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Optimal Carbon Dioxide Concentration for Removal of Striped Bass From the Bypass Pipes and Secondary Channel

Tracy Fish Facility Improvement Program
California-Great Basin · Interior Region 10

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14. ABSTRACT
Predation contributes to fish loss at the Tracy Fish Collection Facility (TFCF), and Striped Bass (*Morone saxatilis*) are considered the most prevalent piscivorous fish species within the facility. To estimate optimal carbon dioxide (CO_2) concentration for removal of juvenile and adult Striped Bass based on removal effectiveness and 96.0-h post-treatment survival, consecutive CO_2 insertions (in the form of dry ice) were performed in the TFCF bypass pipes and secondary channel. While CO_2 concentration significantly influenced removal effectiveness, it did not significantly influence 96.0-h survival. Instead, 96.0-h survival was significantly influenced by water temperature, with higher water temperatures associated with reduced survival. It is recommended the lowest CO_2 concentration estimated to generally be 100% effective at removing Striped Bass (i.e., 185.0 mg/L) be used during predator removals in the bypass pipes and secondary channel at the TFCF. To obtain a CO_2 concentration of 185.0 mg/L within the TFCF bypass pipes and secondary channel using current procedures, approximately 89.8 kg (198.0 lbs) of dry ice should be inserted into each bypass pipe for each treatment. If survival of Striped Bass is a concern, CO_2 predator removals should be avoided at the TFCF when water temperatures exceed 20.0 °C.

15. SUBJECT TERMS
Tracy Fish Collection Facility, predation, piscivorous, fish loss, anesthesia, removal effectiveness, survival, water temperature, Sacramento-San Joaquin River Delta, Striped Bass (Morone saxatilis), optimal carbon dioxide (CO_2) concentration

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Optimal Carbon Dioxide Concentration for Removal of Striped Bass from the Bypass Pipes and Secondary Channel

Tracy Fish Facility Improvement Program
California-Great Basin · Interior Region 10

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Disclaimer

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Executive Summary

The Tracy Fish Collection Facility (TFCF) was constructed by the U.S. Department of the Interior, Bureau of Reclamation (Reclamation), to divert and salvage fish from Sacramento-San Joaquin River Delta (Delta) water destined for export by the C.W. "Bill" Jones Pumping Plant (JPP). To improve the overall salvage process and efficiency of the TFCF, it is necessary to minimize fish loss throughout the facility. Predation contributes to fish loss at the TFCF (Liston et al. 1994, Fausch 2000, Sutphin et al. 2014, Karp et al. 2017, Bridges et al. 2019, Wu et al. 2021), and Striped Bass (*Morone saxatilis*) are considered the most prevalent piscivorous fish species because they are capable of accumulating throughout the facility, including in front of the trashrack, in the primary channel, in bypass pipes, and in the secondary channel (Liston et al. 1994, Sutphin et al. 2014, Bridges et al. 2019).

In 2004, a predator removal method using carbon dioxide (CO_2; in the form of dry ice) was approved for study. Insertion of dry ice does not reduce daily salvage due to secondary channel downtime (i.e., dewatering of the secondary channel) and is likely more efficient and safer for employees and fish than the historic predator removal methods employed at the TFCF (i.e., dip netting, seining, and flushing fish into fyke nets when the secondary channel was dewatered; Wu and Bridges 2014). An initial evaluation of the use of CO_2 as an alternative predator removal technique in the TFCF bypass pipes and secondary channel was completed in September 2007 and demonstrated that elevated CO_2 concentrations are effective for moving piscivorous fish from the bypass pipes and secondary channel to the holding tanks (Wu and Bridges 2014). Results from this initial evaluation have been published as a Tracy Series Report (Wu and Bridges 2014), although the authors did not recommend a CO_2 concentration that should be used upon implementation of this method during monthly efforts to remove piscivorous fish from the TFCF bypass pipes and secondary channel. To estimate the optimal CO_2 concentration for removal of juvenile and adult Striped Bass based on removal effectiveness and 96.0-h post-treatment survival, consecutive dry ice insertions were performed in the TFCF bypass pipes and secondary channel using initial treatments with varying CO_2 concentration immediately followed by treatment with approximately 200.0–300.0 mg/L CO_2 to remove any fish that may have remained after initial CO_2 treatments.

While CO_2 concentration significantly influenced Striped Bass removal effectiveness within the range of initial CO_2 concentrations tested (i.e., 18.0–300.0 mg/L; with higher CO_2 concentrations associated with greater removal effectiveness), it did not independently appear to have a significant influence on 96.0-h post-treatment survival. In addition, size of Striped Bass (within the range of 85.4–507.7 mm average FL) did not appear to have a significant independent influence on 96.0-h post-treatment survival. It was determined that 96.0-h post-treatment survival was significantly influenced by water temperature, with higher water temperatures associated with reduced survival. Based on these results, it is recommended that the lowest CO_2 concentration estimated to generally be 100% effective at removing Striped Bass (i.e., 185.0 mg/L) be used during monthly predator removals in the bypass pipes and secondary channel at the TFCF. To obtain a CO_2 concentration of 185.0 mg/L within the TFCF bypass pipes and secondary channel using current procedures, approximately 89.8 kg (198.0 lbs) of dry ice should be inserted into each bypass pipe for each treatment. If survival of Striped Bass is a concern, CO_2 predator removals should be avoided at the TFCF when Delta water temperatures exceed 20.0 °C.

Introduction

The Tracy Fish Collection Facility (TFCF; Figure 1) was constructed in the mid-1950s by the Department of the Interior, Bureau of Reclamation (Reclamation), to divert and salvage fish from Sacramento-San Joaquin River Delta (Delta) water destined for export by the C.W. "Bill" Jones Pumping Plant (JPP) for primarily agricultural use in the southern San Joaquin Valley (Reyes et al. 2018). To improve the overall salvage process and efficiency of the TFCF, it is necessary to minimize fish loss throughout the facility. Predation by piscivorous fish is a contributing factor to fish loss at the TFCF (Liston et al. 1994, Fausch 2000, Sutphin et al. 2014, Karp et al. 2017, Bridges et al. 2019, Wu et al. 2021) as predators accumulate throughout the facility, including in front of the trashrack, in the primary channel, in bypass pipes, in the secondary channel, and in holding tanks (Liston et al. 1994, Sutphin et al. 2014, Bridges et al. 2019).

Over the years, Reclamation has considered various methods and techniques (e.g., behavioral repellants [light, sound, electricity, chains, bubble curtains, and various visual cues], increased water flow fields and water velocity, dewatering the TFCF secondary channel for physical removal of predators, mechanical crowding of fish, and grading of fish) for removal of piscivorous fish from the TFCF (Liston et al. 1994, Fausch 2000, Sutphin et al. 2014). A predator removal program in the bypass pipes and secondary channel (Figure 1) was studied and implemented in the early 1990s (Liston et al. 1994) and continued through the decade. Predators were flushed into fyke nets, seined, and dip netted out during times when the secondary channel was drained. Striped Bass (*Morone saxatilis*) were the main piscivorous fish species and fish up to 700.0 mm total length were removed (Liston et al. 1994). Other abundant piscivorous fish species at the TFCF include White Catfish (*Ameiurus catus*), Channel Catfish (*Ictalurus punctatus*), Largemouth Bass (*Micropterus salmoides*), Bluegill (*Lepomis macrochirus*), and Redear Sunfish (*L. microlophus*; Sutphin et al. 2014, Wu and Bridges 2014). Stomach analyses of some of these fish have yielded, among others, Chinook Salmon (*Oncorhynchus tshawytscha*), Delta Smelt (*Hypomesus transpacificus*), and Threadfin Shad (*Dorosoma petenense*; Liston et al. 1994, Sutphin et al. 2014).

In 2004, an alternative predator removal method using carbon dioxide (CO_2) was approved for study. Injection of CO_2 does not reduce daily salvage due to secondary channel downtime (i.e., dewatering of the secondary channel) and is likely more efficient and safer for employees and fish than the historic predator removal methods employed at the TFCF (i.e., dip netting, seining, and flushing fish into fyke nets when the secondary channel was dewatered; Wu and Bridges 2014). An initial evaluation of the use of CO_2 as an alternative predator removal technique in the TFCF bypass pipes and secondary channel was completed in September 2007 and demonstrated that elevated CO_2 concentrations are effective for moving piscivorous fish from the bypass pipes and secondary channel to the holding tanks (Wu and Bridges 2014). Results from this initial evaluation have been published as a Tracy Series Report (Wu and Bridges 2014), although the authors did not recommend a CO_2 concentration that should be used upon implementation of this method during monthly efforts to remove piscivorous fish from the TFCF bypass pipes and secondary channel. To estimate the optimal CO_2 concentration for removal of Striped Bass based on removal effectiveness and 96.0-h post-treatment survival, consecutive CO_2 insertions (in the form of dry ice) were performed in the TFCF bypass pipes and secondary channel using initial treatments with varying

CO_2 concentration (18.0–300.0 mg/L) to remove naturally accumulated wild Striped Bass, followed by subsequent treatment with approximately 200.0–300.0 mg/L CO_2 to remove any wild Striped Bass that may have remained after initial CO_2 treatments.

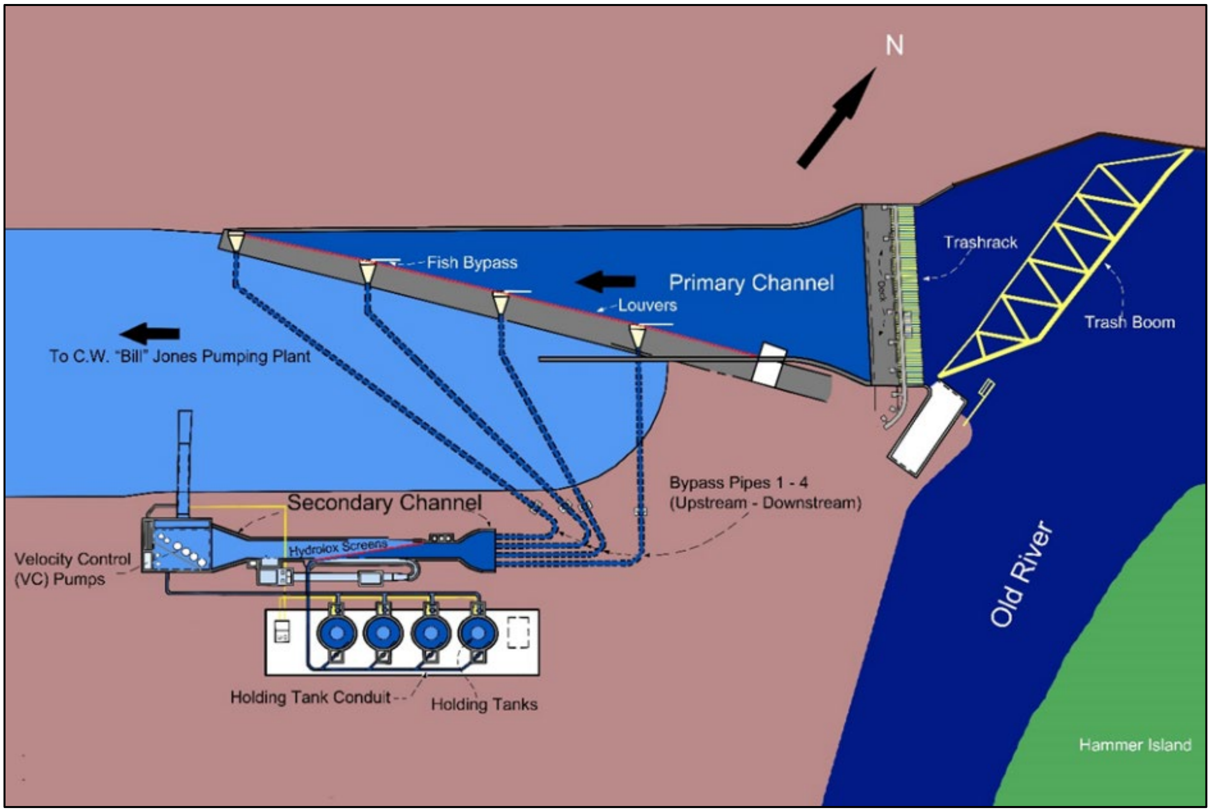

Figure 1.—Diagram of the Tracy Fish Collection Facility (Bureau of Reclamation, Byron, California) showing major facility components, including the trashrack, primary channel, bypass pipes 1–4, secondary channel, and holding tanks.

Methods

Data collection efforts for this study occurred between July 2010 and November 2019 with the intention of performing replicates throughout the yearly range of water temperatures (i.e., 5.8–28.9 °C for July 2010 through November 2019 [CDFW 2022]) and total alkalinities (generally around 50–100 mg/L calcium carbonate [$CaCO_3$; Wu et al. 2014]) observed at the TFCF. This was necessary because these parameters potentially affect the maximum CO_2 concentration that can be obtained at a given pH (Wu and Bridges 2014). There were varying numbers of Striped Bass evaluated per replicate during this study since procedures involved the removal of naturally accumulated wild Striped Bass from the TFCF bypass pipes and secondary channel, and there were differing periods of time allowed for Striped Bass to recolonize these areas of the facility. Replicates were used for analyses if at least 1 naturally accumulated wild Striped Bass was collected in either the initial treatment with varying CO_2 concentration or the subsequent treatment with approximately 200.0–300.0 mg/L CO_2. Fifteen replicates were used to evaluate both removal effectiveness and 96.0-h post-treatment survival, while an additional 5 replicates were used to evaluate only 96.0-h post-treatment survival because it was not possible to develop removal effectiveness estimates for these replicates due to lack of subsequent treatments with approximately 200.0–300.0 mg/L CO_2.

Blocks of dry ice (5.0 kg, 25 x 25 x 5 cm [l x w x h]) were provided by Innovative Federal Operations Group, LLC (Vista, California) the day before insertion and stored in large outdoor coolers (0.85 m^3; Polar Tech Industries, Inc., Genoa, Illinois) at the TFCF. Approximately one h prior to each CO_2 treatment, a predetermined amount of dry ice was removed from storage coolers and placed in smaller coolers (0.14 m^3; Igloo Products Corp., Katy, Texas), which were relocated to the primary channel louver deck near the primary bypass pipe entrances. Dry ice blocks were not weighed prior to being placed into smaller coolers and, based on manufacturer's specifications and sublimation rate estimates, it was assumed that each full block weighed 4.5 kg at the time of insertion (5.0 kg upon delivery minus 10.0% [0.5 kg] sublimation loss per day in storage coolers; Wick 2022, personal communication). This approximation was deemed appropriate since determining the exact weight of dry ice at the time of insertion into each bypass pipe would be difficult because CO_2 continuously sublimates from dry ice at variable rates based on environmental conditions; therefore, even with weighing of the dry ice blocks prior to insertion, the amount of dry ice inserted would likely variably differ from the amount that was weighed.

Prior to each replicate, temperature (°C) and total alkalinity (mg/L $CaCO_3$) of the Delta water was measured using a YSI Pro 2030 DO/conductivity/temperature meter (YSI Incorporated, Yellow Springs, Ohio) and hand-held titration cells (hydrochloric acid titrant and a bromocresol green/methyl red pH indicator; K-9815 [range = 50–500 mg/L $CaCO_3$], CHEMetrics Inc., Midland, Virginia), respectively, and the number of secondary channel Velocity Control (VC) pumps in operation was adjusted to obtain reduced water flow in the TFCF bypass pipes and secondary channel. Water flow was then diverted into an empty holding tank and dry ice was inserted into the bypass pipes to obtain target CO_2 concentrations of 18.0–300.0 mg/L for initial CO_2 treatment. Reduced water flow was maintained in the bypass pipes and secondary channel for 15 minutes to allow sufficient contact time between the CO_2 gas and water (Wu and Bridges 2014). Dry ice could only be inserted into two bypass pipes simultaneously due to limited availability of personnel to perform insertion; therefore, the longer bypass pipes (bypass pipes 3 and 4 (84.0 m long and

97.0 m long, respectively [Reyes et al. 2018]; Figure 1) were treated first, followed by the shorter pipes (bypass pipes 1 and 2; 64 m long and 69 m long, respectively [Reyes et al. 2018]; Figure 1). This was done so that the peak CO_2 concentration in each bypass pipe reached the secondary channel at approximately the same time.

To obtain water samples for monitoring pH and CO_2 concentration, a 1/5-hp submersible pump (Alita Co., Ltd, Baldwin Park, California) and rubber hose (15.9-mm diameter x 30.5-m long) were installed in the TFCF secondary channel. A 3.6-kg weight was attached to the pump before installation to reduce downstream drift in the secondary channel. To install the pump, a 9.5-mm diameter rope was used to lower the pump into the secondary channel, upstream of the Hydrolox™ traveling screens (Figure 1). Using the rope, the pump was secured so that it was centered and maintained at approximately mid-water depth within the upstream secondary channel. The free end of the hose was brought up to a working surface and placed in a cup along with a pH meter probe (pH 110 Series; Oakton Instruments, Vernon Hills, Illinois). With this arrangement, pH was continuously monitored throughout the 15-minute reduced flow treatment period. Since CO_2 acts as an acid in water and produces a predictable drop in pH (Hargreaves and Brunson 1996), CO_2 concentration was measured from a water sample taken at the lowest observed pH to estimate the maximum CO_2 concentration that was achieved during each initial CO_2 treatment. Hand-held titration cells (sodium hydroxide titrant and phenolphthalein indicator; K-1910 [range = 10–100 mg/L CO_2] and K-1920 [range = 100–1,000 mg/L CO_2]; CHEMetrics Inc., Midland, Virginia) were used to take all CO_2 measurements, and it was assumed maximum CO_2 concentrations measured from mid-water depth samples at the center of the upstream secondary channel were representative of maximum CO_2 concentrations in the bypass pipes and all other locations within the upstream secondary channel.

After the 15-minute reduced water flow period, the number of secondary channel VC pumps in operation was adjusted to obtain increased water flow in the bypass pipes and secondary channel for 15 minutes to flush anesthetized fish downstream into a holding tank. After conclusion of the 15-minute increased flow period, water flow was diverted to an empty holding tank, reduced in the bypass pipes and secondary channel, and the process was repeated with the insertion of approximately 136.1 kg (300.0 lbs) of dry ice per bypass pipe with the intention of obtaining a subsequent CO_2 concentration of approximately 200.0–300.0 mg/L in the bypass pipes and secondary channel to remove any fish that may have remained after the initial CO_2 treatment. Carbon dioxide concentrations of approximately 200.0–300.0 mg/L were deemed appropriate to achieve 100% removal of Striped Bass from the TFCF bypass pipes and secondary channel over a 15-minute treatment period since Wu and Bridges (2014) found that Striped Bass generally reached total loss of equilibrium within 10 minutes when CO_2 concentration in the water was $\geq$ 150 mg/L.

Fish collected during each CO_2 treatment were removed from holding tanks (using a 1,544.5-L [408.0-gal] stainless steel fish-haul bucket and a 4-ton electric chain hoist [R&M Loadmate LM20, R&M Materials Handling, Inc., Springfield, Ohio]) and separately transferred to a 2002.1-L (528.9-gal) rectangular trough (356 cm long x 74 cm wide x 76 cm high) equipped with aeration and flow-through raw Delta water. Fish in each holding tank sample were identified and the total number of each fish species in each sample was determined. All fish other than Striped Bass were released back into TFCF salvage for truck transport to the Delta. The number of naturally accumulated wild Striped Bass collected during initial CO_2 treatment, along with the total number of naturally accumulated wild Striped Bass collected per replicate (i.e., during initial and subsequent CO_2 treatments combined), allowed for the estimation of removal effectiveness for each initial

CO_2 concentration tested (i.e., Striped Bass removal effectiveness = # of Striped Bass removed during initial CO_2 treatment/[# of Striped Bass removed during initial CO_2 treatment + # of Striped Bass removed during subsequent CO_2 treatment with approximately 200.0–300.0 mg/L CO_2]).

Ninety-six-h post-treatment survival was determined only for wild Striped Bass collected during initial CO_2 treatments. Survival of wild Striped Bass collected during subsequent treatments with approximately 200.0–300.0 mg/L CO_2 was not determined because fish collected in these samples were exposed to multiple CO_2 concentrations. If more than 80 Striped Bass were collected during an initial CO_2 treatment, a representative subsample of at least 25 Striped Bass was taken into captivity to determine 96.0-h post-treatment survival. Representative subsamples of Striped Bass were randomly chosen and included fish that were noticeably injured and/or unwell since there was no way of accurately discerning which injuries or ailments were potentially due to CO_2 exposure.

Striped Bass that were not taken into captivity for monitoring of 96.0-h post-treatment survival were measured (mm fork length [FL]) and released. Striped Bass saved for evaluation of 96-h survival were removed from the rectangular trough using dipnets with 15.0-cm x 7.0-cm dipped nylon mesh (43.2-cm x 48.3-cm hoop frame, 55.9-cm net depth, 63.5-cm handle; Bass Pro Shops, Springfield, Missouri) and placed in 142.0-L ice chests (Igloo Products Corp., Katy, Texas) containing oxygenated raw Delta water. These Striped Bass were then transported to the Tracy Aquaculture Facility (TAF) and placed in black 757.1-L circular tanks at densities no greater than 5 fish/tank. Throughout the 96.0-h post-treatment survival investigations, each tank was provided aerated, flow-through, filtered and settled Delta water at ambient Delta water temperature. Salt was not applied to water within the tanks and fish were not fed during the 96.0-h observation period. While it is possible that the process of collecting Striped Bass and handling/transferring them to tanks within the TAF was inherently stressful and potentially contributed to some level of mortality during 96.0-h post-treatment monitoring, it was assumed any impact of inherent stress on 96.0-h survival was negligible and similar for all Striped Bass collected during initial CO_2 treatments and retained for 96.0-h post-treatment survival investigations (i.e., it was assumed all Striped Bass retained for 96.0-h post-treatment survival investigations encountered the same amount of inherent stress, and differences in 96.0-h survival were solely dependent on CO_2 concentration during initial CO_2 treatments).

Water quality (Dissolved Oxygen [DO; mg/L] and temperature [° C]) was measured daily from each survival monitoring tank using a YSI Pro 2030 DO/conductivity/temperature meter. In addition, each fish was visually verified to be alive daily. If mortalities were observed, the dead fish was removed from the tank and measured (mm FL) before being disposed. At the conclusion of 96.0-h post-treatment survival investigations, all living Striped Bass were removed from survival tanks and measured (mm FL). Survival for each initial CO_2 concentration was estimated based on the proportion of Striped Bass that remained alive for the entire 96.0-h post-treatment period. There was a lack of control groups during the 96.0-h post-treatment survival investigations because it was not always possible to readily collect juvenile and adult Striped Bass in the TFCF holding tanks without CO_2 treatment unless there was exceptionally high secondary channel velocity during increased flow periods due to an atypically low incoming tide.

Data Analyses

Multivariate analysis was not used during this study because this approach does not compare tests of significance with the statistical software package employed (i.e., Minitab 20); therefore, interpreting results of multivariate analysis is somewhat subjective (Minitab 2003). In addition, multivariate analysis was not employed because the dataset for this study was small and there was an inability to control certain independent variables. Instead of multivariate analysis, polynomial regression analysis was employed to determine if significant relationships exist between independent variables (i.e., CO_2 concentration, water temperature, and fish size) and dependent variables (i.e., removal effectiveness and 96.0-h post-treatment survival). Since polynomial regression analysis does not investigate interactions between independent variables, ability to interpret univariate analyses during this study may be limited.

Polynomial regression analysis (Minitab 20; Minitab, State College, Pennsylvania) was used to determine if significant dose-capture and dose-survival responses existed within the range of initial CO_2 concentrations tested (18.0–300.0 mg/L). In addition, polynomial regression analysis was used to determine if removal effectiveness and 96.0-h post-treatment survival were significantly influenced by Striped Bass size (i.e., average FL) or water temperature (°C). Scatterplots with best-fit trendlines matching polynomial regressions used for analysis (Excel 365; Microsoft Corporation, Redmond, Washington) were used to illustrate the effects of CO_2 concentration, Striped Bass size, and water temperature on Striped Bass removal effectiveness and 96.0-h post-treatment survival. A scatterplot with linear trendline (Excel 365) illustrating the relationship between amount of dry ice inserted (kg) and maximum CO_2 concentration obtained (mg/L) during CO_2 treatments performed at the TFCF throughout the yearly range of water temperatures and total alkalinities observed at the facility (inclusive of initial and subsequent CO_2 treatments from this study, as well as CO_2 treatments performed outside this study [i.e., unpublished data from monthly CO_2 predator removals at the TFCF]) was used to recommend an approximate amount of dry ice (kg) that should be inserted into each TFCF bypass pipe to approximately obtain the optimal CO_2 concentration in the bypass pipes and secondary channel.

Results and Discussion

During this study, there was 0.04–478.9 d (1.0–11,493.6 h) between replicates and the most recent prior predator removal activity (Appendix A [Table A-1]). This information, along with the total number of Striped Bass removed during each replicate (2–606 fish), allowed for estimation of Striped Bass recolonization rate in the TFCF bypass pipes and secondary channel. Average (minimum–maximum) Striped Bass recolonization rate during this study was 33.3 fish/d (0.1–250.0 fish/d), although the average size (i.e., average FL) of Striped Bass collected was highly variable (85.4–503.0 mm average FL; Appendix A [Table A-1]). The high variability in Striped Bass recolonization rate and average size (i.e., average FL) throughout this study (Appendix A [Table A-1]) indicates these factors fluctuate throughout the year and are likely seasonally dependent, which suggests the current monthly frequency of predator removal activity within the TFCF bypass pipes and secondary channel may not be adequate during all times of the year.

Average (minimum–maximum) water depth in the TFCF secondary channel, average (minimum–maximum) water velocity in the TFCF secondary channel, and average (minimum–maximum) water flow in the TFCF secondary channel during reduced flow and increased flow periods of initial and subsequent CO_2 treatments are reported in Appendix B (Tables B-1 and B-2). In general, hydraulic data from this study demonstrated that secondary channel water depth, secondary channel water velocity, and secondary channel water flow were similar between initial and subsequent CO_2 treatments but varied among reduced flow and increased flow periods.

The maximum CO_2 concentration obtained in the TFCF secondary channel during initial CO_2 treatments ranged from 18.0–300 mg/L (Appendix C [Table C-1] and Appendix D [Table D-1]) and varied mainly because differing amounts of dry ice were inserted per bypass pipe. It is also possible differences in secondary channel water depth during reduced flow periods of initial CO_2 treatments (range = 1.6–3.3 m; Appendix B [Table B-1]), differences in secondary channel water velocity during reduced flow periods of initial CO_2 treatments (range = 0.1–0.3 m/s; Appendix B [Table B-1]), differences in secondary channel water flow during reduced flow periods of initial CO_2 treatments (range = 0.5–1.8 m^3/s; Appendix B [Table B-1]), differences in temperature of Delta water at the time of initial CO_2 treatment (range = 10.8–26.1 °C; Appendix C [Table C-1]; Hargreaves and Brunson 1996, Wu and Bridges 2014), and/or differences in total alkalinity of Delta water at the time of initial CO_2 treatment (range = 50.0–110.0 mg/L $CaCO_3$; Appendix C [Table C-1]); Hargreaves and Brunson 1996, Wu and Bridges 2014) contributed to variability of maximum CO_2 concentrations obtained during initial CO_2 treatment.

The maximum CO_2 concentration obtained during subsequent CO_2 treatments with approximately 136.1 kg (300.0 lbs) of dry ice per bypass pipe ranged from 195.0 to 300.0 mg/L and averaged 267.3 mg/L (Appendix C [Table C-1]). Variability in the maximum CO_2 concentration obtained during subsequent CO_2 treatments with the insertion of the same amount of dry ice per bypass pipe was potentially due to differences in secondary channel water depth during reduced flow periods (range = 1.7–3.2 m; Appendix B [Table B-2]), differences in secondary channel water velocity during reduced flow periods (range = 0.1–0.2 m/s; Appendix B [Table B-2]), differences in secondary channel water flow during reduced flow periods (range = 0.5–1.1 m^3/s; Appendix B [Table B-2]), differences in temperature of Delta water at the time of CO_2 treatment (range = 10.8–26.1 °C;

Appendix C [Table C-1]; Hargreaves and Brunson 1996, Wu and Bridges 2014), and/or differences in total alkalinity of Delta water at the time of CO_2 treatment (range = 50.0–110.0 mg/L $CaCO_3$; Appendix C [Table C-1]); Hargreaves and Brunson 1996, Wu and Bridges 2014).

Removal Effectiveness

CO_2 Concentration vs. Removal Effectiveness

Regression analysis demonstrated that a significant dose-capture relationship exists for Striped Bass within the range of initial CO_2 concentrations tested (18.0–300.0 mg/L; $P = 0.001$; polynomial regression analysis), with higher CO_2 concentrations associated with greater Striped Bass removal effectiveness (Figure 2; Appendix C [Table C-1]). The best-fit trendline for maximum CO_2 concentration versus Striped Bass removal effectiveness yields a substantial R^2 value (Chin 1998; $R^2 = 0.71$) and suggests the lowest CO_2 concentration that is generally 100% effective at removing Striped Bass from the bypass pipes and secondary channel at the TFCF is approximately 185.0 mg/L (Figure 2). It is important to note the best-fit trendline for maximum CO_2 concentration versus Striped Bass removal effectiveness provides an average/mean estimate of removal effectiveness for a given maximum CO_2 concentration; therefore, Figure 2 includes data points showing 100% removal effectiveness for maximum CO_2 concentrations less than 185.0 mg/L, as well as data points showing removal effectiveness less than 100% for maximum CO_2 concentrations greater than 185.0 mg/L. Observations during data collection suggest removal effectiveness estimates were potentially reduced due to delayed collection of Striped Bass anesthetized during initial CO_2 treatments (i.e., collection of anesthetized Striped Bass from initial CO_2 treatments after initiation of subsequent CO_2 treatments), which may have been caused by impingement on structures within the secondary channel or holding tank conduit. Since there is presumably a greater probability of impingement with increased extent of Striped Bass anesthesia/immobilization reached, it is likely removal effectiveness estimates developed for higher CO_2 concentrations within the range tested (i.e., $\geq$ 150 mg/L) were predominantly affected by potential delay in collection of anesthetized Striped Bass.

A CO_2 concentration of 185.0 mg/L is higher than the range of concentrations estimated by Wu and Bridges (2014) to be optimal for the removal of Striped Bass from the TFCF bypass pipes and secondary channel with a 10-minute exposure time (50.0-150.0 mg/L), although it is comparable to the threshold CO_2 concentration that elicited avoidance behaviors from juvenile Bighead Carp (*Hypophthalmichthys nobilis*) while using a "shuttle box" choice arena (Loligo Inc., Hobro, Denmark) in a laboratory setting (180 $\pm$ 32 mg/L; Dennis et al. 2015), and is also within the range of CO_2 concentrations determined to effectively deter upstream movement of adult Bighead Carp and Grass Carp (*Ctenopharyngodon idella*) throughout navigation locks and other pinch-points (121.0–213.0 mg/L; Cupp et al. 2020). In addition, a CO_2 concentration of 185.0 mg/L is lower than the concentration found by Wu and Bridges (2014) to cause mortality in Striped Bass and Chinook Salmon after 20 minutes of exposure (250.0 mg/L and 300.0 mg/L, respectively).

While a CO_2 concentration of 185.0 mg/L is greater than the concentration found to induce mortality in Delta Smelt by Wu and Bridges (2014; 60.0% mortality over 96.0 hours with a 20-minute exposure time to 50.0 mg/L CO_2), this species has been infrequently salvaged at the TFCF since 2018 ($\leq$ 1 fish/year; CDFW 2022), which suggests the likelihood of a Delta Smelt being affected by CO_2 treatment within the TFCF bypass pipes and secondary channel is minimal, especially when considering that CO_2 treatment of these facility components only takes a small portion of a day (i.e., approximately 0.5 h) to complete. Also, it is possible that fewer Delta Smelt may be salvaged at the TFCF due to predation if Striped Bass are not regularly removed from the bypass pipes and secondary channel (Wu and Bridges 2014).

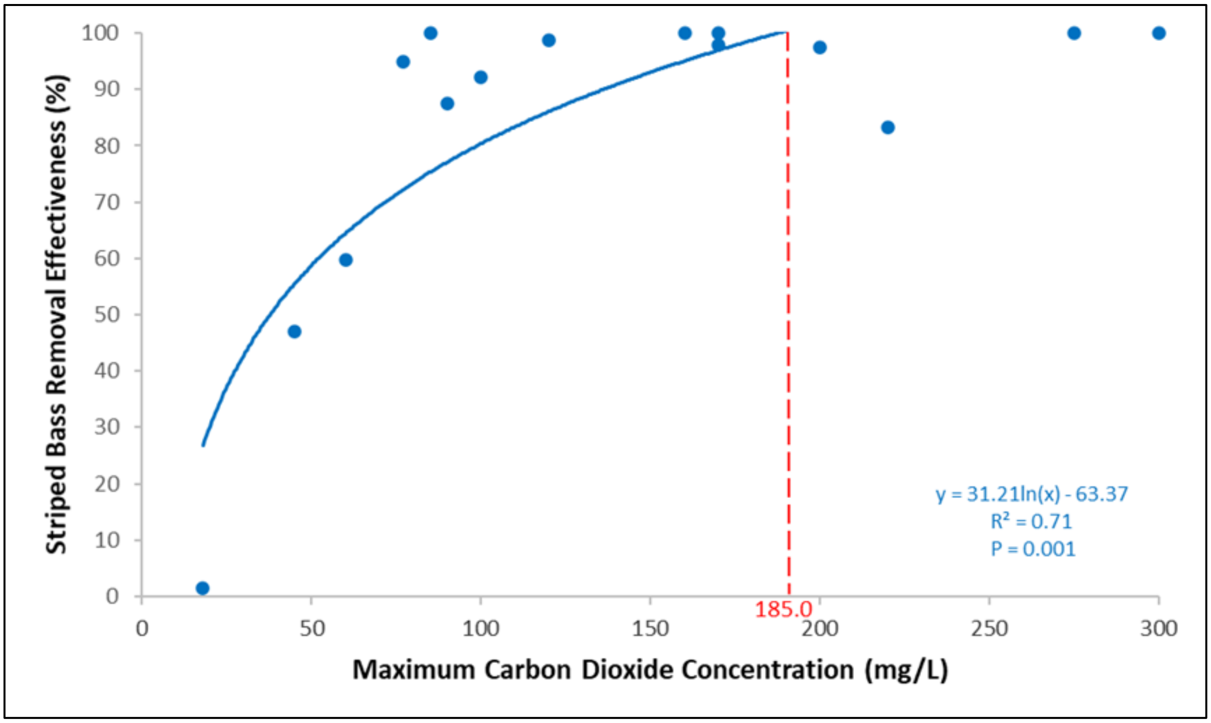

Figure 2.—Maximum carbon dioxide (CO_2) concentration (mg/L) versus removal effectiveness (%) of Striped Bass from the Tracy Fish Collection Facility bypass pipes and secondary channel (with trendline limited to 100% removal effectiveness). According to the best-fit trendline, a CO_2 concentration of approximately 185.0 mg/L should be used to achieve 100% Striped Bass removal effectiveness (red dashed line and red font).

Striped Bass Size vs. Removal Effectiveness

Striped Bass size (i.e., average FL; within the range of 122.2–503.0 mm average FL) did not appear to have a significant independent effect on removal effectiveness from the TFCF bypass pipes and secondary channel ($P = 0.490$; polynomial regression analysis; Figure 3; Appendix C [Table C-1]). While the best-fit trendline for average Striped Bass FL versus removal effectiveness appeared to show increased removal effectiveness as average fish size increased, the dataset was highly variable and the R^2 value of the trendline was weak (Chin 1998; $R^2 = 0.11$; Figure 3; Appendix C [Table C-1]). This result suggests a single, set CO_2 concentration can be used throughout the year to remove Striped Bass in the TFCF bypass pipes and secondary channel regardless of the size of Striped Bass present within the facility.

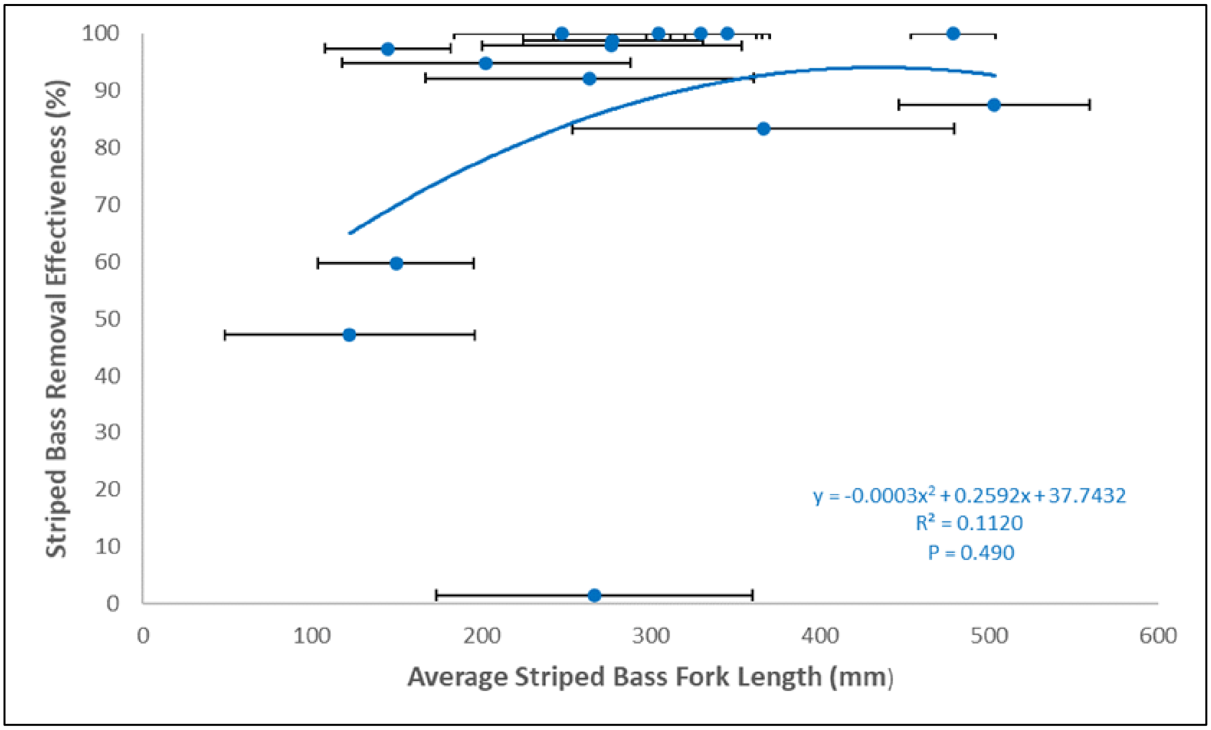

Figure 3.—Average Striped Bass fork length (mm; with standard deviation error bars) versus removal effectiveness (%) from the Tracy Fish Collection Facility bypass pipes and secondary channel.

Water Temperature vs. Removal Effectiveness

Water temperatures of 10.8–23.8 °C, which are within the yearly range of water temperatures typically observed at the TFCF (i.e., 5.8–28.9 °C; CDFW 2022), did not appear to significantly influence Striped Bass removal effectiveness from the TFCF bypass pipes and secondary channel on an independent basis ($P = 0.949$; polynomial regression analysis; Figure 4; Appendix C [Table C-1]). Removal effectiveness data was highly variable for water temperatures less than 20.0 °C, and R^2 value of the best-fit trendline was weak (Chin 1998; $R^2 = 0.01$; Figure 4; Appendix C [Table C-1]). This result suggests a single, set CO_2 concentration can be used to remove Striped Bass throughout the year in the TFCF bypass pipes and secondary channel regardless of Delta water temperature.

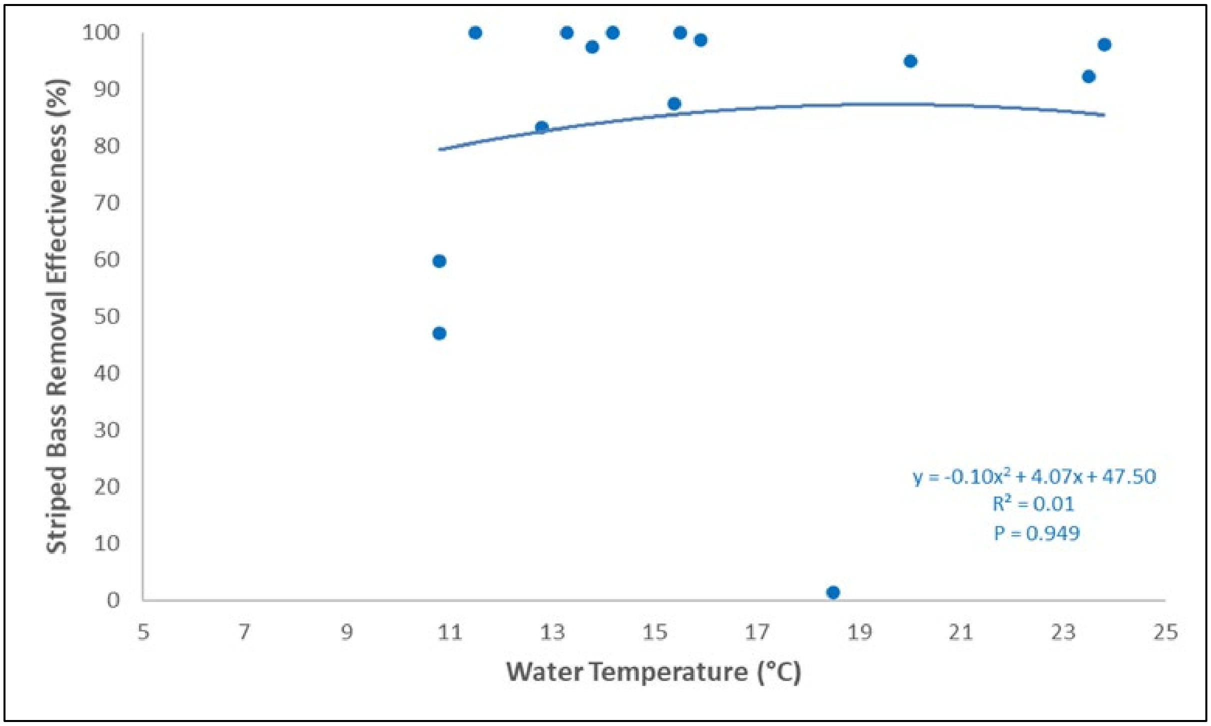

Figure 4.—Water temperature (°C) versus Striped Bass removal effectiveness (%) from the Tracy Fish Collection Facility bypass pipes and secondary channel.

Post-Treatment Survival

Water temperature and dissolved oxygen (DO) generally remained within an acceptable range during the 96-h post-treatment survival assessment. For all replicates combined, average (minimum–maximum) water temperature during 96-h post-treatment survival monitoring was 16.4 °C (8.8–26.1 °C), while average (minimum–maximum) DO was 11.0 mg/L (6.5–17.4 mg/L; Appendix D [Table D-1]).

CO_2 Concentration vs. Post-Treatment Survival

There was not a significant dose-survival response for Striped Bass within the range of CO_2 concentrations tested ($P = 0.874$; polynomial regression analysis; Figure 5; Appendix D [Table D-1]). While the best-fit trendline appeared to suggest reduced 96.0-h post-treatment survival at CO_2 concentrations between 150 and 200 mg/L, the R^2 value of the trendline was weak (Chin 1998; $R^2 = 0.02$) due to high variability in survival data throughout the range of CO_2 concentrations tested (Figure 5, Appendix D [Table D-1]), which was potentially a result of interacting effects of variables on 96-h survival (not investigated during this study). On an independent basis, this result appears to suggest 96.0-h post treatment survival of Striped Bass is not strongly dependent on maximum CO_2 concentration within the range of 0–300.0 mg/L, and that CO_2 concentrations up to 300.0 mg/L can be used for removal of Striped Bass from the TFCF bypass pipes and secondary channel without significantly affecting survival.

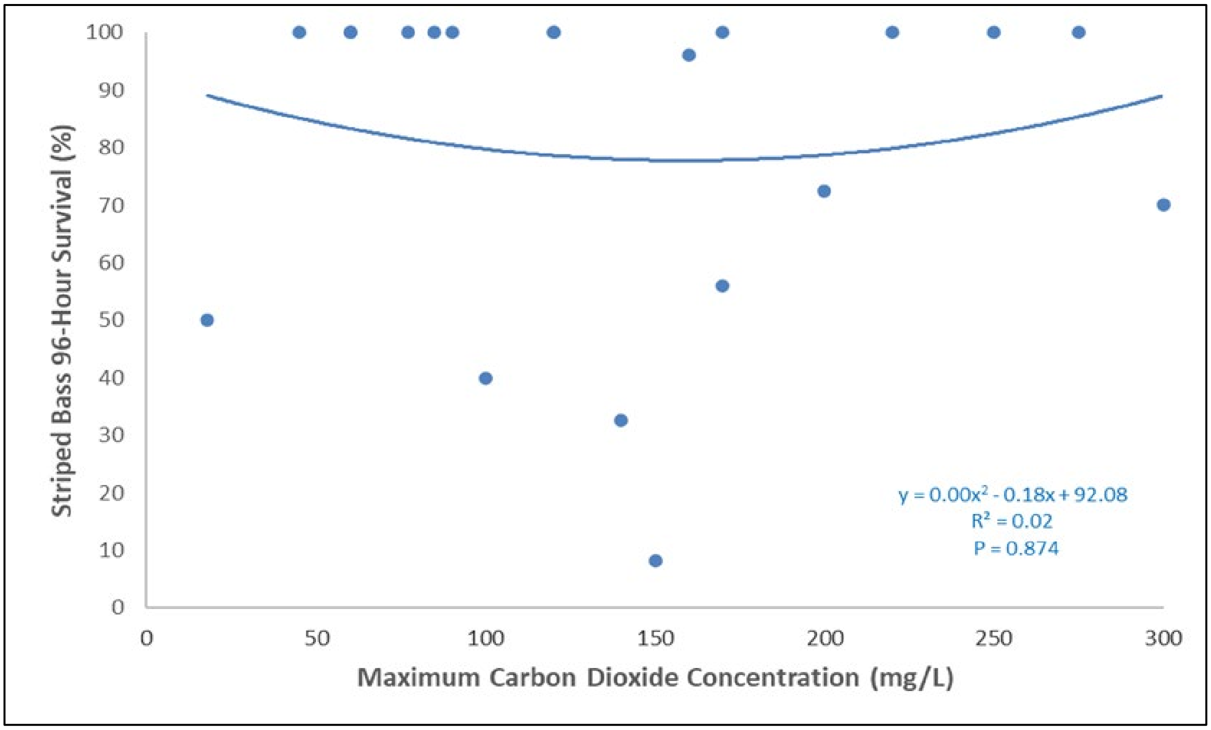

Figure 5.—Maximum carbon dioxide concentration (mg/L) versus 96.0-h post-treatment survival (%) of Striped Bass removed from the Tracy Fish Collection Facility bypass pipes and secondary channel.

Striped Bass Size vs. Post-Treatment Survival

Ninety-six-h post-treatment survival of Striped Bass also did not appear to be significantly influenced solely by size (i.e., average FL) for Striped Bass with average FL within the range of 85.4–507.7 mm FL ($P = 0.576$; polynomial regression analysis; Figure 6; Appendix D [Table D-1]). While the best-fit trendline for average Striped Bass FL versus 96-h post-treatment survival appeared to show increased 96-h post-treatment survival as fish size increased, the data was highly variable and R^2 value of the trendline was weak (Chin 1998; $R^2 = 0.11$; Figure 6; Appendix D [Table D-1]), which was potentially a result of interacting effects of variables on 96-h survival (not investigated during this study). This result supports that a single, set CO_2 concentration can be used throughout the year to remove Striped Bass in the TFCF bypass pipes and secondary channel regardless of the size of Striped Bass present within the facility.

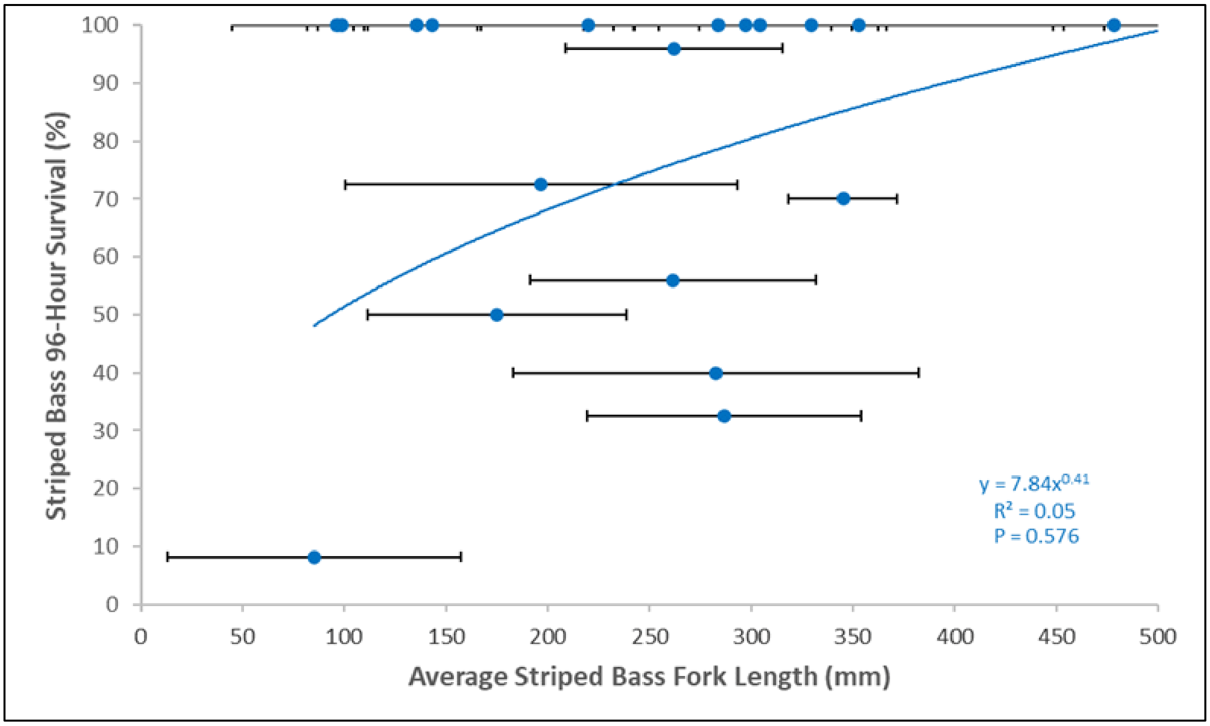

Figure 6.—Average Striped Bass fork length (mm; with standard deviation error bars) versus 96.0-h post-treatment survival (%).

Water Temperature vs. Post-Treatment Survival

Water temperature during 96.0-h post-treatment survival monitoring was variable due to the use of Delta water at ambient temperature. Due to this, it was necessary to use average water temperature (the average of 1–2 point estimates per tank taken daily over 96.0-h) for analyses. It was determined that 96.0-h post-treatment survival of Striped Bass was significantly influenced by average water temperature within the range of 9.7–25.2 °C ($P = <0.001$; polynomial regression analysis; Figure 7; Appendix D [Table D-1]). The best-fit trendline for average water temperature versus 96.0-h post-treatment survival exhibited a substantial R^2 value (Chin 1998; $R^2 = 0.73$) and demonstrated the association between higher average water temperatures during 96.0-h observation periods and reduced 96.0-h post-treatment survival (Figure 7). Significantly reduced Striped Bass survival with increased average water temperature may be due to increased susceptibility of fish to disease with increased water temperature (Marcos-López et al. 2010), as well as generally increased growth and invasiveness of fish pathogens with elevated water temperatures (Wedemeyer 1996).

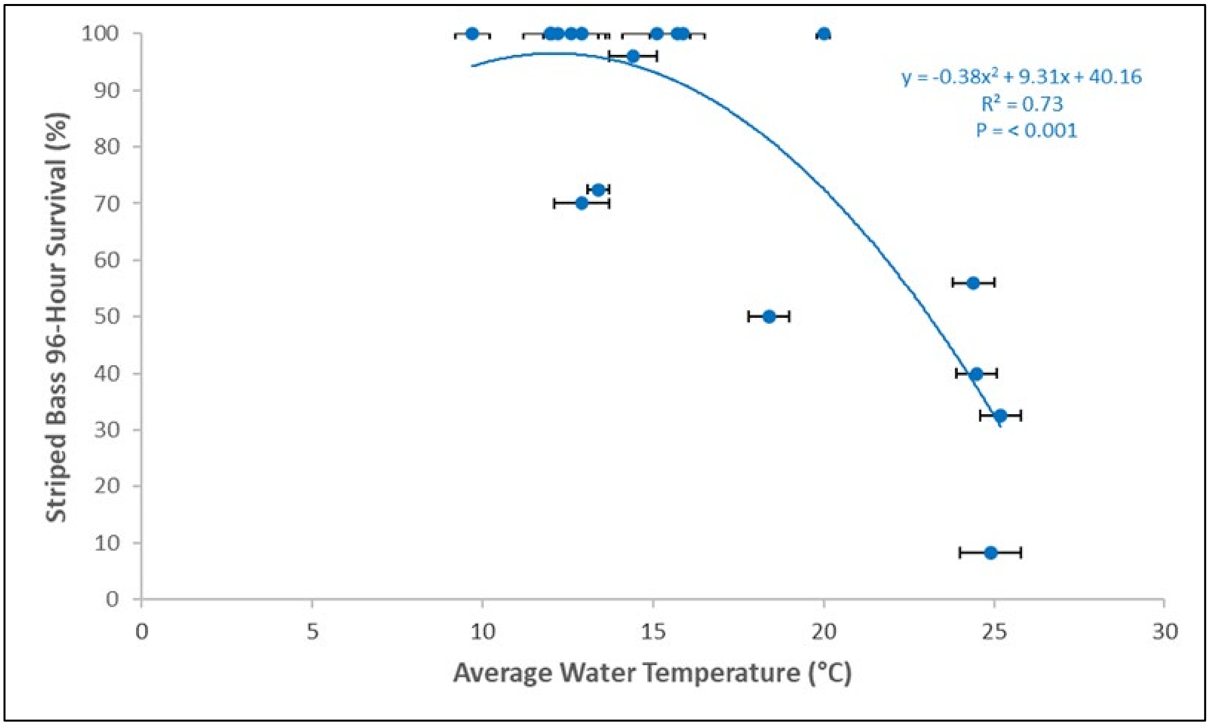

Figure 7.—Average water temperature (°C; with standard deviation error bars) versus 96.0-h post-treatment survival of Striped Bass (%).

Conclusions and Recommendations

Results suggest 96.0-h post-treatment survival of Striped Bass will be comparable regardless of the CO_2 concentration used (up to 300.0 mg/L). Considering this, as well as the reduction in cost associated with the use of less dry ice, it appears the lowest CO_2 concentration estimated by the best-fit trendline to generally be 100% effective at removing Striped Bass from the TFCF bypass pipes and secondary channel should be employed. Since size of Striped Bass did not appear to significantly influence removal effectiveness or 96.0-h post-treatment survival, and water temperature did not appear to significantly affect removal effectiveness, it seems that a single, set CO_2 concentration can be used throughout the year despite potential seasonal differences in water temperature and/or Striped Bass size at the TFCF. If high survival of Striped Bass removed from the TFCF is desired, it may be necessary to avoid performing CO_2 predator removals when Delta water temperature exceeds a certain threshold value.

Based on results of this evaluation, it is recommended that a CO_2 concentration of approximately 185.0 mg/L be used during monthly predator removals at the TFCF. This CO_2 concentration appears to be appropriate because it is the lowest CO_2 concentration estimated by the best-fit trendline to generally be 100% effective at removing all sizes of Striped Bass from the TFCF bypass pipes and secondary channel (Figure 2) and was also determined not to significantly influence 96.0-h post-treatment survival of Striped Bass (Figure 5). In addition, a CO_2 concentration of 185.0 mg/L is lower than the concentration found by Wu and Bridges (2014) to cause mortality in Chinook Salmon after 20 minutes of exposure (i.e., 300.0 mg/L), and fish species identified by Wu and Bridges (2014) to be intolerant to this CO_2 concentration (i.e., Delta Smelt) are infrequently salvaged at the TFCF. Since size of Striped Bass did not appear to significantly influence removal effectiveness (Figure 3) or 96.0-h post-treatment survival (Figure 6), and water temperature did not appear to significantly affect removal effectiveness (Figure 4), it is recommended that this CO_2 concentration be used throughout the year regardless of potential seasonal differences in water temperature and/or size of Striped Bass within the facility.

Based on a scatterplot with linear trendline for the relationship between amount of dry ice inserted (kg) and maximum CO_2 concentration obtained (mg/L) during CO_2 treatments within the bypass pipes and secondary channel at the TFCF when maximum CO_2 concentration was measured (including CO_2 treatments outside this study), it is recommended that approximately 89.8 kg (198.0 lbs) of dry ice be inserted into each bypass pipe for each treatment to obtain a CO_2 concentration of approximately 185.0 mg/L within the TFCF bypass pipes and secondary channel using current procedures (Figure 8; Appendix E [Table E-1]). Since data used for Figure 8 was collected throughout the yearly range of water temperatures and total alkalinities observed at the TFCF, the variability in CO_2 concentration due to differences in these environmental conditions is incorporated in the trendline. Despite this, the amount of dry ice recommended for insertion into each bypass pipe for each treatment (i.e., 89.8 kg [198.0 lbs]) should be used as a general guideline that may need to be adjusted to achieve 185.0 mg/L under certain circumstances (i.e., when total alkalinity and/or water temperature are outside of the range encountered during this study).

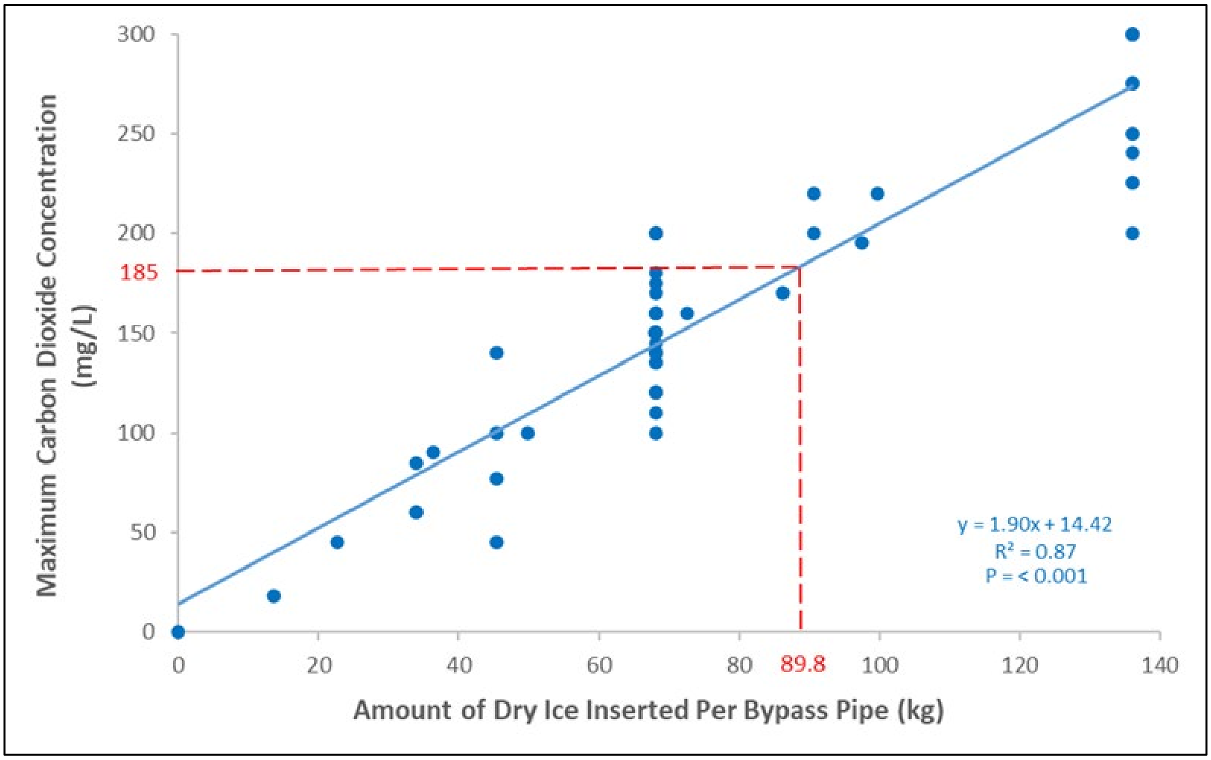

Figure 8.—Amount of dry ice inserted (kg) into each bypass pipe versus maximum carbon dioxide (CO_2) concentration (mg/L) obtained in the Tracy Fish Collection Facility (TFCF) secondary channel during CO_2 treatments at the TFCF when maximum CO_2 concentration was measured (including CO_2 treatments outside this study). To obtain the optimal CO_2 concentration of 185.0 mg/L in the TFCF bypass pipes and secondary channel, it is recommended that approximately 89.8 kg of dry ice be inserted into each bypass pipe for each treatment (red dashed lines and red font).

If survival of Striped Bass removed from the TFCF is a concern, it is recommended that Reclamation avoid performing CO_2 predator removals when Delta water temperature exceeds 20.0 °C (68.0 °F). This recommendation appears to be justified since all 96.0-h post-treatment survival estimates for Striped Bass developed with water temperatures greater than 20.0 °C were under 60.0% (Figure 7). In addition, salvage of Endangered Species Act-listed fish species (i.e., spring-run Chinook Salmon, winter-run Chinook Salmon, Steelhead Trout [*O. mykiss*], Delta Smelt, Longfin Smelt [*Spirinchus thaleichthys*], and Green Sturgeon [*Acipenser medirostris*]) at the TFCF is reduced when Delta water temperatures exceed 20.0 °C (CDFW 2022), which suggests there is likely a limited and lesser benefit to removing piscivorous fish from the TFCF bypass pipes and secondary channel when water temperatures exceed this value.

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Appendix A—Data Associated With Estimation of Striped Bass Recolonization Rate Within the Tracy Fish Collection Facility Bypass Pipes and Secondary Channel

Table A-1.—Summary of data associated with estimation of Striped Bass recolonization rate for replicates completed to determine optimal CO_2 concentration for removal of Striped Bass from the bypass pipes and secondary channel at the Tracy Fish Collection Facility.

Date of CO_2 Optimal Dose Replicate	Time of CO_2 Optimal Dose Replicate (0000-2400)	Date of Most Recent Prior Predator Removal Activity	Time of Most Recent Prior Predator Removal Activity (0000-2400)	Recolonization Time (d)	Total Number of Striped Bass Removed	Average (minimum–maximum) Striped Bass Fork Length (mm)	Recolonization Rate (fish/d)
07/13/2010	1300	07/06/2010	1120	7.1	133	286.7 (193.0–555.0)	18.7
07/22/2010	1100	07/13/2010	1300	8.9	49	85.4 (37.0–337.0)	5.5
11/04/2011	1030	11/01/2011	1330	2.9	520	277.6 (94.0–440.0)	179.3
11/16/2011	0900	11/04/2011	1030	11.9	18	283.7 (218.0–417.0)	1.5
02/16/2012	1241	01/27/2012	1230	20.0	17	122.2 (71.0–345.0)	0.9
02/16/2012	1352	02/16/2012	1241	0.05	9	143.4 (71.0–345.0)	180.0
02/17/2012	1530	02/16/2012	1352	1.1	2	96.5 (86.0–107.0)	1.8
02/24/2012	1230	02/17/2012	1530	6.9	11	329.7 (259.0–362.0)	1.6
02/24/2012	1330	02/24/2012	1230	0.04	10	345.2 (316.0–395.0)	250.0
12/06/2012	1200	04/27/2012	2359	222.5	606	144.7 (90.0–476.0)	2.7
12/18/2012	1200	12/06/2012	1200	12.0	119	149.4 (89.0–415.0)	9.9
04/11/2014	0830	12/18/2012	1200	478.9	98	202.7 (124.0–830.0)	0.2
10/23/2018	0930	07/10/2018	0900	106.0	147	266.7 (114.0–445.0)	1.4
11/14/2018	0900	10/23/2018	0930	22.0	2	478.5 (461.0–496.0)	0.1

Date of CO_2 Optimal Dose Replicate	Time of CO_2 Optimal Dose Replicate (0000-2400)	Date of Most Recent Prior Predator Removal Activity	Time of Most Recent Prior Predator Removal Activity (0000-2400)	Recolonization Time (d)	Total Number of Striped Bass Removed	Average (minimum–maximum) Striped Bass Fork Length (mm)	Recolonization Rate (fish/d)
03/05/2019	0900	02/20/2019	0900	13.0	5	304.4 (256.0–385.0)	0.4
05/21/2019	0900	04/02/2019	1159	47.9	8	503.0 (443.0–612.0)	0.2
07/11/2019	0915	06/12/2019	1136	29.9	128	263.6 (43.0–550.0)	4.3
08/29/2019	0915	07/11/2019	1015	50.0	239	276.9 (167.0–815.0)	4.8
10/29/2019	1245	8/29/2019	0915	61.1	119	247.8 (63.0–410.0)	1.9
11/26/2019	900	10/29/2019	1245	27.8	6	366.7 (217.0–453.0)	0.2
Average	**Not Applicable**	**Not Applicable**	**Not Applicable**	**56.5**	**112.3**	**Not Applicable**	**33.3**
Minimum–Maximum	**Not Applicable**	**Not Applicable**	**Not Applicable**	**0.04–478.9**	**2–606**	**Not Applicable**	**0.1–250.0**

Appendix B—Secondary Channel Depth and Hydraulic Data During Reduced Flow and Increased Flow Periods of Initial and Subsequent Carbon Dioxide Treatments

Table B-1.—Water depth (m), velocity (m/s), and flow (m^3/s) in the Tracy Fish Collection Facility secondary channel for reduced flow and increased flow periods during initial carbon dioxide (CO_2) treatments completed to determine optimal CO_2 concentration for removal of Striped Bass from the bypass pipes and secondary channel at the Tracy Fish Collection Facility.

Date	Initial CO_2 Treatment – Reduced Flow Period Secondary Channel Depth (m)	Initial CO_2 Treatment – Reduced Flow Period Water Velocity (m/s)	Initial CO_2 Treatment – Reduced Flow Period Water Flow (m^3/s)	Initial CO_2 Treatment – Increased Flow Period Secondary Channel Depth (m)	Initial CO_2 Treatment – Increased Flow Period Water Velocity (m/s)	Initial CO_2 Treatment – Increased Flow Period Water Flow (m^3/s)
07/13/2010	2.1	0.2	0.8	1.6	1.0	4.0
07/22/2010	2.0	0.2	0.9	No Data	No Data	No Data
11/04/2011	1.6	0.2	0.8	1.4	1.0	3.4
11/16/2011	1.7	0.2	1.0	No Data	No Data	No Data
02/16/2012	2.5	0.1	0.9	1.9	1.0	4.5
02/16/2012	2.6	0.1	0.9	2.2	0.8	4.3
02/17/2012	2.6	0.1	0.8	2.2	0.8	4.4
02/24/2012	2.0	0.2	0.8	1.6	1.0	3.9
02/24/2012	1.7	0.2	0.9	1.4	1.0	3.6
12/06/2012	No Data	No Data	No Data	No Data	No Data	No Data
12/18/2012	1.9	0.3	1.2	No Data	No Data	No Data
04/11/2014	2.3	0.2	1.1	1.8	0.9	4.1
10/23/2018	2.2	0.3	1.8	1.4	1.0	3.6

Date	Initial CO_2 Treatment – Reduced Flow Period Secondary Channel Depth (m)	Initial CO_2 Treatment – Reduced Flow Period Water Velocity (m/s)	Initial CO_2 Treatment – Reduced Flow Period Water Flow (m^3/s)	Initial CO_2 Treatment – Increased Flow Period Secondary Channel Depth (m)	Initial CO_2 Treatment – Increased Flow Period Water Velocity (m/s)	Initial CO_2 Treatment – Increased Flow Period Water Flow (m^3/s)
11/14/2018	1.9	0.2	0.8	1.5	0.9	3.3
03/05/2019	2.7	0.1	0.5	2.2	0.7	4.0
05/21/2019	3.3	0.1	0.7	2.8	0.6	3.8
07/11/2019	2.0	0.2	1.2	1.4	1.0	3.4
08/29/2019	2.5	0.2	1.1	2.0	0.8	3.7
10/29/2019	2.3	0.1	0.6	1.8	0.8	3.4
11/26/2019	2.3	0.1	0.7	1.8	0.9	3.7
Average	**2.2**	**0.2**	**0.9**	**1.8**	**0.9**	**3.8**
Minimum–Maximum	**1.6–3.3**	**0.1–0.3**	**0.5–1.8**	**1.4–2.8**	**0.6–1.0**	**3.3–4.5**

Table B-2.—Water depth (m), velocity (m/s), and flow (m^3/s) in the Tracy Fish Collection Facility secondary channel during reduced flow and increased flow periods for subsequent carbon dioxide (CO_2) treatments completed to determine optimal CO_2 concentration for removal of Striped Bass from the bypass pipes and secondary channel at the Tracy Fish Collection Facility.

Date	Subsequent CO_2 Treatment – Reduced Flow Period Secondary Channel Depth (m)	Subsequent CO_2 Treatment – Reduced Flow Period Water Velocity (m/s)	Subsequent CO_2 Treatment – Reduced Flow Period Water Flow (m^3/s)	Subsequent CO_2 Treatment – Increased Flow Period Secondary Channel Depth (m)	Subsequent CO_2 Treatment – Increased Flow Period Water Velocity (m/s)	Subsequent CO_2 Treatment – Increased Flow Period Water Flow (m^3/s)
07/13/2010	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only
07/22/2010	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only
11/04/2011	1.7	0.2	0.8	1.4	1.1	3.8

Date	Subsequent CO_2 Treatment – Reduced Flow Period Secondary Channel Depth (m)	Subsequent CO_2 Treatment – Reduced Flow Period Water Velocity (m/s)	Subsequent CO_2 Treatment – Reduced Flow Period Water Flow (m^3/s)	Subsequent CO_2 Treatment – Increased Flow Period Secondary Channel Depth (m)	Subsequent CO_2 Treatment – Increased Flow Period Water Velocity (m/s)	Subsequent CO_2 Treatment – Increased Flow Period Water Flow (m^3/s)
11/16/2011	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only
02/16/2012	2.6	0.1	0.9	2.2	0.8	4.3
02/16/2012	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only
02/17/2012	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only	Not Applicable – Survival Only
02/24/2012	1.7	0.2	0.9	1.4	1.0	3.6
02/24/2012	No Data	No Data	No Data	No Data	No Data	No Data
12/06/2012	No Data	No Data	No Data	No Data	No Data	No Data
12/18/2012	2.0	0.2	0.9	1.6	0.9	3.8
04/11/2014	2.0	0.2	1.0	1.5	1.0	3.7
10/23/2018	No Data	No Data	No Data	No Data	No Data	No Data
11/14/2018	2.0	0.2	0.9	1.5	1.0	3.6
03/05/2019	2.6	0.1	0.7	2.2	0.7	4.0
05/21/2019	3.2	0.1	0.7	2.7	0.5	3.5
07/11/2019	1.8	0.2	0.9	No Data	No Data	No Data
08/29/2019	2.4	0.2	1.1	No Data	No Data	No Data
10/29/2019	2.1	0.1	0.5	No Data	No Data	No Data
11/26/2019	2.2	0.1	0.7	1.7	0.9	3.6
Average	**2.2**	**0.2**	**0.8**	**1.8**	**0.9**	**3.8**
Minimum–Maximum	**1.7–3.2**	**0.1–0.2**	**0.5–1.1**	**1.4–2.7**	**0.5–1.1**	**3.5–4.3**

Appendix C—Data Associated With Use of Carbon Dioxide to Evaluate Striped Bass Removal Effectiveness From the Tracy Fish Collection Facility Bypass Pipes and Secondary Channel

Table C-1.—Summary of data associated with evaluation of Striped Bass removal effectiveness for replicates completed to determine optimal CO_2 concentration for removal of Striped Bass from the bypass pipes and secondary channel at the Tracy Fish Collection Facility.

Date	Maximum Initial CO^2 Concentration (mg/L)	Maximum Subsequent CO^2 Concentration (mg/L)	Water Temperature (°C)	Total Alkalinity (mg/L $CaCO_3$)	Number of Striped Bass Removed During Initial CO^2 Treatment	Total Number of Striped Bass Removed	Average (minimum–maximum) Striped Bass Fork Length (mm)	Removal Effectiveness (%)
07/13/2010	140	Not Applicable	25.1	62.0	77	77	286.7 (193.0–555.0)	Not Applicable
07/22/2010	150	Not Applicable	26.1	60.0	45	45	85.4 (37.0–337.0)	Not Applicable
11/04/2011	120	200	15.9	55.0	514	520	277.6 (94.0–440.0)	98.8
11/16/2011	120	Not Applicable	13.1	55.0	11	11	283.7 (218.0–417.0)	Not Applicable
02/16/2012	45	250	10.8	110.0	8	17	122.2 (71.0–345.0)	47.1
02/16/2012	250	Not Applicable	10.8	110.0	9	9	143.4 (71.0–345.0)	Not Applicable
02/17/2012	60	Not Applicable	12.2	97.0	2	2	96.5 (86.0–107.0)	Not Applicable
02/24/2012	85	300	14.2	95.0	11	11	329.7 (259.0–362.0)	100
02/24/2012	300	300	14.2	95.0	10	10	345.2 (316.0–395.0)	100
12/06/2012	200	300	13.8	105.0	590	606	144.7 (90.0–476.0)	97.4
12/18/2012	60	240	10.8	105.0	71	119	149.4 (89.0–415.0)	59.7
04/11/2014	77	275	20.0	90.0	93	98	202.7 (124.0–830.0)	94.9
10/23/2018	18	250	18.5	70.0	2	147	266.7 (114.0–445.0)	1.4

Date	Maximum Initial CO^2 Concentration (mg/L)	Maximum Subsequent CO^2 Concentration (mg/L)	Water Temperature (°C)	Total Alkalinity (mg/L $CaCO_3$)	Number of Striped Bass Removed During Initial CO^2 Treatment	Total Number of Striped Bass Removed	Average (minimum–maximum) Striped Bass Fork Length (mm)	Removal Effectiveness (%)
11/14/2018	170	195	11.5	65.0	2	2	478.5 (461.0–496.0)	100
03/05/2019	275	275	13.3	75.0	5	5	304.4 (256.0–385.0)	100
05/21/2019	90	300	15.4	50.0	7	8	503.0 (443.0–612.0)	87.5
07/11/2019	100	225	23.5	80.0	118	128	263.6 (43.0–550.0)	92.2
08/29/2019	170	300	23.8	85.0	234	239	276.9 (167.0–815.0)	97.9
10/29/2019	160	300	15.5	70.0	119	119	247.8 (63.0–410.0)	100
11/26/2019	220	300	12.8	85	5	6	366.7 (217.0–453.0)	83.3
Total	**Not Applicable**	**Not Applicable**	**Not Applicable**	**Not Applicable**	**1,933**	**2,179**	**Not Applicable**	**Not Applicable**
Average	**140.5**	**267.3**	**16.1**	**81.0**	**97**	**109**	**Not Applicable**	**84.0**
Minimum–Maximum	**18.0–300.0**	**195.0–300.0**	**10.8–26.1**	**50.0–110.0**	**2–590**	**2–606**	**Not Applicable**	**1.4–100**

Appendix D—Data Associated With Evaluation of Striped Bass 96.0-H Post-Carbon Dioxide Treatment Survival

Table D-1.—Summary of data associated with evaluation of Striped Bass 96.0-h post-carbon dioxide treatment survival for replicates completed to determine optimal CO_2 concentration for removal of Striped Bass from the bypass pipes and secondary channel at the Tracy Fish Collection Facility.

Date	Maximum Initial CO^2 Concentration (mg/L)	Number of Striped Bass Removed During Initial CO^2 Treatment	Number of Striped Bass Retained for 96.0-H Post-Treatment Survival	Average (minimum–maximum) Fork Length of Striped Bass Retained for 96.0-H Post-Treatment Survival (mm)	Average (minimum–maximum) Water Temperature (°C)	Average (minimum–maximum) Dissolved Oxygen (mg/L)	96.0-H Post-Treatment Survival (%)
07/13/2010	140	77	77	286.7 (193.0–555.0)	25.2 (24.3–26.1)	7.3 (6.8–7.6)	32.5
07/22/2010	150	45	45	85.4 (37.0–337.0)	24.9 (23.9–26.1)	7.0 (6.5–7.3)	8.2
11/04/2011	120	514	30	297.1 (218.0–378.0)	15.9 (15.9–15.9)	9.8 (9.8–9.8)	100
11/16/2011	120	11	11	283.7 (218.0–417.0)	15.1 (14.2–15.9)	10.3 (9.8–10.7)	100
02/16/2012	45	8	8	98.4 (88.0–122.0)	12.0 (11.8–12.3)	15.2 (14.1–15.8)	100
02/16/2012	250	9	9	143.4 (71.0–345.0)	12.0 (11.8–12.3)	14.4 (13.3–15.1)	100
02/17/2012	60	2	2	96.5 (86.0–107.0)	12.2 (12.1–12.2)	14.4 (13.7–15.7)	100
02/24/2012	85	11	11	329.7 (259.0–362.0)	12.9 (12.0–14.2)	14.9 (12.6–16.0)	100
02/24/2012	300	10	10	345.2 (316.0–395.0)	12.9 (12.0–14.2)	14.5 (11.8–15.9)	70
12/06/2012	200	590	40	196.7 (113.0–476.0)	13.4 (12.7–13.9)	12.4 (10.7–15.5)	72.5
12/18/2012	60	71	71	135.8 (89.0–279.0)	9.7 (8.8–10.8)	16.0 (14.7–17.4)	100
04/11/2014	77	93	25	220.1 (163.0–379.0)	20.0 (19.7–20.5)	8.9 (6.9–10.1)	100
10/23/2018	18	2	2	175.0 (130.0–220.0)	18.4 (18.0–19.3)	8.9 (8.7–9.2)	50

Date	Maximum Initial CO^2 Concentration (mg/L)	Number of Striped Bass Removed During Initial CO^2 Treatment	Number of Striped Bass Retained for 96.0-H Post-Treatment Survival	Average (minimum–maximum) Fork Length of Striped Bass Retained for 96.0-H Post-Treatment Survival (mm)	Average (minimum–maximum) Water Temperature (°C)	Average (minimum–maximum) Dissolved Oxygen (mg/L)	96.0-H Post-Treatment Survival (%)
11/14/2018	170	2	2	478.5 (461.0–496.0)	12.6 (11.5–13.4)	10.2 (9.7–11.0)	100
03/05/2019	275	5	5	304.4 (256.0–385.0)	12.9 (11.9–13.7)	10.5 (10.4–10.7)	100
05/21/2019	90	7	7	507.7 (443.0–612.0)	15.7 (15.3–17.0)	9.9 (9.7–10.0)	100
07/11/2019	100	118	25	282.6 (170.0–550.0)	24.5 (23.8–25.4)	8.3 (7.9–9.1)	40
08/29/2019	170	234	25	261.7 (167.0–380.0)	24.4 (23.4–25.0)	8.3 (8.3–8.5)	56
10/29/2019	160	119	25	262.1 (187.0–364.0)	14.4 (13.3–15.5)	10.2 (9.9–11.0)	96
11/26/2019	220	5	5	353.0 (217.0–453.0)	12.0 (11.2–12.8)	10.7 (10.5–10.9)	100
Total	**Not Applicable**	**1,933**	**435**	**Not Applicable**	**Not Applicable**	**Not Applicable**	**Not Applicable**
Average	**140.5**	**97**	**22**	**Not Applicable**	**Not Applicable**	**Not Applicable**	**81.3**
Minimum–Maximum	**18.0–300.0**	**2–590**	**2–77**	**Not Applicable**	**Not Applicable**	**Not Applicable**	**8.2–100**

Appendix E—Carbon Dioxide (CO_2) Treatments Used to Estimate Amount of Dry Ice to Insert per Bypass Pipe to Obtain the Optimal CO_2 Concentration (185.0 mg/L) Within the Tracy Fish Collection Facility Secondary Channel

Table E-1.—Summary of CO_2 treatments within the bypass pipes and secondary channel at the Tracy Fish Collection Facility used to develop a scatterplot with linear trendline for the relationship between amount of dry ice inserted per bypass pipe (kg) and maximum CO_2 concentration obtained in the secondary channel (mg/L; including CO_2 treatments outside this study).

Date	Amount of Dry Ice Injected per Bypass Pipe (kg)	Maximum CO_2 Concentration Obtained (mg/L)	Source
—	0.0	0	—
04/01/2010	90.7	220	Unpublished TFCF CO_2 Predator Removal Data
07/13/2010	45.4	140	This Study - Survival Only
07/22/2010	68.0	150	This Study - Survival Only
01/03/2011	68.0	150	Unpublished TFCF CO_2 Predator Removal Data
01/04/2011	68.0	100	Unpublished TFCF CO_2 Predator Removal Data
01/05/2011	68.0	140	Unpublished TFCF CO_2 Predator Removal Data
01/06/2011	68.0	180	Unpublished TFCF CO_2 Predator Removal Data
01/07/2011	68.0	140	Unpublished TFCF CO_2 Predator Removal Data
04/05/2011	68.0	200	Unpublished TFCF CO_2 Predator Removal Data
04/11/2011	68.0	160	Unpublished TFCF CO_2 Predator Removal Data
04/12/2011	68.0	175	Unpublished TFCF CO_2 Predator Removal Data
04/13/2011	68.0	160	Unpublished TFCF CO_2 Predator Removal Data

Date	Amount of Dry Ice Injected per Bypass Pipe (kg)	Maximum CO_2 Concentration Obtained (mg/L)	Source
04/15/2011	68.0	200	Unpublished TFCF CO_2 Predator Removal Data
06/27/2011	68.0	160	Unpublished TFCF CO_2 Predator Removal Data
06/28/2011	68.0	135	Unpublished TFCF CO_2 Predator Removal Data
06/29/2011	68.0	145	Unpublished TFCF CO_2 Predator Removal Data
06/30/2011	68.0	150	Unpublished TFCF CO_2 Predator Removal Data
07/01/2011	68.0	110	Unpublished TFCF CO_2 Predator Removal Data
08/22/2011	68.0	140	Unpublished TFCF CO_2 Predator Removal Data
08/24/2011	68.0	140	Unpublished TFCF CO_2 Predator Removal Data
08/25/2011	49.9	100	Unpublished TFCF CO_2 Predator Removal Data
08/26/2011	68.0	135	Unpublished TFCF CO_2 Predator Removal Data
11/04/2011	68.0	120	This Study - Initial Treatment
11/04/2011	136.1	200	This Study - Subsequent Treatment
11/10/2011	68.0	120	Unpublished TFCF CO_2 Predator Removal Data
11/16/2011	68.0	120	This Study - Survival Only
02/16/2012	22.7	45	This Study - Initial Treatment
02/16/2012	136.1	250	This Study - Subsequent Treatment
02/17/2012	34.0	60	This Study - Survival Only
02/24/2012	34.0	85	This Study - Initial Treatment
02/24/2012	136.1	300	This Study - Subsequent Treatment
03/16/2012	68.0	200	Unpublished TFCF CO_2 Predator Removal Data
12/06/2012	90.7	200	This Study - Initial Treatment
12/06/2012	136.1	300	This Study - Subsequent Treatment
12/18/2012	34.0	60	This Study - Initial Treatment
12/18/2012	136.1	240	This Study - Subsequent Treatment
04/11/2014	45.4	77	This Study - Initial Treatment

Date	Amount of Dry Ice Injected per Bypass Pipe (kg)	Maximum CO_2 Concentration Obtained (mg/L)	Source
04/11/2014	136.1	275	This Study - Subsequent Treatment
01/23/2018	72.6	160	This Study - Initial Treatment (No Striped Bass Collected)
01/23/2018	136.1	245	This Study - Subsequent Treatment (No Striped Bass Collected)
10/23/2018	13.6	18	This Study - Initial Treatment
10/23/2018	136.1	250	This Study - Subsequent Treatment
11/14/2018	86.2	170	This Study - Initial Treatment
11/14/2018	97.5	195	This Study - Subsequent Treatment
12/18/2018	45.4	45	This Study – Initial Treatment (No Striped Bass Collected)
12/18/2018	136.1	225	This Study – Subsequent Treatment (No Striped Bass Collected)
03/05/2019	136.1	275	This Study - Initial Treatment
03/05/2019	136.1	275	This Study - Subsequent Treatment
05/21/2019	36.3	90	This Study - Initial Treatment
05/21/2019	136.1	300	This Study - Subsequent Treatment
07/11/2019	45.4	100	This Study - Initial Treatment
07/11/2019	136.1	225	This Study - Subsequent Treatment
08/29/2019	68.0	170	This Study - Initial Treatment
08/29/2019	136.1	300	This Study - Subsequent Treatment
10/29/2019	68.0	160	This Study - Initial Treatment
10/29/2019	136.1	300	This Study - Subsequent Treatment
11/26/2019	99.8	220	This Study - Initial Treatment
11/26/2019	136.1	300	This Study - Subsequent Treatment