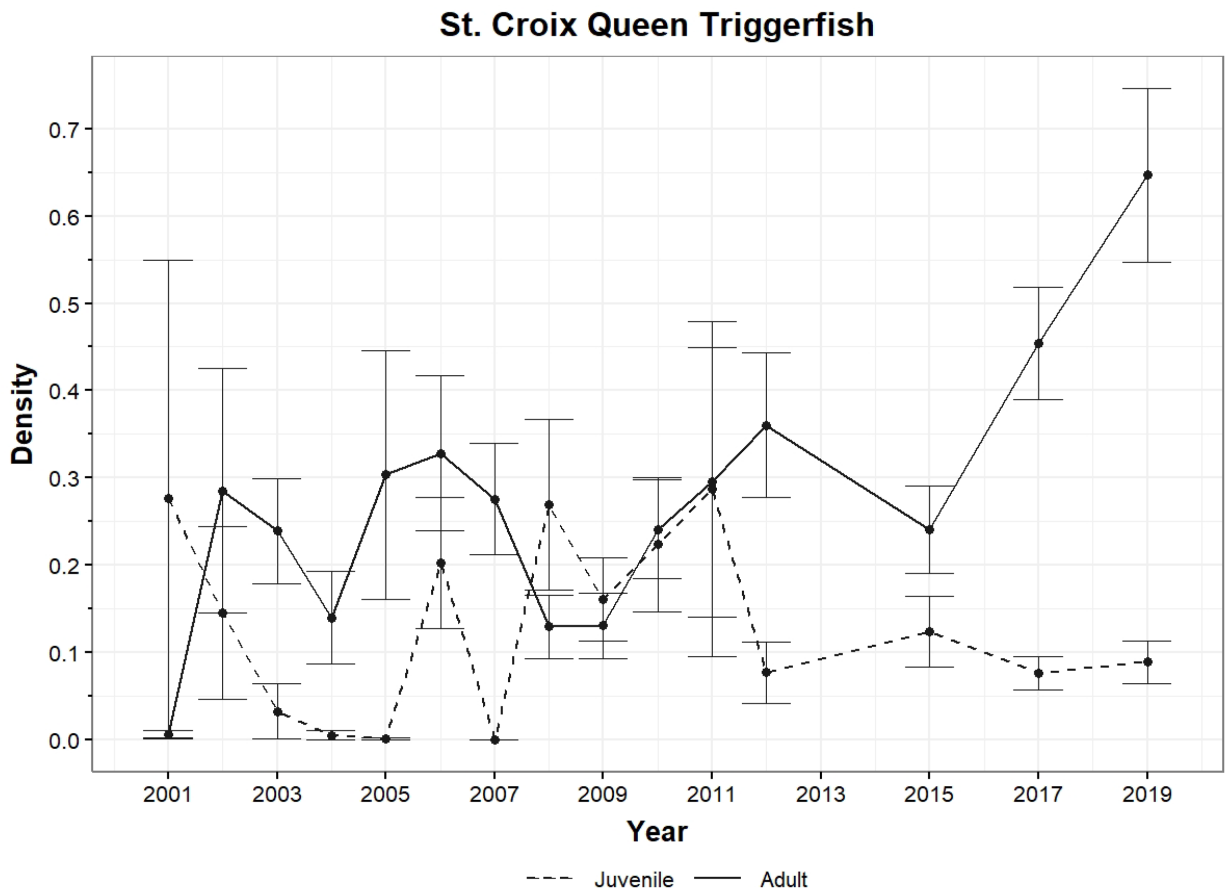

Figure 20.- Time series (2001–2019) of juvenile (dashed line) and adult (solid line) queen triggerfish mean population density (number per 178 m^2, ± 1 *se*) from the reef fish visual survey in the St. Croix coral reef ecosystem. Length at first maturity (21.4 cm fork length) from SEDAR80 working paper by Shervette and Rivera-Hernandez (2022).

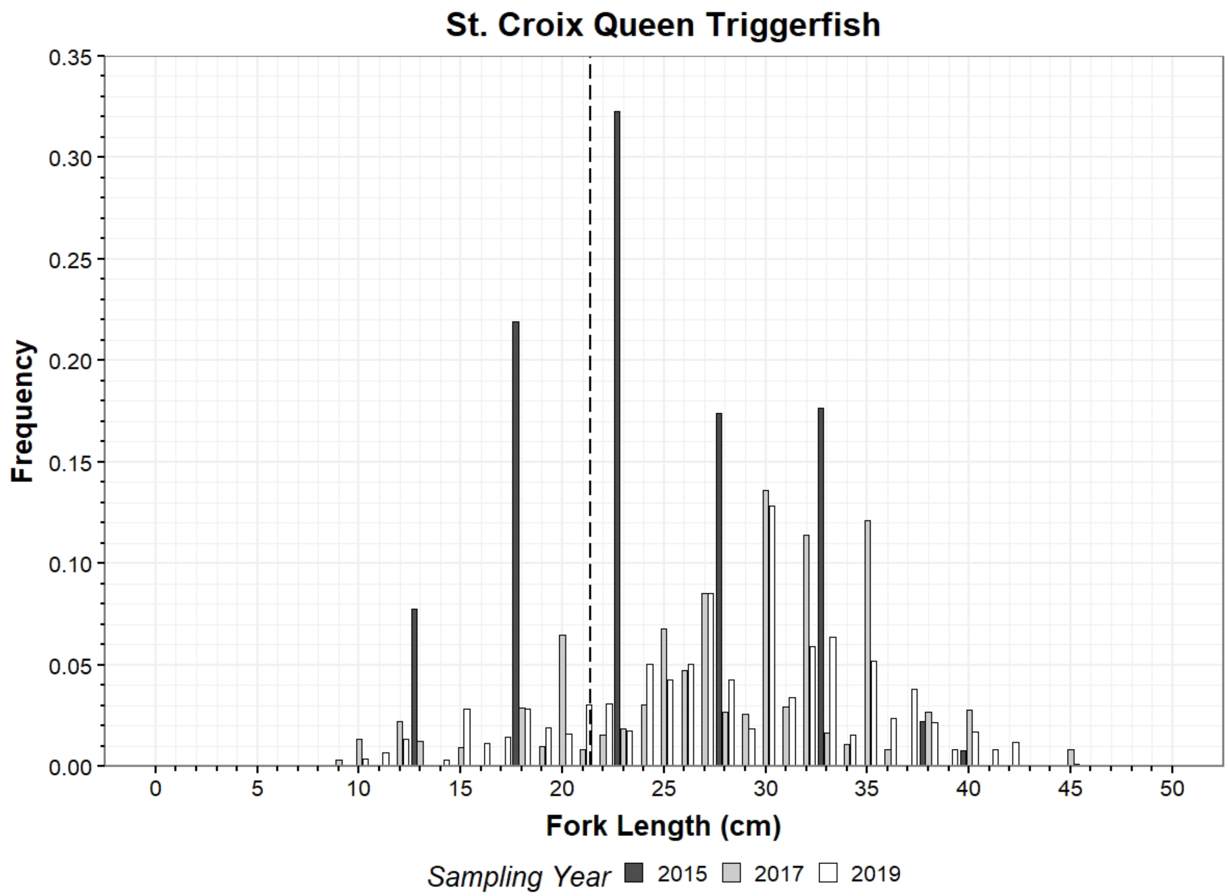

Figure 21.- Queen triggerfish population size-frequency distribution at 1-cm bins from the NCRMP RVC-SPC for the 2015 (n = 78), 2017 (n = 137), and 2019 (n = 241) St. Croix coral reef ecosystem surveys. Vertical dashed line is length at first maturity (21.4 cm fork length).

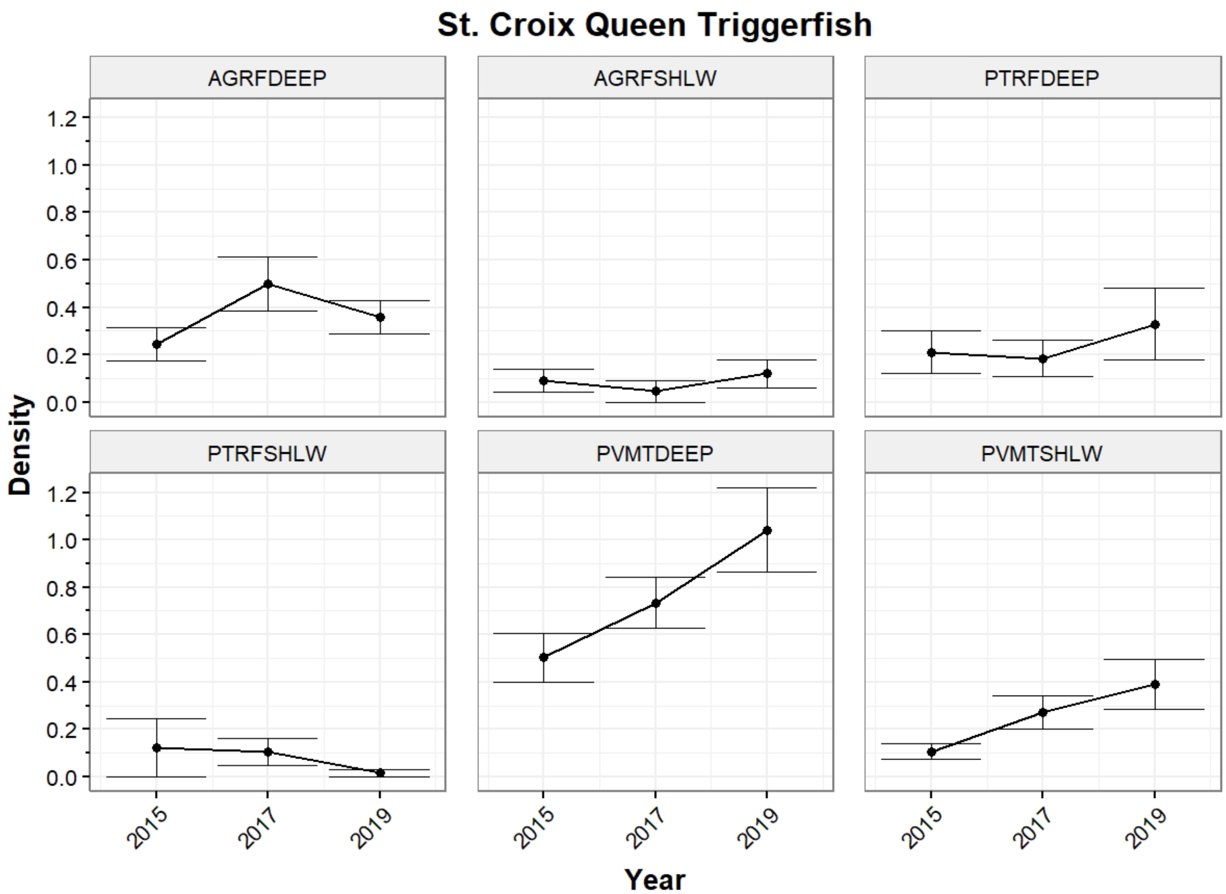

Figure 22.- Habitat stratum specific queen triggerfish population density (number per 178 m^2, ± 1 *se*) from the NCRMP RVC-SPC for the 2015, 2017, and 2019 St. Croix coral reef ecosystem surveys.

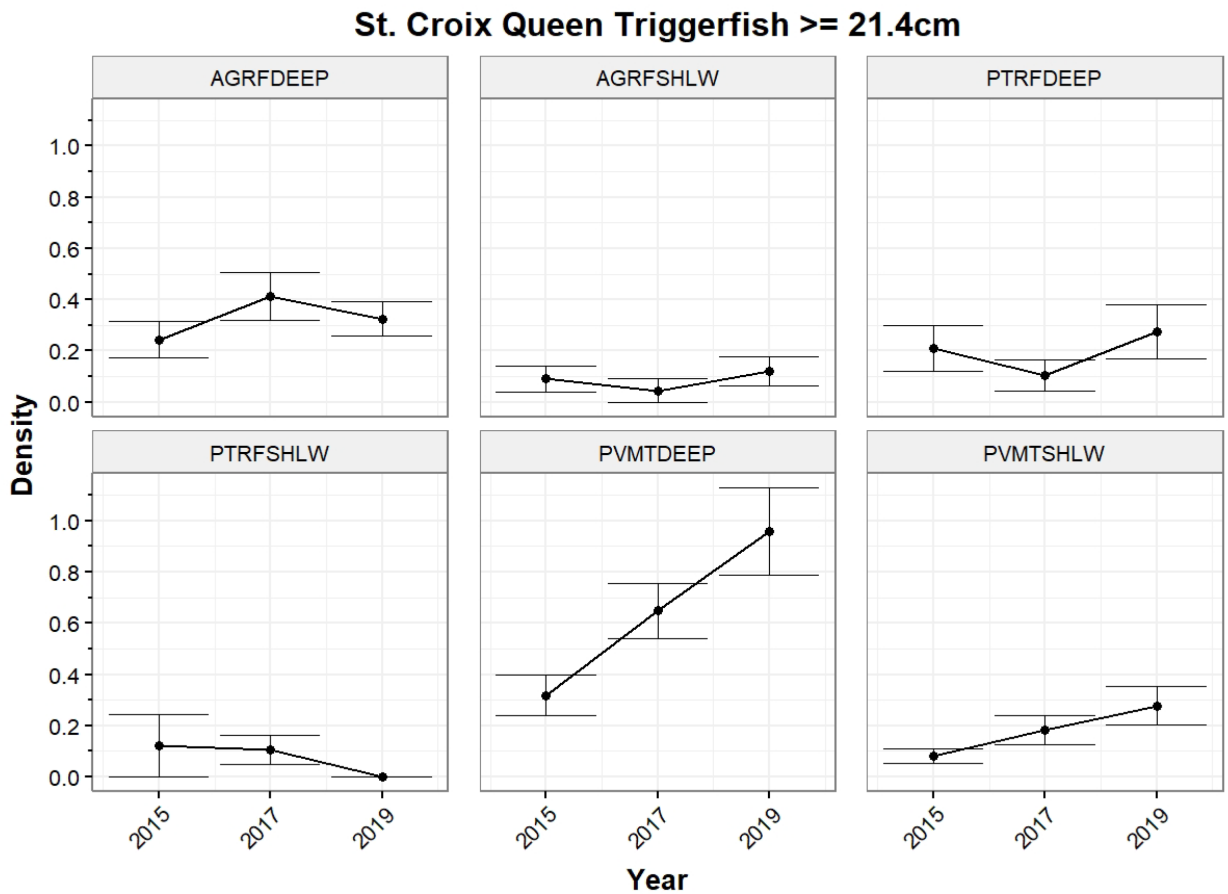

Figure 23.- Habitat stratum specific mature queen triggerfish population density (number per 178 m^2, ± 1 *se*) for fish $\geq$ 21.4 cm from the NCRMP RVC-SPC for the 2015, 2017, and 2019 St. Croix coral reef ecosystem surveys.

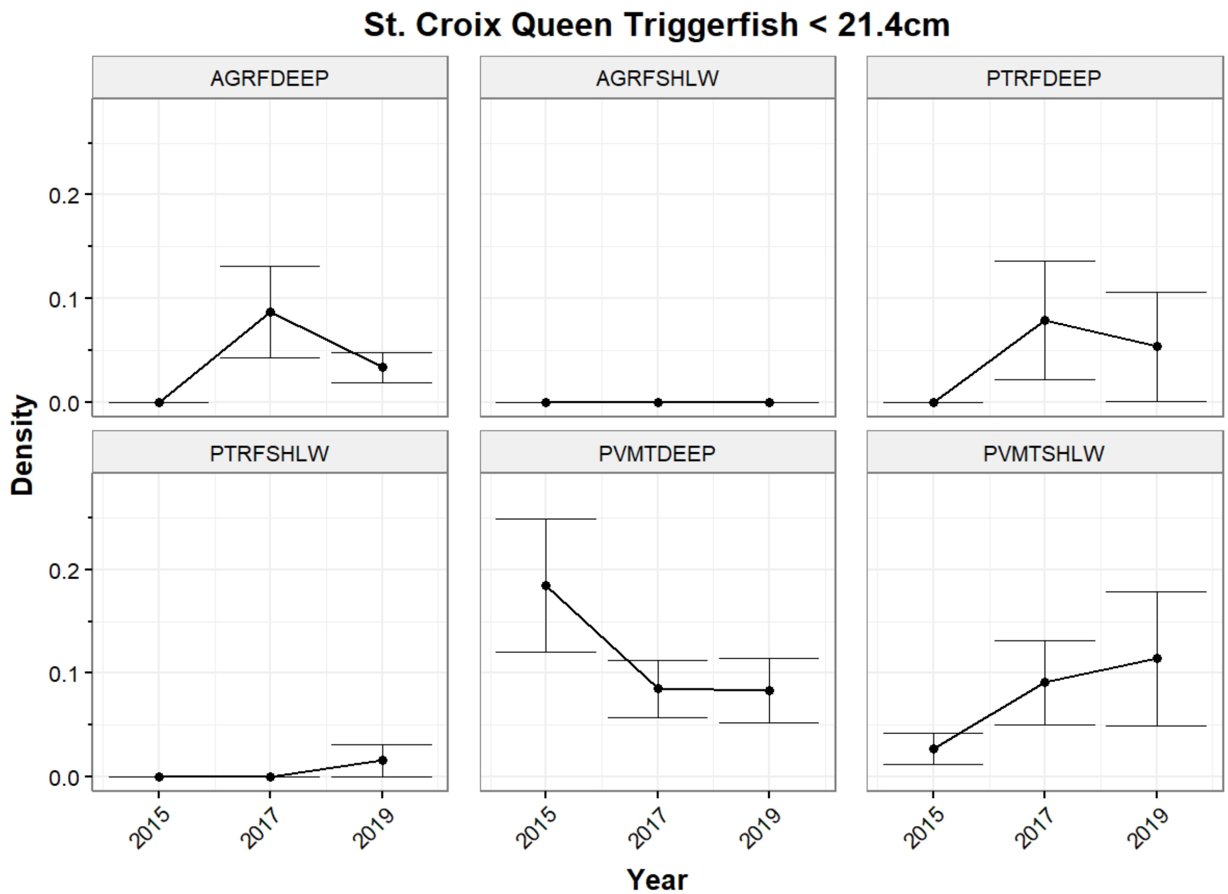

Figure 24.- Habitat stratum specific immature queen triggerfish population density (number per 178 m^2, ± 1 *se*) for fish < 21.4 cm from the NCRMP RVC-SPC for the 2015, 2017, and 2019 St. Croix coral reef ecosystem surveys.

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APPENDIX I

Gear Calibration

Fishery-independent visual surveys have been conducted in the U.S. Caribbean (Puerto Rico and U.S. Virgin Islands) since 2001. These data are essential to regional stock assessments to ensure the sustainability of the coral reef fish community. However, the belt transect (BT), the original monitoring method, was later changed in 2015 to a reef visual census stationary point count (RVC-SPC) due to a number of technical and practical efficiencies. The principal challenge facing the program was how to develop a robust statistical method that preserved the historical time-series data using BT and allowed conversion of these data comparable to those collected with RVC-SPC. To accomplish this, we extended the Robson's (1966) relative fishing power method using a new machine learning statistical approach that included application of generalized linear models in a two-stage regression "Delta model" framework (Ault et al. 2020).

The catchability (or in this case, sight-ability) coefficient q is strictly proportional to average population size which generally differs amongst survey methods, and nominal sampling effort f has different units for the different methods, typically because the area or volume search probabilities vary according to the method. To formally inter-calibrate the q of the various gears, we implemented an advanced statistical variant of Robson's (1966) relative "fishing power" method to provide estimates of the catchability (sight-ability) among different methods to convert catch rates or densities from one gear (survey method) to another. For two independent gears fishing the same unit stock, the CPUE or "density *D*" (i.e., number of fish per unit area sampled) obtained for gears 1 and 2 are, $D_1 = \frac{Y_{N_1}}{f_1} = q_1\bar{N}$ and $D_2 = \frac{Y_{N_2}}{f_2} = q_2\bar{N}$, respectively. These densities can generally be re-expressed as a gear calibration factor Θ or the relative fishing power of the gears to convert the density of one gear to the other

$$\frac{\frac{Y_{N_1}}{f_1}}{\frac{Y_{N_2}}{f_2}} = \frac{q_1\bar{N}}{q_2\bar{N}} = \frac{q_1}{q_2} = \Theta \ . \qquad (1)$$

In this particular case, we arbitrarily designated gear 2 to be the "standard"; thus, by multiplying the density of gear 2 by the gear calibration factor Θ produces an comparable CPUE (or density *D*) value for gear 1,

$$\frac{Y_{N_2}}{f_2}\Theta = \frac{Y_{N_1}}{f_1} \ . \qquad (2)$$

Analysis-ready data were obtained from an *a priori* paired-method experimental design conducted across regions, depths and rugosity in the U.S. Caribbean during 2018, 2019 and 2020. The general space-time blocking scheme was fashioned after the stratification scheme employed by the U.S. Caribbean RVC program (Bryan et al. 2015). All gear calibration experiment data for a particular U.S. Caribbean region were collected within the same time period (i.e., Puerto Rico, 2018; USVI, 2019), and the spatial domain was broken into 12 strata based on region, water depth, and habitat rugosity. The model partitioned variation in sampled density D_{ijk} (i.e., number of fish seen per unit area sampled) observations n_{ijk} into two main factors: (1) gears ($g = 1, \dots, m$) employed; and, (2) the area-time station blocks ($s = 1, \dots, n$). Imposition of ANOVA-like sigma constraints allows representation as a 2-way ANOVA

$$Y_{ijk} = \mu + \alpha_j + \beta_k + \xi_{gsi} \qquad \xi_{ijk} \sim N(0, \sigma^2) \qquad (3)$$

where μ is a constant (i.e., the mean), α_j is a gear coefficient, β_k is a station block coefficient, ξ_{gsi} is an additive error term with the constraints $\sum_{j=1}^{g} \alpha_j = 0$ and $\sum_{k=1}^{s} \beta_k = 0$. The principal assumption was that for any given species, each gear capture efficiency (and thus the coefficient α_j) was constant. It follows that log-linear model was

$$\mu_{jk} = \mathrm{E}(Y_{ijk}) = \mu + \alpha_j + \beta_k \quad (4)$$

Eq(4) is a model for independence because it does not distinguish a response variable *per se*, but does specify that the row and column variables in the contingency table are unrelated. As such, we initially focused on development of a linear statistical model to obtain accurate and precise gear and station block parameters that controlled for spatial variation in density Y_{ijk}

$$Y_{ijk} = \alpha + b_{j_1} X_{ij_1} + \cdots + b_{j_{g-1}} X_{ij_{g-1}} + \cdots + b_{k_1} X_{ik_1} + \cdots + b_{k_{s-1}} X_{ik_{s-1}} + \xi_{ijk} \quad (5)$$

where the parameters to be estimated were the intercept α, gear coefficients b_j's, and station block coefficients b_k's.

To facilitate a more flexible and robust parameter estimation scheme for the 2-way ANOVA model, we transformed Eq. (5) to a generalized linear model (GLM) framework. A GLM has three components: (1) a *random component* specifying the conditional distribution of the response variable; (2) a *linear predictor*

$$\eta_i = \alpha + b_{j_1} X_{ij_1} + \cdots + b_{j_{g-1}} X_{ij_{g-1}} + \cdots + b_{k_1} X_{ik_1} + \cdots + b_{k_{s-1}} X_{ik_{s-1}} \; ; \quad (6)$$

and, (3) a smooth and invertible *link function* $g(\mu_{jk})$, which transforms the expectation of the response variable, $\mu_{jk} = \mathrm{E}(Y_{ijk})$ to the linear predictor

$$g(\mu_{jk}) = \eta_i = \alpha + b_{j_1} X_{ij_1} + \cdots + b_{j_{g-1}} X_{ij_{g-1}} + \cdots + b_{k_1} X_{ik_1} + \cdots + b_{k_{s-1}} X_{ik_{s-1}}$$

Because the link is invertible, we can also write

$$\mu_{jk} = g^{-1}(\eta_{jk}) = g^{-1}\left(\alpha + b_{j_1} X_{ij_1} + \cdots + b_{j_{g-1}} X_{ij_{g-1}} + \cdots + b_{k_1} X_{ik_1} + \cdots + b_{k_{s-1}} X_{ik_{s-1}}\right)$$

and thus, the GLM may be thought of as a linear model for a transformation of the expected response, or as a nonlinear regression model for the response. The inverse link is also called the mean predictor. The identity link returns its argument unaltered, $\eta_{jk} = g(\mu_{jk}) = \mu_{jk}$, and thus,

$$\mu_{jk} = g^{-1}(\eta_{jk}) = \eta_{jk}.$$

The survey data contained a substantial proportion of zero observations, so that an appropriate single error PDF may not exist. In this situation, to better estimate the parameters of Eq(6), observations were modeled using a two-stage regression or "delta model". The first stage uses positive non-zero density observations fit to the GLM following Eq(6) by letting $Y_{ijk} = \mu_{jk}$. The second stage fits Eq(6) to a GLM with strictly presence-absence (0, 1) data for the response variable Y_{ijk} obtained as

$$Y_{ijk} = \begin{cases} 0 & \text{if} \quad D_{ijk} = 0 \\ 1 & \text{if} \quad D_{ijk} > 0 \end{cases} \quad (7)$$

Because Y_{ijk} can take on only values of 0 and 1, the conditional distribution of the ξ_{ijk} is dichotomous, thus, the error PDF is specified as the discrete binomial distribution and parameter estimation is carried out using logistic regression. More than 125 coral reef fish species were seen in the experimental sampling, and 65 met restrictions that allowed robust statistical modeling. Queen triggerfish were selected here for more detailed analysis of gear (method) correction factors (GCF) to allow conversion of historical density observations collected by the BLT method (D_{BLT}) to those obtained by the current gear D_{SPC}, that is,

$D_{BLT} \text{x} \frac{\hat{D}_{SPC}}{\hat{D}_{BLT}} = D_{BLT}\Theta = D_{SPC}$, where Θ is the gear correction factor (GCF). Queen triggerfish GCFs ranged from [0.5736, 0.6126].

APPENDIX II

Expanded Analysis Description

A fishery-independent sampling survey was conducted throughout the U.S. Caribbean (Puerto Rico and the U.S. Virgin Islands) to estimate key population metrics for the reef fish complex. The development of the statistical sampling methods and survey design are detailed in Bryan et al. (2013, 2016). The survey domain encompassed the full extent of mapped habitats from 0 to 30 m depths. The survey frame was comprised of 500 x 500 m primary sample units (PSUs) stratified according to depth and habitat categories (Table 1A, 1B). Samples were allocated among strata following a Neyman scheme (Cochran, 1977), and primary sample units (PSU) within strata were randomly selected without replacement from a discrete uniform probability distribution to ensure equal probability of selection (Law, 2007). To ensure geographical coverage with respect to islands, PSUs were proportionally allocated within strata to island area.

At a selected PSU, queen triggerfish density (numbers per sampled area) and length composition were obtained. Two, replicate, randomized, surveys were conducted within each PSU. Estimation of queen triggerfish population metrics followed standard procedures for stratified random sampling (Cochran, 1977; Ault et al., 1999; Lohr, 2010; Smith et al., 2011; Ault et al. 2018). The number of fish per sample unit U_N was the principal metric used to develop the statistical sampling design. Computational formulae for estimating the mean number of fish $\bar{U}_N$, a relative index of population abundance, and associated variance at both the stratum and survey frame levels are provided in Table X1. Survey design estimation was carried out using the R (R Development Core Team, v 3.1.3) software package.

Estimation of population total biomass entailed multiplying the mean biomass per unit $\bar{U}_B$ (T-9) by the number of sample units in the survey frame. Biomass in a sample unit (Table X1, eq. T-3) was obtained by converting length to weight of each individual fish via an allometric weight-length function, and then summing the weights for all observed fish.

The number of PSUs in the island group survey frame was determined from the habitat maps. However, a standard PSU sample likely did not cover the entire area of the PSU (250,000 m^2), requiring use of a two-stage sampling process, with a standard sample treated as a second-stage unit (SSU) (Cochran, 1977; Smith et al., 2011). Estimation of population biomass was achieved by multiplying the mean biomass per sample unit $\bar{U}_B$ for the survey frame (Table X1, eq. T-9) by the number of SSUs in each PSU, and then by the number of PSUs in the survey frame (Table X1, eq. T-10). The computational equations for the relative abundance indices of mean number per sample unit $\bar{U}_N$ (Table X1, eqs. T-1 and T-8) and mean biomass per sample unit $\bar{U}_B$ (Table X1, eqs. T-2 and T-9), and their associated variances (Table X1, eqs. T-6 and T-7), simplify to single-stage design equations.

Table X1. Computational formulae for the stratified random sampling design used for reef fish visual surveys.

Symbol	Definition	Computational Formula	Equation Number
$\bar{U}_{Nh}$	Mean number of fish per sample unit in stratum *h*	$\bar{U}_{Nh} = \frac{1}{n_h}\sum_i U_{Nhi}$	T-1
n_h	Number of units sampled in stratum *h*		
U_{Nhi}	Number in sample unit *i* in stratum *h*		
$\bar{U}_{Bh}$	Mean biomass of fish per sample unit in stratum *h*	$\bar{U}_{Bh} = \frac{1}{n_h}\sum_i U_{Bhi}$	T-2
U_{Bhi}	Biomass in sample unit *i* in stratum *h*	$U_{Bhi} = \sum_j W_{hij}$	T-3
W_{hij}	Weight of fish *j* in sample unit *i* in stratum *h*	$W_{hij} = \alpha\left(L_{hij}\right)^{\beta}$	T-4
L_{hij}	Length of fish *j* in sample unit *i* in stratum *h*		
α, β	Parameters of allometric weight-length function		T-5
$\mathrm{var}[\bar{U}_h]$	Variance of mean number or biomass per unit in stratum *h*	$var[\bar{U}_h] = \left(1 - \frac{n_h}{PSUs_h}\right)\frac{s_h^2}{n_h}$	T-6
$PSUs_h$	Total number of primary units (map grid cells) in stratum *h*		
s_h^2	Sample variance of number or biomass in stratum *h*	$s_h^2 = \frac{\sum_i (U_{hi} - \bar{U}_h)^2}{n_h - 1}$	T-7
$\bar{U}_N$	Mean number per unit for the full survey frame	$\bar{U}_N = \sum_h w_h \bar{U}_{Nh}$	T-8
$\bar{U}_B$	Mean biomass per unit for the full survey frame	$\bar{U}_B = \sum_h w_h \bar{U}_{Bh}$	T-9

w_h	Stratum h weighting factor	$w_h = \frac{PSUs_h}{\sum_h PSUs_h}$	
$\mathrm{var}[\bar{U}]$	Variance of survey frame mean number or biomass per unit	$var[\bar{U}] = \sum_h w_h^2\, var[\bar{U}_h]$	
$\mathrm{SE}[\bar{U}]$	Standard error of survey frame mean number or biomass per unit	$SE[\bar{U}] = \sqrt{var[\bar{U}]}$	
$\mathrm{CV}[\bar{U}]$	Coefficient of variation of mean number or biomass per unit	$CV[\bar{U}] = \frac{SE[\bar{U}]}{\bar{U}}$	
$\bar{B}$	Mean population biomass in survey frame	$\bar{B} = \bar{U}_B \times PSUs \times SSUs$	T-10
$PSUs$	Number of grid cells in survey frame		
$SSUs$	Number of sample units within each grid cell in survey frame		
$\mathrm{SE}[\bar{B}]$	Standard error of population biomass	$SE[\bar{B}] = \sqrt{var[\bar{U}_B]\,(PSUs \times SSUs)^2}$	
$\bar{L}$	Mean length in exploited phase in survey frame	$\bar{L} = \frac{\bar{Y}}{\bar{X}}$	T-11
$\bar{X}$	Per unit mean number in exploited phase in survey frame	$\bar{X} = \sum_h w_h \bar{X}_h$	
$\bar{Y}$	Per unit mean sum of lengths in exploited phase in survey frame	$\bar{Y} = \sum_h w_h \bar{Y}_h$	
$\bar{X}_h$	Per unit mean number in exploited phase in stratum h	$\bar{X}_h = \frac{1}{n_h}\sum_i X_{hi}$	
X_{hi}	Number in exploited phase in sample unit i in stratum h		
$\bar{Y}_h$	Per unit mean sum of lengths in exploited phase in stratum h	$\bar{Y}_h = \frac{1}{n_h}\sum_i Y_{hi}$	
Y_{hi}	Sum of lengths in exploited phase in sample unit i in stratum h		

var[$\bar{L}_h$]	Variance of mean length in exploited phase in stratum *h*	$var[\bar{L}_h] = \left(1 - \frac{n_h}{PSUs_h}\right)\frac{s_h^2(Y\|X)}{n_h\bar{X}_h}$	
$s_h^2(Y\|X)$	Sample variance of Y conditioned on X in stratum *h*	$s_h^2(Y\|X) = \frac{\sum_i (Y_{hi} - \bar{L}X_{hi})^2}{n_h - 1}$	
SE[$\bar{L}$]	Standard error of mean length in exploited phase in survey frame	$SE[\bar{L}] = \sqrt{\sum_h w_h^2\, var[\bar{L}_h]}$	T-12