Striped Bass in the San Joaquin River Restoration Area: Population and Bioenergetics Modeling

SAN JOAQUIN RIVER
RESTORATION PROGRAM

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Self-Certification of Peer Review

This proposal has been peer reviewed by the following two individuals, at least one of whom is from outside my work group:

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I certify that, to my best knowledge, these two individuals are qualified to review this work, and that they have peer reviewed this proposal.

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1.0 Introduction

1.1 Background

The San Joaquin River Restoration Program (SJRRP) aims to establish sustainable Chinook Salmon (*Oncorhynchus tshawytscha*) populations within the mainstem San Joaquin River below Friant Dam to the confluence of the Merced River (referred to as the SJRRP Restoration Area; SJRRP 2018). Predation of juvenile salmon is identified as a “critical stressor” to the population within the San Joaquin River and the SJRRP’s success (SJRRP 2018). In addition to the SJRRP’s priorities of providing adequate flows, volitional passage, habitat restoration and reintroductions, the Fisheries Management Plan and Fisheries Framework identified the importance of understanding and managing predators for the restoration of Chinook Salmon (SJRRP 2010 and SJRRP 2018). Assessing predation levels, identifying impacts to juvenile salmon survival, and detecting areas of high predation to adjust management actions will also be a component of the Long-Term Monitoring Plan (SJRRP *In Draft*).

Striped Bass (*Morone saxatilis*) are non-native to California but have well-established populations throughout the San Joaquin/Sacramento Delta and adjacent rivers systems (Nobriga et al. 2021, Sabal et al. 2019). Within the Restoration Area, Striped Bass are the dominant piscivore caught during annual steelhead (*O. mykiss*) and adult Chinook Salmon monitoring (Sutphin and Root 2021, Root and Sutphin 2021). They are mobile, schooling and often found where juvenile salmon congregate (Sabal et al. 2016, Nobriga et al. 2021). As juveniles, Striped Bass feed mostly on invertebrates, but become predominantly piscivorous after two years (Lindley and Mohr 2003). Migration patterns and behavior are variable, and not well understood within the San Joaquin River (Sabal et al. 2019, Goertler et al. 2021). However, it appears Striped Bass often make upriver spawning migrations and spend more time in rivers during the spring compared to delta or bay areas (Sabal et al. 2019). Spawning occurs between April and June, which overlaps with juvenile Spring- and Fall-Run Chinook Salmon emigration (Sabal et al. 2019, Satterthwaite et al. 2017). Striped Bass reportedly leave riverine habitats and move towards Bay-Delta habitat in the winter (January – March; Le Doux-Bloom et al. 2021) but are frequently observed within the Restoration Area during this time (Root and Sutphin 2021).

Using data collected during SJRRP’s Central Valley Steelhead Monitoring and Adult Spring-Run Chinook Salmon Monitoring, Trap and Haul programs, we present a hierarchal approach using two Striped Bass models (a population model and a bioenergetics model) where results from the population model will be used to inform results of the bioenergetics model. Results from these simplistic preliminary models help describe the potential impact of Striped Bass to native fish, like juvenile salmon, and highlight the value of increased data collection to improve the accuracy and relevance of these models.

2.0 Methods

2.1 Striped Bass Captures and Recaptures

Data from Striped Bass captured during SJRRP's Central Valley Steelhead Monitoring and Adult Spring-Run Chinook Salmon Monitoring, Trap and Haul efforts (Root and Sutphin 2021, Sutphin and Root 2021) were used as model inputs. Central Valley Steelhead Monitoring occurs annually between December and March/April. This is followed seamlessly by Adult Spring-Run Chinook Salmon Monitoring, Trap and Haul, which continues until water temperatures or flow create unsuitable habitat for salmon and adults are no longer being captured (typically late-May/early-June). Both sampling/monitoring efforts are completed in the lower reaches of the Restoration Area (Reaches 4b and 5) and employ 8- or 10-foot (ft) wire fyke traps or 4- or 6- ft fyke nets designed to capture large fish moving through or adjacent to the thalweg. The upstream extent of sampling during these efforts can change year-to-year depending on flows, but sample sites in Reach 5 are generally consistent. During Steelhead Monitoring, electrofishing within Reach 5 supplements the trapping effort to increase the probability of detecting Steelhead.

Throughout standardized steelhead and adult Chinook Salmon monitoring efforts, all non-target species, including Striped Bass, are recovered from sample gear, identified to species, measured for total length (millimeters; mm), and released upstream of sample gear to minimize likelihood of recapture. In addition, to support on-going efforts by FISHBIO to study distribution and movements of non-native piscivores in the San Joaquin River, all captured Striped Bass were scanned for a Passive Integrated Transponder (PIT) tag. If no PIT tag was present, a new tag was implanted.

2.2 Striped Bass Population Model

All data analyses for the population model were conducted in program MARK (Cooch and White 2020) using R version 4.3.1 statistical program (R Development Core Team 2016). Individual capture histories (captured = 1, not captured = 0) were created for each month (December-June) of each sample year (2019-2021) using PIT tagged Striped Bass collected during Winter/Spring seasons of 2019/2020 and 2020/2021 (n = 373). After release, each fish was considered independent and remixed back into the population. Year and monthly time intervals were used as a covariate since it is thought that Striped Bass demonstrate migratory behavior temporarily (Sabal et al. 2019). Striped Bass population estimation were generated using the POPAN model (Schwarz and Arnason 1996) for open populations based on the Jolly-Seber method using the link function mlogit. Three primary parameters are estimated using the POPAN model: probability of an animal surviving between occasions i and i+1 (φ); the probability of capture at occasion i (p); and the probability that an animal from the super-population (N) would enter the population between occasions i and i + 1 and survive to the next sampling occasion i + 1 (pent). Pent can also be considered a combination of birth and immigration into the population. The POPAN model produces a super-population estimate which is a total abundance estimate of the population of individuals that occupy the sample area during the entire sampling effort as well as individuals who only inhabit the sampling area for a limited portion of the sampling time. In the context of this project, the Striped Bass super-population estimate is considered the individual Striped Bass that both inhabit and "visit/migrate" into the sampling area during the sampling period.

Three population models were tested with different combinations of fixed and random φ and pent time (month, year). Model creation was limited and reflected ecologically probable situations that could occur in the San Joaquin River. Model selection was based on an information theory approach, using the corrected Akaike information criterion (AICc) and calculated weight. The top model was considered the model with the lowest AICc and where the difference between that model's AICc and the AICc of the other models (ΔAIC_c) was greater than 2.00 (Burnham and Anderson 2002).

2.3 Striped Bass Bioenergetics Model

Modeling was conducted in Fish Bioenergetics 4.0 (Deslauriers et al. 2017) and combined with the results from the Striped Bass population model (Section 2.2) to estimate predation impacts on emigrating juvenile salmon. Model parameters were gathered from the available scientific literature or calculated from capture data of SJRRP monitoring programs (Section 2.1). Monthly average biomass of juvenile salmon was estimated from captured juvenile Chinook Salmon measurements obtained during previous years' SJRRP juvenile salmon rotary screw trap (RST) efforts in the upper reaches of the Restoration Area (Hutcherson and Sutphin 2023). San Joaquin River water temperatures used for the model were downloaded from California Data Exchange Center Newman (SMN) gauging station (https://cdec.water.ca.gov/). Detailed information on model and post-processing inputs are provided in Appendix A.

Striped Bass were delineated into three age-classes by total length: Age-1 (150 to 300 mm), Age-2 (300 to 400 mm), and Age-3+ (Adult; > 400mm; Mansueti 1961). Model simulations estimated the prey consumption by each age-class for each month when steelhead and adult Chinook Salmon monitoring occurs (January through May). The model was fit to P-value, which predicts consumption based on a constant proportion of the maximum consumption rate (Cmax) at which the fish is feeding (Hanson et al. 1997). The P-value for each simulation was assigned by age-class and the average river temperature for that month (Hartman and Brandt 1995). P-values used in the simulation were derived from lab-based studies and extrapolated to fit the San Joaquin River system.

Monthly initial weights for each age-class were derived using length-weight relationships for Striped Bass taken from Nobriga and Branch (2009) and average lengths of Striped Bass captured during SJRRP monitoring (Section 2.1). Prey Energy Density of Chinook Salmon was set to 4,800 J/g (Adrean 2011). Striped Bass (Predator) Energy Density was determined by age-class and set to 5659.5 J/g (Age-1), 6860 J/g (Age-2) and 7,681 J/g (Age-3+; Loboschefsky et al. 2012). Oxycalorific coefficient was set at 13,560 Joules Per Gram (J/g) O2 (Loboschefsky et al. 2012). Consumption was set to 100 percent since most Striped Bass that reach Age-1 or older will feed predominantly on fish (Vatland et al. 2008, Loboschefsky et al. 2012). Indigestible prey was set to 3.3 percent to reflect the proportion of fish body that cannot be digested (Hanson et al.1997). Each simulation was run with an initial population size of one individual and total prey consumption was calculated in grams (g).

To simulate the impact of diet on net consumption, the percent of Striped Bass diet made up by Chinook Salmon was set to 10 percent (Sabal et al. 2016), 50 percent (midpoint) and 80 percent (Blackwell and Juanes 1998), based on studies of Striped Bass. Monthly water temperature used within these simulations, and to determine the P-value, was the average monthly San Joaquin River temperature combined from 2020 and 2021 data collected at the SMN gauging station.

To simulate how rising temperatures may influence consumption rates of Striped Bass on Chinook Salmon, average monthly river temperatures measured at the SMN gauging station that were increased by 1 and 2 degrees Celsius (°C) and P-values were assigned based on adjusted temperature and age-class. When modeling temperature variations, the proportion of Chinook Salmon in the Striped Bass diet was fixed at 10 percent.

To estimate the number of individual Chinook Salmon (n) consumed by Striped Bass, the predicted consumed biomass of Chinook Salmon was divided by the estimated average weights of juvenile spring-run Chinook Salmon captured during five seasons (2017 to 2022) of RST monitoring data in the upper reaches of the Restoration Area (Hutcherson and Sutphin 2023). Length-at-date regressions were derived from the first three years of efforts (2017/2018, 2018/2019, and 2019/2020) where fish have been genetically identified as spring-run. These regressions were applied to the raw data and any outliers beyond the 99 percent prediction bands were removed. Remaining data was averaged by collection month (December to May). Live fish whose total length was less than 45 mm were not weighed due to the potential scale of error caused by residual water clinging to the fish. Weights measured early in the season (i.e., December) are, therefore, predominantly from deceased fish and mortalities recovered from the RSTs could also be biased if those carcasses gained or lost water through any post-mortality processes.

Monthly age-class structure of Striped Bass was calculated from length data collected between 2018 and 2021 during SJRRP steelhead and adult Chinook Salmon monitoring (Section 2.1), excluding duplicate recaptures of PIT tagged individuals recaptured within the same month and compiled by month of capture (regardless of year). The age-class structure was combined with averaged monthly results from the POPAN population model (Section 2.2) to extrapolate the simulation results and estimate total monthly consumption of Chinook Salmon.

3.0 Results

Striped Bass were the most frequently captured piscivore during the 2019/2020 (54 percent) and the second most frequently encountered in the 2020/2021 (30 percent) SJRRP’s Central Valley Steelhead Monitoring and Adult Spring-Run Chinook Salmon Monitoring, Trap and Haul seasons (Figure 1). Most Striped Bass captured were greater than 400 mm in total length (Figure 2).

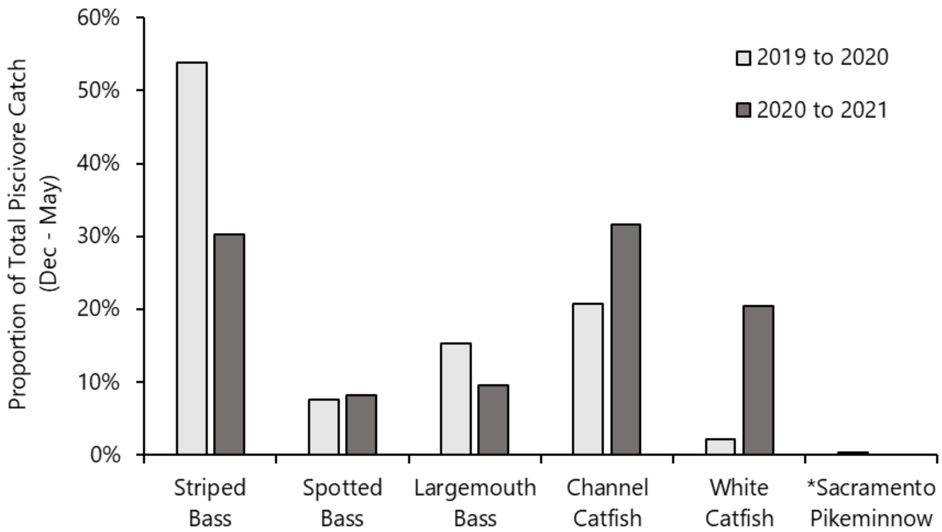

Figure 1. Proportion of total annual piscivore catch by species and sampling season (December to May) of 2019/2020 (n = 740) and 2020/2021 (n = 377) during SJRRP's Central Valley Steelhead Monitoring and Adult Spring-Run Chinook Salmon Monitoring, Trap and Haul programs using electrofishing, Fyke nets and Fyke traps. *Native species to the San Joaquin River.

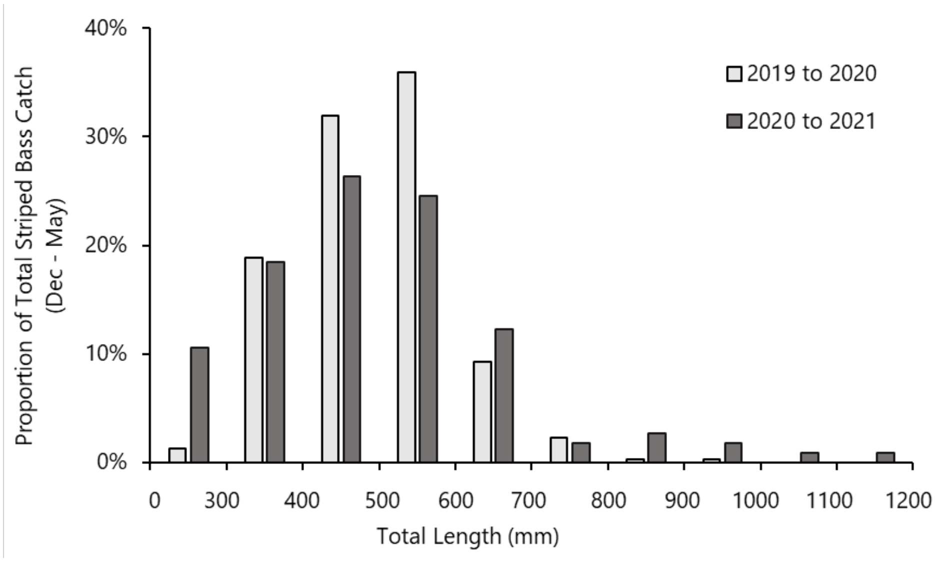

Figure 2. Proportion of total annual catch of Striped Bass by total length increments (100 mm) and sampling season (December to May) of 2019/2020 and 2020/2021 during SJRRP's Central Valley Steelhead Monitoring and Adult Spring-Run Chinook Salmon Monitoring, Trap and Haul programs (n = 512). Length data includes 128 individuals that were not PIT tagged.

3.1 Striped Bass Population Model

A total of 373 Striped Bass were captured over 105 sampling days between December 2019 and May 2021. During that time there was a recapture rate of 6 percent (n = 21). The top model, with all the weight, allowed φ to vary by the additive effects of month and year, pent to vary by day, and p to remain fixed (Table 1).

Table 1. Models tested for Striped Based population estimation using the POPAN model. The total number of parameters (npar), Akaike's information criterion (AIC_c), increase over the lowest AIC_c (ΔAIC_c), and Akaike model weight (weight).

Model	Npar	AICc	Δ AICc	weight
φ (~Month + Year)p(~1)pent(~time)N(~1)	17	2063.77	0.00	1.00
φ (~1)p(~1)pent(~time)N(~1)	12	2108.88	45.11	0.00
φ (~Month)p(~1)pent(~Month + Year)N(~1)	8	2771.47	707.70	0.00

Super-population was calculated for each month and year with the greatest population occurring in April 2020 (N = 384; SE ± 35.96) while the smallest population occurring February 2020 (N = 30; SE ± 4.69; Figure 3). The large error bars in February 2021 reflects the very low captures and recaptures during that month.

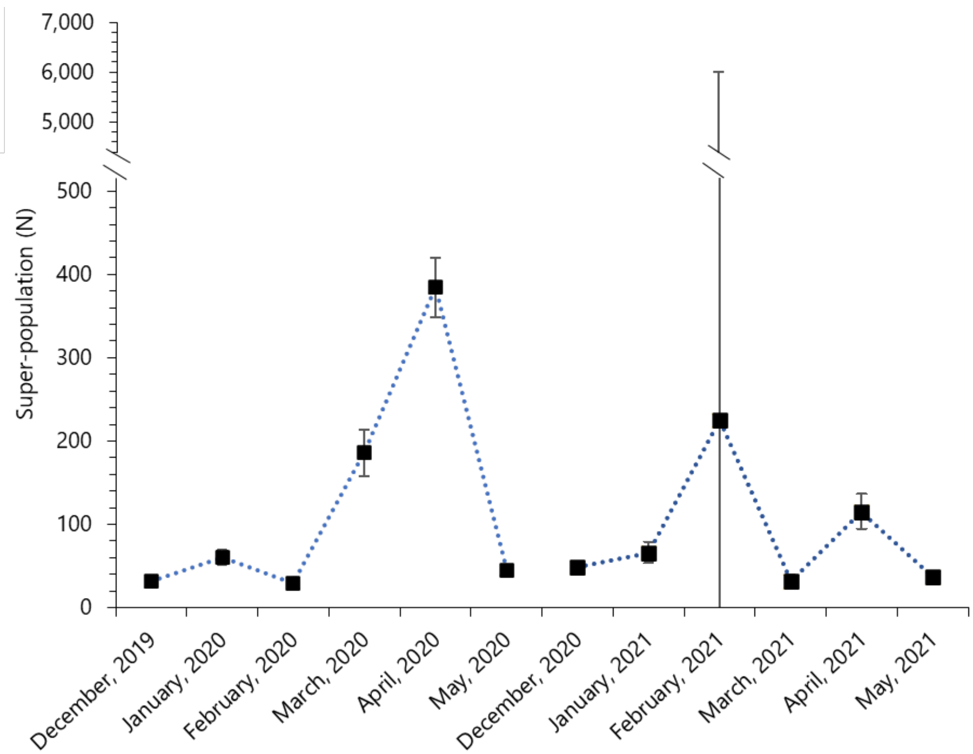

Figure 3. Striped Bass super-population estimates (N; solid dot) and standard errors for each sampling month of each year. Sampling occurred from December 2019 – May 2021 in the San Joaquin River, CA during annual SJRRP's Central Valley Steelhead Monitoring and Adult Spring-Run Chinook Salmon Monitoring, Trap and Haul programs.

3.2 Striped Bass Bioenergetics Model

Estimated total consumption of Chinook Salmon was highest between February and April (Figure 4), when the Striped Bass super-population peaked (see Section 3.1). While total biomass consumption (g; Figure 4a) showed an increasing trend during this period, consumption of individuals (total fish; N; Figure 4b) peaked during February.

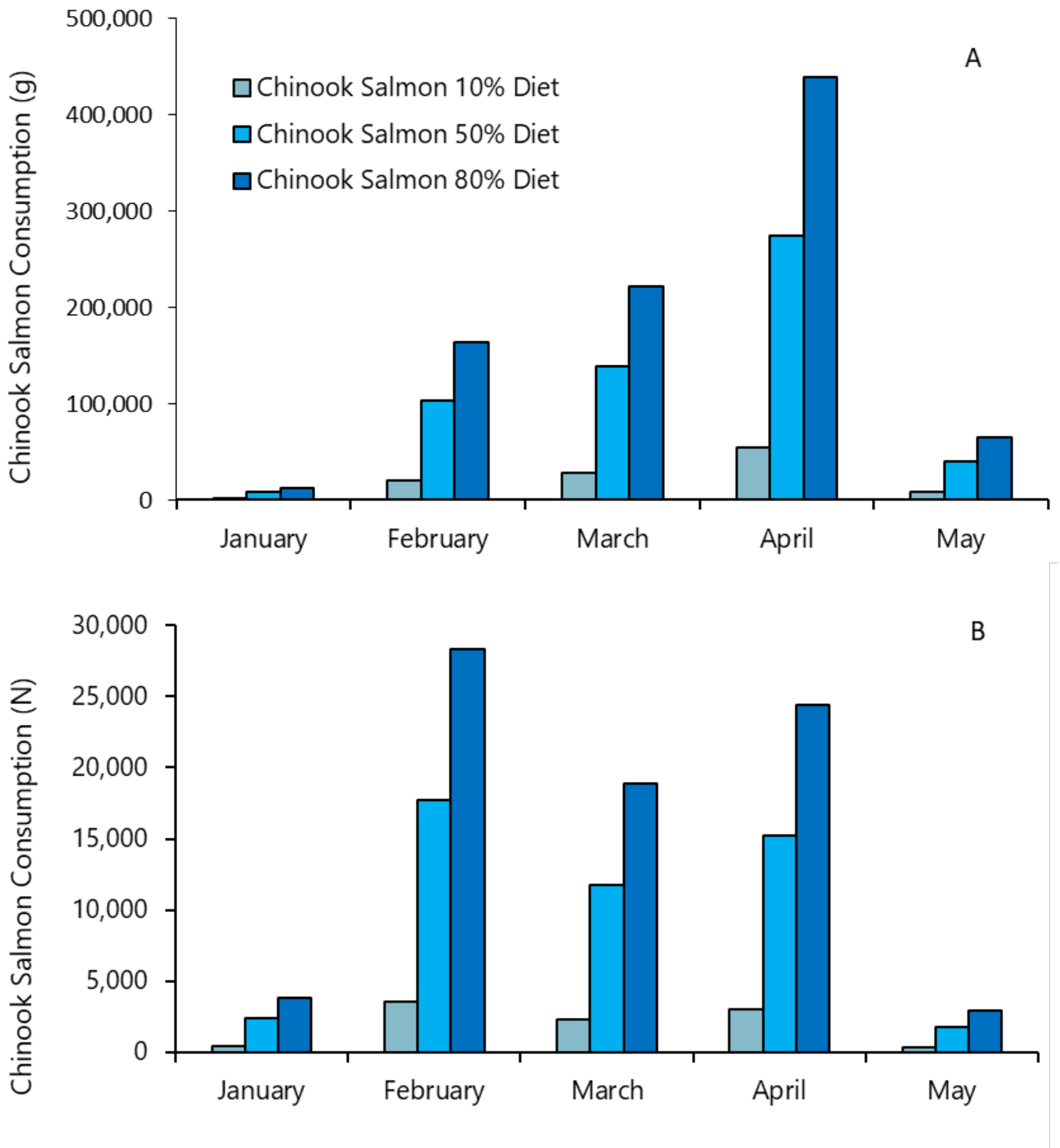

Figure 4. Simulated Chinook Salmon consumption by Striped Bass in the San Joaquin River, CA over three different percentages of Striped Bass Diet.
A: Biomass of Chinook Salmon consumed (g).
B: Number of individual Chinook Salmon consumed (N) calculated from Biomass consumed and average Chinook Salmon weight (g).

Table 2. Striped Bass and Chinook Salmon Weight inputs and San Joaquin River temperature by month.

Variable	January	February	March	April	May
Striped Bass Age-1 Weight (g)*	109.07	86.91	141.55	109.38	225.79
Striped Bass Age-2 Weight (g)	491.29	596.94	582.57	571.90	529.44
Striped Bass Age-3+ Weight (g)	1661.44	1510.58	1919.40	1417.57	1435.38
Chinook Salmon Weight (g)**	3.36	5.81	11.75	18.03	22.51
San Joaquin River Temperature 2021 (ºC)***	9.49	12.13	13.21	18.54	20.76

*Striped Bass weight calculated from measured lengths based on Nobriga and Branch (2009).

**Chinook Salmon Weight measured in RST operations between 2017 and 2019 (Hutcherson and Sutphin 2032).

***Temperature measured in SJRRP and recovered from California Data Exchange Center SMN gauging station.

Consumption of Chinook Salmon increased proportionally when Chinook Salmon comprised a higher percentage of the diet of Striped Bass. Total consumption of individual Chinook Salmon between January and May was estimated between 9,789 (10 percent diet) and 78,309 individuals (80 percent diet).

Increasing average river temperature by 1 or 2°C did not appear to impact annual Chinook Salmon consumption when the diet is fixed (Figure 5). Average water temperatures from February to May were between 10 and 30 °C (Table 2), where the model assumes Striped Bass are feeding close to their maximum rate (P-Value = 0.98; Appendix A). As a result, the P-Value model input remained constant across all simulations aside from January, where the average unadjusted temperature was 9.49°C and different P-Values were used when comparing adjusted and unadjusted temperatures.

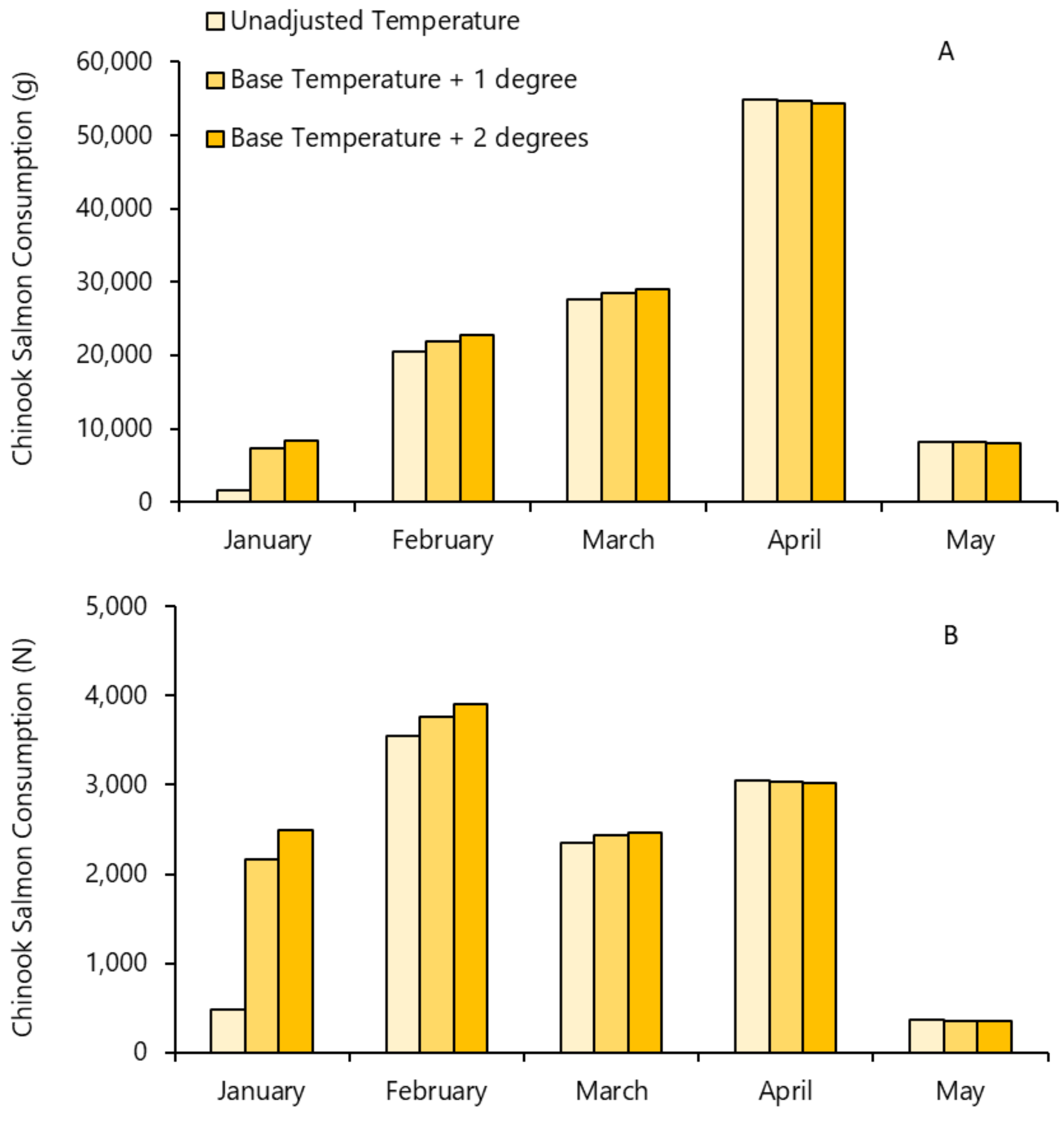

Figure 5. Simulated Chinook Salmon consumption by Striped Bass in the San Joaquin River, CA over three different San Joaquin River temperatures regimes (measured temperature with no adjustment, adding 1°C and adding 2°C).
A: Biomass of Chinook Salmon consumed (g).
B: Number of individual Chinook Salmon consumed (N) calculated from Biomass consumed and average Chinook Salmon weight (g).

4.0 Discussion

The population and bioenergetics models presented here represent simplistic estimates of Striped Bass population and salmon consumption within the lower reaches (4b and 5) of the Restoration

Area from 2019 to 2021. Model results should be interpreted cautiously because they are based on a small dataset within a brief temporal period. Estimates of juvenile salmon consumption did not account for prey availability or predator interactions and were extrapolated based on population estimates. Even with these limitations, these results present important information for better understanding the population and predator-prey interactions within the San Joaquin River.

Understanding the dynamics of the Striped Bass population and estimated consumption of Chinook Salmon over changing conditions (i.e., water temperature) could help improve conceptual models and identify the most effective periods and locations for management actions, such as predator removals, habitat restoration, juvenile Chinook Salmon release strategies, etc. As the population model (Figure 3) and catch results (Figure 6) demonstrate, the population of the Striped Bass in Reach 5 of the Restoration Area was highest in April and May. This overlaps with peak juvenile salmon smolt emigration (Hutcherson et al. 2020), and actions to reduce predator effects during this time may have the greatest impact on reducing salmon loss.

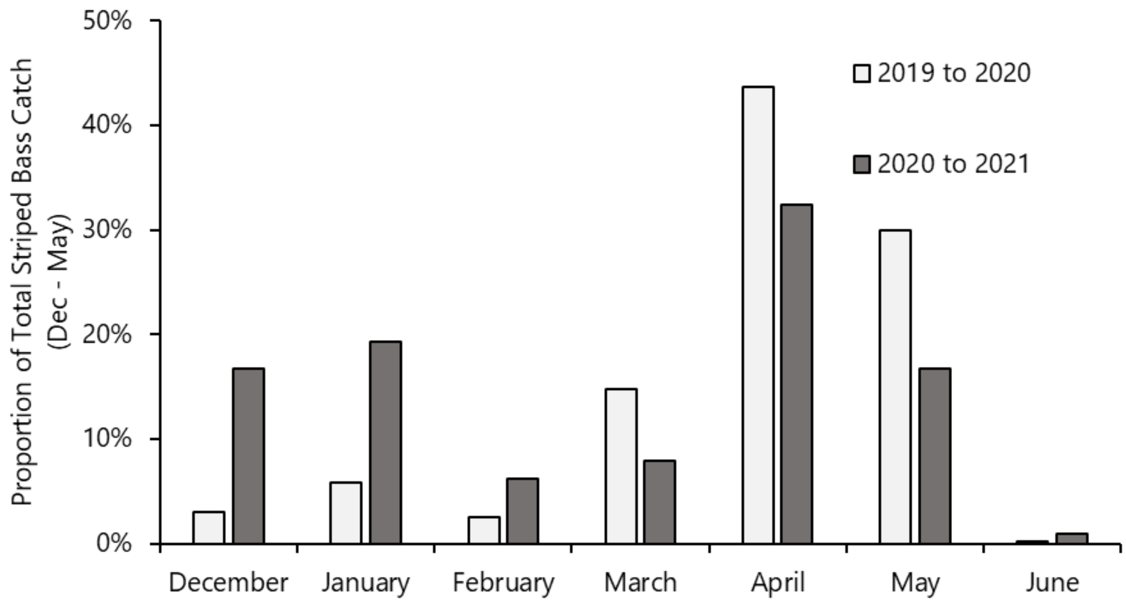

Figure 6. Proportion of total Striped Bass catch by month and sampling season (December to May) of 2019/2020 and 2020/2021 SJRRP's Central Valley Steelhead Monitoring and Adult Spring-Run Chinook Salmon Monitoring, Trap and Haul programs using electrofishing, Fyke nets and Fyke traps.

The bioenergetics model suggests consumption of individuals (N) is highest in February (Figure 4b) when salmon are smaller and less developed. However, juvenile salmon are not likely present in abundance in Reaches 4b and 5 during that timeframe as juvenile salmon monitoring in Reach 1 indicates most salmon initiate downstream emigration in March and April (Hutcherson et al. 2020). As these estimates are based on the caloric requirements of fixed diets and not prey availability, until competing data is presented, the SJRRP should focus data interpretation to what is presented for March – May timeframe. Decreased Chinook Salmon consumption in May (Figure 4) could be attributed to reduced metabolic efficiency driven by increased river temperatures and, to a larger extent, the fewer Striped Bass in the area as predicted by the POPAN model.

Striped Bass were selected as the primary species of interest due to their frequency of capture during other SJRRP studies and reported impacts on salmon, but other species should also be considered if a complete understanding of salmon predation loss in the Restoration Area is of concern. For example, Michel et al. (2018) reported salmonids comprised over 30 percent of the diets of Channel Catfish (*Ictalurus punctatus*) from the San Joaquin River. Channel Catfish are the second most frequently encountered large piscivore during steelhead and adult Chinook Salmon monitoring (Figure 1). Additional common piscivores within the Restoration Area include Largemouth Bass (*Micropterus salmoides*), White Catfish (*Ameiurus catus*), Green Sunfish (*Lepomis cyanellus*), and Black Crappie (*Pomoxis nigromaculatus*); Michel et al. 2018, Sutphin and Root 2021). The interaction between these predators and Striped Bass, as well as their direct or indirect influence on juvenile salmon should be considered.

As the population and biogenetic models suggest, Striped Bass in the Restoration Area have the potential to consume large amounts of juvenile salmon during their emigration. Further data are needed to better quantify the risk by Striped Bass and other predators on juvenile salmon and to inform management actions.

5.0 Model Limitations and Future Research Considerations

Results of the models presented here provide broad estimates of Striped Bass population levels and potential Chinook salmon consumption extrapolated from population estimates. Supplemental data and studies will be necessary to increase the precision of model outputs and refine model design and inputs. Potential future efforts could focus on but should not be limited to:

- Additional years of capture history for monthly population estimates.
- Localized estimates of the feeding frequency, diet composition/prey selection, and stomach fullness of Striped Bass measured by non-lethal stomach content sampling of captured fish (i.e., gastric lavage) and subsequent DNA and/or physical analysis.
- Evaluating the impact of temporal, predator or prey size-dependence, flow and temperature changes on the metabolic efficiency or feeding behavior of Striped Bass.
- Exploring the distribution and catchability of juvenile salmonids within the lower reaches of the RA
- Assessing the effects of predator interactions on feeding behavior or distribution within the RA.
- Exploring habitat restorations that benefit juvenile salmon but reduce predator consumption

Striped Bass have shown variability in behavior and diet (Sabal et al. 2016) and the more data collected from individuals within the San Joaquin River, the more accurately models can aid management decisions.

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Appendix A:

Model Variables and Parameters

Table A-1. Fish Bioenergetics 4.0 standard inputs (see Hanson et al.1997 and Deslauriers et al. 2017)

Initial Settings	Species	*Striped Bass (select target Age-class)
	Initial Day	1
	Final Day	*28, 30, or 31, depending on month
	Initial Weight (g)	*Monthly average weights by age-class. Derived from average TL (n = 1051) of Striped Bass captured 2018-2021 (Root and Sutphin 2021; Sutphin and Root 2021) and published length-weight relationships (Nobriga and Branch 2009). *See Tables A-2 (Size Class) and A-4 (Monthly Parameters)*
	Oxycaloric Coefficient (J/g 02)	13,569 (J/g) O2 (Loboschefsky, et al. 2012)
	Fit to	p-value (proportion of Cmax)
	(Fit to Value)	*Binned Cmax values from literature determined by average monthly temperature and age-class *See Table A-3 (Cmax)* **Experimental Simulations: Adding 1 or 2 ?C to monthly temperature.**
Input Files (.csv)	Water Temperature	*Average monthly temperature between 2020 and 2021 collected from California Data Exchange Center SMN gauging station. *See Table A-4* **Experimental Simulations: Adding 1 or 2 ?C ?C to monthly temperature.**
	Prey Composition (Diet_prop)	*Standard 10% (Sabal et al. 2016) **Experimental Simulations: 50% (Sabal et al. 2016), 80% (Blackwell and Juanes 1998)**
	Prey Energy Density (Prey_E)	Chinook Salmon = 4800 J/g (Adrean 2011)
	Predator Energy Density (Pred_E)	*Determined by Age-class (Loboschefsky, et al. 2012) *See Table A-2*
	Indigestible Prey	3 % (Hanson et al. 1997)

*Input dependent on simulation (Month, Age-class, Diet, Temperature Change)

Table A-2. Size Class and Energy Density for Striped Bass. Adapted from *Mansueti (1961) and **Loboschefsky et al. (2012).

Species	Minimum Total Length (mm)*	Maximum Total Length (mm)*	Energy Density (J/g)**
Striped Bass Age-1	150	< 300	5659.5
Striped Bass Age-2	300	< 400	6860
Striped Bass Adult/Age-3+	400	+	7681

Table A-3. Proportion of Cmax (Maximum Consumption) Variable (P-Value). Adapted to bin categories from Hartman and Brandt (1995).

Parameter Value	**P-Value**		
Temperature Range	*Age-1*	*Age-2*	*Age-3+*
6? to 10? C	0.262	0.255	0.323
11 ? to 30? C	0.98	0.98	0.98
> 30? C	0.85	0.9	0.85

Table A-4. Monthly Parameter Tables

Use	**Parameter**	**January**	**February**	**March**	**April**	**May**
Input Settings for Fish Bioenergetics 4.0	Striped Bass Age-1 Weight (g)*	109.07	86.91	141.55	109.38	225.79
	Striped Bass Age-2 Weight (g)	491.29	596.94	582.57	571.9	529.44
	Striped Bass Age-3+ Weight (g)	1,661.44	1,510.58	1,919.40	1,417.57	1,435.38
Input Files for Fish Bioenergetics 4.0	San Joaquin River Temperature 2021 (?C)***	9.49	12.13	13.21	18.54	20.76
Post Processing Calculations	Chinook Salmon Weight (g)**	3.36	5.81	11.75	18.03	22.51
	Average Population Size from POPAN Model (N)****	63.37	127.5	108.78	250.01	41.12
	Proportion of Age 1 of Captured Fish	0.2	0.059	0.019	0.001	0.01
	Proportion of Age 2 of Captured Fish	0.24	0.176	0.097	0.073	0.27
	Proportion of Age 3 of Captured Fish	0.56	0.765	0.883	0.926	0.719

*Striped Bass weight calculated from Striped Bass captured between 2018 and 2021 (Root and Sutphin 2021, Sutphin and Root 2021).
**Chinook Salmon Weight measured in RST operations between 2017 and 2021 (Hutcherson personal communication 2023).
***Temperature measured in SJRRP and recovered from California Data Exchange Center gauging station.
**** Averaged output of POPAN model by Month
Proportion of Age-class by month calculated from Striped Bass captured between 2018 and 2021 (Root and Sutphin 2021, Sutphin and Root 2021) using length-at-age estimates derived from Mansueti (1961).