Supporting Information

This PDF file includes:

Supporting Information Text

Multi-species functional response (MSFR) model

MSFR model prior distributions

Below are the vague prior distributions used for MSFR model parameters.

Handling time of species i:

$$h_i \sim \text{Uniform}(0, 1000)$$

Log-scale attack rate for species i:

$$\log(b_i) \sim \text{Uniform}(-100, 100)$$

MSFR exponent:

$$q \sim \text{Uniform}(-2, 2)$$

Abundance of available Pacific lamprey at time t:

$$L_t^A \sim \text{Uniform}(0, 1000000)$$

Abundance of available Chinook salmon at time t:

$$S_t^A \sim \text{Uniform}(0, 1000000)$$

Beta distribution shape parameters informing the lamprey probability of detection in visual fish ladder surveys:

$$\alpha^D \sim \text{Uniform}(0, 100)$$
$$\beta^D \sim \text{Uniform}(0, 100)$$

MSFR data sources

Here we outline the data sources used to fit the multi-species functional response model (MSFR, Equations 8-18). The model uses two sources of data: 1) gastro-intestinal consumption data from 107 euthanized California sea lions (CSL) and 2) Bonneville dam passage data from day-time visual counts in fish ladders, night-time visual counts in fish ladders, and mechanical counts in lamprey passage structures (LPS). The dam passage data is used to inform both 1) the observed abundance of fish passed, L_t^P and S_t^P, during the time window, t surrounding CSL euthanasia and 2) the probability of lamprey detection in day-time visual counts in fish ladders.

To estimate CSL consumption rates, we use data on prey items recovered in the gastro-intestinal tracks of 107 California sea lions euthanized below Bonneville dam in 2017-2019 and 2021-2023 (Table S3, Table S6). This diet analysis is based on the identification of undigested prey remains from the stomachs and large intestines of euthanized CSLs following the procedures in Lance et al. (2001), where prey were enumerated by examining all structures (otoliths, tail structures, cephalopod beaks, etc.) to determine the minimum number of individual prey items in the sample (Lance et al. 2001). These data were retrieved from annual reports to the National Marine Fisheries Service (NMFS) documenting compliance with the terms and conditions of the authorization for lethal removal of California sea lions under the Marine Mammal Protection Act (Clark et al. 2021, 2023; Edwards et al. 2022).

While above-surface pinniped predation events are monitored at Bonneville dam and have previously been used to estimate the CSL functional response for salmonid prey (Hatch, Lessard, and Whiteaker 2018), these above-surface data likely underestimate lamprey predation, as lamprey predation typically occurs below surface (Tidwell, Braun, and Leeuw 2023). We therefore use the gastro-intestinal data to reduce differences in consumption observation error between fish species. We subset the prey item data to those identified as adult Chinook salmon and Pacific lamprey, and we assume the prey items represent consumption in the 24 hours before euthanasia, as this is the time typically taken for CSL prey to pass through the digestive system (Tidwell, personal communication).

To estimate the abundance of the prey available to CSL during the period of consumption, L_t^A and S_t^A, we use fish passage data from Bonneville dam. For Chinook salmon, these data include daily, visual daytime counts across all Bonneville dam fish ladders, retrieved from the Columbia River DART database. For Pacific lamprey, however, these visual daytime counts in the fish ladders underestimate abundance, as 1) Pacific lamprey also use Lamprey Passage Structures (LPS) in addition to the fish ladders and 2) lamprey tend to migrate at night, rather than during the day (Cates, McClain, and Gibbons 2020) (Figure 2). In 2017 and 2019, mechanical counts of Pacific lamprey in five LPS and visual nighttime counts in the fish ladders were recorded and available through the Fish Passage Center database. We use these data to estimate the probability of detecting lamprey during daytime visual counts in the remaining years (2018, 2021-2023) (Table S4).

The observed number of salmon and lamprey passing through the dam, S_t^P and L_t^P respectively, is paired with the time point t of California sea lion (CSL) euthanasia. To pair these data, we take the sum of fish passing through the dam during a time window surrounding the date of euthanasia, t. This time window accounts for a time lag in both 1) the passage of fish remains through the body of the California sea lion (CSL) and 2) movement of fish from the entrance of the dam as prey to their moment of observation through the fish windows or lamprey passage structures (LPS) (See "Dam count data sensitivity analysis" below, Figure S11).

For our main analysis, we chose a three-day time window to calculate S_t^P and L_t^P (one day before the date of CSL euthanasia to one day following the date of CSL euthanasia). To assess the sensitivity of our results to the selection of this time window, we conducted a sensitivity analysis with a four-day time window (one day before the date of CSL euthanasia to two days following the date of euthanasia) and a five-day time window (one day before the date of CSL euthanasia to three days following the date of euthanasia) (Table S6).

MSFR model code

Below is the NIMBLE model code for MSFR model (Equations 8-12, 14-18) and for estimating the lamprey probability of detection by visual counts at Bonneville fish ladders (Equation 13).

```
##############
# MSFR model #
##############

MSFR_model <- nimbleCode({

  ###############################
  # Chinook salmon prey abundance

  for (t in 1:n_time) {

    # Equation 8
    # get expected number of salmon passed
    S[t] ~ dpois(S_P[t])

    # Equation 9
    # get expected number of salmon available
    S_P[t] ~ dbinom(size = round(S_A[t] - F_day[t, 2]),
                    prob = salmon_PE)
  }

  ########################
  # Lamprey prey abundance

  # Equation 10
  # get expected number of available lamprey passed - exact years
  for (t in 1:n_exact) {
    L_exact[t] ~ dpois(L_P[t_exact[t]])
  }

  # get expected number of available lamprey passed - inexact years
  for (t in 1:n_inexact) {
    # Equation 11
    L_inexact[t] ~ dbinom(size = L_P[t_inexact[t]],
                          prob = p_D[t])
    # Equation 12
    p_D[t] ~ dbeta(alpha_D, beta_D)
  }

  for (t in 1:n_time) {
    # Equation 14
    # get expected number of lamprey available
    L_P[t] ~ dbinom(size = round(L_A[t] - F_day[t, 1]),
                    prob = lamprey_PE)
  }

  ###############
  # Consumed prey
```

```
  # number of prey consumed
  for (j in 1:n_obs) {

    for (i in 1:n_species) {

      # Equations 15-16
      consumed[j, i] ~ dpois(F_exp[obs_ref[j], i])

    }
  }

  ###################################
  # Multi-species functional response

  for (t in 1:n_time) {

    # Equations 17-18
    # expected number of prey consumed - function of available fish
    F_exp[t, 1:n_species] <- get_MSFR(L_A[t] / N_scale,
                                      S_A[t] / N_scale,
                                      q, h[1:n_species],
                                      b_log[1:n_species])
  }


  ##########
  # priors #
  ##########

  # MSFR params
  for (i in 1:n_species) {
    h[i] ~ dunif(0, 1000) # handling time
    b_log[i] ~ dunif(-100, 100) # attack rate
  }

  q ~ dunif(-2, 2)

  # total expected number of lamprey and salmon available
  for (t in 1:n_time) {
    L_A[t] ~ dunif(0, 1000000)
    S_A[t] ~ dunif(0, 1000000)
  }

})

# MSFR
get_MSFR <- nimbleFunction (
  # input and output types
  run = function(L = double(0), S = double(0),
                 q = double(0), h = double(1),
                 b_log = double(1))
  {
    returnType(double(1))
```

```r
    # combine abundance into one vector
    x <- c(L, S)

    # calculate the denominator
    denominator <- 1 + (exp(b_log) * h) %*% x ^ (1 + q)

    L_prey <- exp(b_log[1]) * L ^ (1 + q) / denominator

    S_prey <- exp(b_log[2]) * S ^ (1 + q) / denominator

    return(c(L_prey, S_prey))
  }
)
assign("get_MSFR", get_MSFR, envir = .GlobalEnv)
```

```r
############################
# probability of detection #
############################

# calculate proportion
LPS_prop <- C_V / C_T

LPS_model <- nimbleCode({

  alpha_D ~ dunif(0, 100)
  beta_D ~ dunif(0, 100)

  for (i in 1:nprop) {
    LPS_prop[i] ~ dbeta(alpha_D, beta_D)
  }

})
```

MSFR model fitting

We fit the MSFR model in a Bayesian framework using NIMBLE v.1.3.0 (de Valpine et al. 2017). To enable convergence, the model was fit sequentially, where the beta distribution shape parameters, α^D and β^D, informing the probability of lamprey detection in daytime visual counts, p^D, (Equation 13) were fit first using data, C_d^V and C_d^T. The median posterior values for α^D and β^D were then used to fit the rest of the MSFR model.

For MSFR model fitting, available prey abundance, S_t^A and L_t^A, was rescaled by a factor of 10000 so that abundance would range from 0 to ~1 to assist numerical performance and convergence (Ransijn et al. 2021). We used vague priors for all parameters, which are provided in Appendix 2.1. Parameters were estimated by running four Markov chain Monte Carlo (MCMC) chains of 50 000 000 iterations, thinned by a factor of 10 000. Of these 5 000 samples, 200 were discarded as burn-in. We used visual inspection of the MCMC chains and the Brooks and Gelman diagnostic $\hat{R}$ to assess model convergence, and we found that all parameters had an $\hat{R} \leq 1.1$ (Brooks and Gelman 1998). All analyses were conducted in R version 4.5.1 (R Core Team 2025). Posterior summaries, as well as convergence diagnostics and trace plots of model parameters can be found in Table S2 and Figure S2.

Dam count data sensitivity analysis

The observed number of salmon and lamprey passing through the dam, S_t^P and L_t^P respectively, is paired with the time point t of California sea lion (CSL) euthanasia. To pair these data, we take the sum of fish passing through the dam during a time window surrounding the date of euthanasia, t. This time window accounts for a time lag in both 1) the passage of fish remains through the body of the California sea lion (CSL) and 2) movement of fish from the entrance of the dam as prey to their moment of observation through the fish windows or lamprey passage structures (LPS).

For our main analysis, we chose a three-day time window to calculate S_t^P and L_t^P (one day before the date of CSL euthanasia to one day following the date of CSL euthanasia). To assess the sensitivity of our results to the selection of this time window, we conducted a sensitivity analysis with a four-day time window (one day before the date of CSL euthanasia to two days following the date of euthanasia) and a five-day time window (one day before the date of CSL euthanasia to three days following the date of euthanasia) (Figure S11).

We fit the same Bayesian multi-species functional response (MSFR) model described in Equations 8-12, 14-18 where the number of salmon and lamprey passing through the dam, S_t^P and L_t^P, respectively, were calculated using the four-day and five-day time windows. We then compared the results of our main analysis (3-day time window) to the results with the four- and five-day time window by comparing the 1) MSFR parameter estimates (Table S7) and 2) MSFR model predictions calculated with the posterior samples (Figure S12).

With these results taken together, we conclude that although some parameter estimates change slightly (Table S7), the selection of time window has a negligible effect on the the MSFR model predictions.

Tables

Table S1. Summary of parameters used in dynamical model. The asterisk indicates that the parameter takes on many values.

parameter symbol	description	parameter value	source
b_i	Density-dependent attack rate coefficient for prey species i	*	1
q	Multi-species functional response exponent	*	1
h_i	Handling time for prey species i	*	1
α_L	Lamprey production parameter (combines freshwater mortality and population intrinsic rate of growth)	*	2
α_S	Salmon production parameter (combines freshwater mortality and population intrinsic rate of growth)	225	3
K_S	Lamprey carrying capacity	3e6	3
K_L	Salmon carrying capacity	3e6	3
D_S	Coefficient scaling the rate at which salmon survival decreases as a function of lamprey density	9e7, 7e6, 5e6	4
D_L	Coefficient scaling the rate at which lamprey survival increases as a function of salmon density	5e-5	5
s^o	Density-independent ocean survival, shared between both species	0.0602	6
P	Expected number of California sea lion estuary days (i.e., daily abundance in estuary x days)	10000	7

[1] Parameter is estimated with data using the Bayesian multi-species functional response statistical model (Equations 8-18).

[2] Parameter is treated as the decision maker's action, and therefore takes on many values.

[3] The salmon production parameter and carrying capacity are chosen such that the equilibrium salmon abundance at low lamprey production (~120,000, Figure 4A) is similar to the observed mean abundance of salmon entering Bonneville dam (Figure S8). Lamprey carrying capacity is chosen to be equal to salmon carrying capacity.

[4] Research on the adult Pacific lamprey parasitic phase remains sparse, with little consensus on the relationship between Pacific lamprey abundance and survival of Pacific salmon in their marine phase. Pacific salmon are well-documented hosts of Pacific lampreys, evidenced by observations of Pacific lampreys in catch and inflicted wounds on hosts (Beamish 1980). Murauskas et al. 2013 found a statistically significant relationship between marine abundance indicators of Chinook salmon and Pacific lamprey adult returns to the Columbia River, concluding that abundance of host species is the leading contributor Pacific lamprey ocean survival, characteristic of a predator-prey relationship (Murauskas, Orlov, and Siwicke 2013). The authors suggest that Pacific lampreys may be an overlooked and substantial predator of marine fish, yet the magnitude of this predation is not quantified. Additionally, Weitkamp et al. 2015 examined host selection of multiple lamprey species in the Columbia River estuary, and while around 1% of Chinook salmon exhibited lamprey wounds, these wounds were attributed to River lamprey, rather than Pacific lamprey (Weitkamp, Hinton, and Bentley 2015). These results, however, may reflect the behavior of Pacific lamprey as they migrate through the estuary, rather than their behavior in the ocean.

To reflect uncertainty in the magnitude of Pacific lamprey predation on Chinook salmon, we choose parameter values for D_S that range from no impact on Chinook salmon ocean survival ($D_S = 9e7$, Figure 2) to a relatively high impact on Chinook salmon ocean survival that decreases ocean survival by 2% at high lamprey abundance ($D_S = 3e6$, Figure 2).

[5] Murauskas et al. 2013 found that the abundance of host species is the leading contributor Pacific lamprey ocean survival. The parameter value for D_L is chosen to reflect a scenario where lamprey survival increases rapidly as a function of salmon density (Figure S9) (Murauskas, Orlov, and Siwicke 2013).

[6] The parameter value is chosen based on two sources: 1) the Columbia River Chinook salmon smolt-to-adult ratio in Bonneville dam from the DART database and 2) the survival rate of adult spring-run Chinook salmon from the mouth of the Columbia River estuary to Bonneville dam, estimated using passive integrated transponder tags (Wargo Rub et al. 2019) (Figure S10). The smolt-to-adult ratio, R^{SAR}, measures the proportion of salmon smolts that returned to Bonneville dam. This ratio is the product of the mortality rate in the ocean (from exiting dam as a smolt to entering the Columbia River as an adult, s^o) and the mortality rate in the estuary (from entering the Columbia River as an adult to entering Bonneville dam, s^e): $R^{\text{SAR}} = s^o \times s^e$. To isolate just the mortality rate in the ocean, we divide the mean R^{SAR} across years 2003 - 2024 by the mortality rate in the estuary estimated by Wargo Rub et al., 2019 in years 2010 - 2015 (Figure S10). The value for s^o is shared between salmon and lamprey, as their ocean survival is documented to be highly correlated due to shared environmental conditions (Murauskas, Orlov, and Siwicke 2013).

[7] While the abundance of California sea lions in the Columbia River varies from year to year, we inform P, the annual CSL abundance in the Columbia River estuary (daily abundance $\times$ number of days), using estimates of CSL abundance made by Hatch et al. 2018 (Figure 5 in report). The authors estimated abundance based on boat surveys across four zones from the mouth of the Columbia River to Bonneville dam each week from the beginning of March to mid-May (Hatch, Lessard, and Whiteaker 2018). We use a conservative estimate of $P = 10000$ lower than the estimated CSL abundance, recognizing that the CSL prey attack rate estimated in our analysis using the diet of CSLs euthanized at Bonneville dam is likely higher than other locations in the estuary, as the fish are easier to attack at they enter the dam passage structures.

Table S2. Posterior summaries of the estimated parameters in the multi-species functional response (MSFR) model. Summaries including the mean, standard deviation, 95% credibility interval (highest density interval), $\hat{R}$, and effective sample size for the MSFR parameters and estimates of available prey, $A_t = \{L_t^A, S_t^A\}$ (Equations 17-18). Trace plots of posterior samples can be found in Figure S2.

\

parameter	mean	sd	95 CI	Rhat	ESS
b_L	2.25	0.815	(0.815, 3.888)	1.00	18115
b_S	2.042	0.449	(1.252, 2.917)	1.00	18538
h_L	0.2049	0.1353	(0, 0.4563)	1.00	18521
h_S	0.1447	0.0609	(0.0162, 0.2494)	1.00	18706
q	-0.6031	0.0839	(-0.7579, -0.4366)	1.00	18215
L_1^A	2.141	2.213	(0, 6.548)	1.00	19314
L_2^A	5.254	2.551	(2.5, 10.31)	1.00	19208
L_3^A	2.15	2.214	(0, 6.509)	1.00	18858
L_4^A	1.681	1.861	(0, 5.377)	1.00	19147
L_5^A	6.063	3.86	(0.5, 13.369)	1.00	18528
L_6^A	7.946	4.492	(0.594, 16.481)	1.00	19505
L_7^A	125.6	17.5	(92, 159.8)	1.00	19208
L_8^A	99.83	16.41	(68.29, 132.07)	1.00	18838
L_9^A	114.5	17.3	(81.2, 147.9)	1.00	19208
L_{10}^A	218.3	24.1	(170.8, 264.3)	1.00	19707
L_{11}^A	181.3	21.7	(140.5, 225.1)	1.00	19208
L_{12}^A	22.88	44.85	(1.5, 71.77)	1.06	15846
L_{13}^A	4.602	7.716	(0, 16.64)	1.00	18908
L_{14}^A	11.84	18.09	(0.5, 38.8)	1.00	18327
L_{15}^A	7.068	12.519	(0, 24.417)	1.01	19000
L_{16}^A	7.441	12.829	(0, 25.896)	1.00	19208

(continued)

parameter	mean	sd	95 CI	Rhat	ESS
L^A_{17}	6.979	9.418	(0.501, 22.067)	1.00	19195
L^A_{18}	10.05	20.9	(0, 35.1)	1.01	17510
L^A_{19}	9.538	16.447	(0, 33.729)	1.00	18720
L^A_{20}	21.72	34.06	(1.5, 69.57)	1.00	19528
L^A_{21}	168.8	128	(38.6, 390.9)	1.00	19208
L^A_{22}	363.1	393.7	(67.7, 953.3)	1.01	14641
L^A_{23}	2782	3122	(631, 6835)	1.02	5290
L^A_{24}	4.485	3.127	(0.501, 10.481)	1.00	19467
L^A_{25}	9.045	4.209	(2.505, 17.03)	1.00	19208
L^A_{26}	9.056	4.222	(2.509, 17.073)	1.00	19208
L^A_{27}	6.201	3.92	(0.501, 13.695)	1.00	19208
L^A_{28}	6.192	3.938	(0.5, 13.76)	1.00	19113
L^A_{29}	12.63	5.34	(3.48, 23.05)	1.00	18161
L^A_{30}	23.3	7.38	(10.36, 38.18)	1.00	19558
L^A_{31}	10.44	20.48	(0, 36.24)	1.01	18801
L^A_{32}	7.097	10.998	(0, 25.217)	1.01	18978
L^A_{33}	10.57	18.8	(0, 37.46)	1.00	19624
L^A_{34}	6.217	9.786	(0.001, 21.874)	1.00	18947
L^A_{35}	10.98	21.72	(0, 37.95)	1.03	16566
L^A_{36}	10.24	24.71	(0, 35.16)	1.01	15906
L^A_{37}	9.312	16.39	(0, 32.777)	1.01	19208
L^A_{38}	10.61	21.47	(0, 37.3)	1.00	17536
L^A_{39}	11.79	19.05	(0.5, 37.35)	1.02	17083
L^A_{40}	10.26	18.49	(0, 35.32)	1.01	19137

(continued)

parameter	mean	sd	95 CI	Rhat	ESS
L^A_{41}	8.706	14.967	(0, 30.576)	1.00	18030
L^A_{42}	15.15	18.8	(0.5, 44.98)	1.00	18951
L^A_{43}	89.58	109.91	(11.66, 243.45)	1.01	15530
L^A_{44}	81.1	101.71	(7.32, 244.21)	1.00	17950
L^A_{45}	380.8	439	(51.4, 1079)	1.00	14871
L^A_{46}	2761	3060	(492, 6938)	1.04	3415
S^A_1	413.9	23.9	(368.9, 462.5)	1.00	18967
S^A_2	999.3	36.7	(928.7, 1071.7)	1.00	19208
S^A_3	815.3	33.5	(748.9, 879.5)	1.00	21515
S^A_4	2213	55	(2104, 2321)	1.00	19208
S^A_5	6472	94	(6293, 6661)	1.00	19208
S^A_6	13180	140	(12910, 13450)	1.00	18829
S^A_7	4646	80	(4486, 4801)	1.00	18849
S^A_8	4200	76	(4055, 4353)	1.00	19015
S^A_9	4679	80	(4524, 4837)	1.00	19636
S^A_{10}	7509	102	(7311, 7713)	1.00	19461
S^A_{11}	6369	94	(6190, 6557)	1.00	18937
S^A_{12}	38.11	7.19	(24.62, 52.55)	1.00	19593
S^A_{13}	53.35	8.18	(37.84, 69.65)	1.00	19889
S^A_{14}	114	12.3	(90, 137.6)	1.00	19344
S^A_{15}	144	14	(117.8, 172.3)	1.00	19208
S^A_{16}	141.3	13.9	(114.3, 168.5)	1.00	18973
S^A_{17}	543.6	27.1	(491.7, 597.4)	1.00	19897

(continued)

parameter	mean	sd	95 CI	Rhat	ESS
S^A_{18}	753.3	32.2	(690.8, 816)	1.00	19451
S^A_{19}	3113	65	(2989, 3243)	1.00	18918
S^A_{20}	9657	116	(9438, 9889)	1.00	19208
S^A_{21}	18090	160	(17790, 18410)	1.00	18583
S^A_{22}	11620	130	(11370, 11870)	1.00	19166
S^A_{23}	11160	120	(10930, 11410)	1.00	19591
S^A_{24}	5484	87	(5312, 5654)	1.00	19465
S^A_{25}	10610	120	(10380, 10850)	1.00	19415
S^A_{26}	12080	130	(11820, 12320)	1.00	19208
S^A_{27}	11670	130	(11420, 11920)	1.00	18948
S^A_{28}	11610	130	(11360, 11860)	1.00	18949
S^A_{29}	5152	85	(4987, 5318)	1.00	19208
S^A_{30}	4168	76	(4026, 4320)	1.00	19610
S^A_{31}	1288	42	(1206, 1370)	1.00	18989
S^A_{32}	14480	140	(14200, 14760)	1.00	18857
S^A_{33}	17410	160	(17120, 17730)	1.00	19037
S^A_{34}	33430	210	(33010, 33850)	1.00	19208
S^A_{35}	31620	210	(31210, 32030)	1.00	19260
S^A_{36}	20930	170	(20610, 21270)	1.00	19208
S^A_{37}	16880	150	(16600, 17190)	1.00	19208
S^A_{38}	17130	150	(16820, 17420)	1.00	19208
S^A_{39}	387.8	22.9	(343.7, 432.7)	1.00	19830
S^A_{40}	8601	109	(8392, 8818)	1.00	18981

(continued)

parameter	mean	sd	95 CI	Rhat	ESS
S_{41}^{A}	6017	91	(5838, 6194)	1.00	18890
S_{42}^{A}	4875	82	(4717, 5036)	1.00	18890
S_{43}^{A}	21770	180	(21440, 22120)	1.00	18924
S_{44}^{A}	24990	190	(24620, 25350)	1.00	18171
S_{45}^{A}	25280	190	(24920, 25650)	1.00	19172
S_{46}^{A}	17640	160	(17340, 17940)	1.00	19208

Table S3. Dates of California sea lion euthanasia and gastro-intestinal analysis. The date, t, corresponds to t in the above Table S2, and N corresponds to the number of euthanized CSL individuals at time t.

t	date	N
1	2017-04-19	1
2	2017-04-25	6
3	2017-04-27	1
4	2017-05-02	4
5	2017-05-03	1
6	2017-05-04	1
7	2017-05-09	4
8	2017-05-10	2
9	2017-05-11	1
10	2017-05-16	1
11	2017-05-17	2
12	2018-04-10	1
13	2018-04-11	4
14	2018-04-17	2
15	2018-04-18	2
16	2018-04-19	2
17	2018-04-24	5
18	2018-04-25	1
19	2018-05-01	2
20	2018-05-03	2
21	2018-05-08	5
22	2018-05-09	1
23	2018-05-15	1

24	2019-04-30	1
25	2019-05-01	5
26	2019-05-02	4
27	2019-05-07	1
28	2019-05-08	1
29	2019-05-14	3
30	2019-05-15	4
31	2022-04-20	1
32	2022-04-26	3
33	2022-04-28	1
34	2022-05-03	4
35	2022-05-04	1
36	2022-05-05	1
37	2022-05-10	1
38	2022-05-11	2
39	2023-04-19	2
40	2023-05-02	2
41	2023-05-03	2
42	2023-05-04	4
43	2023-05-09	1
44	2023-05-10	3
45	2023-05-11	3
46	2023-05-16	5

Table S4. Observed abundance of fish passed in Bonneville dam passage structures, where t corresponds to the date of CSL euthanasia, time window set corresponds to the time window sets described in Equations 10 and 11, S^P corresponds to the sum of Chinook salmon counted in visual, day-time fish ladders in the three-day time window, L^P (Fish ladder) corresponds to the sum of Pacific lamprey counted in visual, day-time and night-time fish ladders in the three-day time window, L^P (LPS) corresponds to the sum of Pacific lamprey counted in the three mechanical lamprey passage structures (LPS) in the three-day time window, and L^P total corresponds to the total number of Pacific lamprey counted across all passage structures. “NR” indicates that the count of Pacific lamprey was not recorded in the associated passage structure in that time period.

			L^P (Fish ladder)			
t	time window set	S^P	Day-time	Night-time	L^P (LPS)	L^P total
2017-04-19	λ^I	346	0	0	0	0
2017-04-25	λ^I	827	0	0	0	0
2017-04-27	λ^I	682	0	0	0	0
2017-05-02	λ^I	1845	0	0	0	0
2017-05-03	λ^I	5433	0	2	0	2
2017-05-04	λ^I	11070	0	3	0	3
2017-05-09	λ^I	3893	0	61	0	61
2017-05-10	λ^I	3526	0	52	2	54
2017-05-11	λ^I	3926	0	59	3	62
2017-05-16	λ^I	6305	41	78	0	119
2017-05-17	λ^I	5343	33	65	0	98
2018-04-10	λ^E	30	0	NR	NR	0
2018-04-11	λ^E	40	0	NR	NR	0
2018-04-17	λ^E	93	0	NR	NR	0
2018-04-18	λ^E	117	0	NR	NR	0
2018-04-19	λ^E	116	0	NR	NR	0
2018-04-24	λ^E	445	0	NR	NR	0
2018-04-25	λ^E	631	0	NR	NR	0
2018-05-01	λ^E	2613	0	NR	NR	0

2018-05-03	λ^E	8104	0	NR	NR	0
2018-05-08	λ^E	15169	17	NR	NR	17
2018-05-09	λ^E	9761	30	NR	NR	30
2018-05-15	λ^E	9374	258	NR	NR	258
2019-04-30	λ^I	4601	0	1	0	1
2019-05-01	λ^I	8907	0	2	0	2
2019-05-02	λ^I	10131	0	2	0	2
2019-05-07	λ^I	9802	0	2	0	2
2019-05-08	λ^I	9752	0	2	0	2
2019-05-14	λ^I	4316	0	5	0	5
2019-05-15	λ^I	3493	8	4	0	12
2022-04-20	λ^E	1081	0	NR	NR	0
2022-04-26	λ^E	12150	0	NR	NR	0
2022-04-28	λ^E	14624	0	NR	NR	0
2022-05-03	λ^E	28056	0	NR	NR	0
2022-05-04	λ^E	26557	0	NR	NR	0
2022-05-05	λ^E	17577	0	NR	NR	0
2022-05-10	λ^E	14175	0	NR	NR	0
2022-05-11	λ^E	14384	0	NR	NR	0
2023-04-19	λ^E	321	0	NR	NR	0
2023-05-02	λ^E	7224	0	NR	NR	0
2023-05-03	λ^E	5048	0	NR	NR	0
2023-05-04	λ^E	4088	1	NR	NR	1
2023-05-09	λ^E	18285	7	NR	NR	7
2023-05-10	λ^E	20981	3	NR	NR	3
2023-05-11	λ^E	21229	21	NR	NR	21

2023-05-16	λ^E	14806	187	NR	NR	187

Table S5. Counts of lamprey in 2017 and 2019 passing through fish passage structures at Bonneville dam, used to inform the probability of lamprey detection in day-time visual fish ladder counts. Counts include 1) visual day-time counts in Bradford Island (BI) and Washington Shores (WS) fish ladders, 2) visual night-time counts in BI and WS fish ladders, and 3) mechanical corrected counts in three lamprey passage structures (LPS): Bradford Island auxiliary water supply (BI-AWS), Washington shore fish ladder auxiliary water supply (WA-AWS), and Cascades Island entrance (CI-ENT). (Cates, McClain, and Gibbons 2020). The column C_V corresponds to the sum of visual day-time counts in the two fish ladders, and the column C_T corresponds to the sum of counts across all structures. The proportion of lamprey observed by visual day-time counts (C_V/C_T) is used to inform beta distribution parameters, α_D and β_D (Equation 13, Figure S7). Date corresponds to the first day of the three-day time interval. Counts were summed across this three-day time interval to account for day-to-day stochasticity. Time intervals were included if at least 20 total lamprey passed through all structures (i.e., $C_T > 20$).

	Fish ladder				LPS					
	Day-time		Night-time							
Date	BI	WS	BI	WS	BI-AWS	CI-ENT	WA-AWS	C_V	C_T	C_V / C_T
2017-05-07	0	29	0	0	0	0	11	29	40	0.72
2017-05-10	0	31	0	0	1	2	28	31	62	0.50
2017-05-13	0	26	2	18	0	0	42	26	88	0.30
2017-05-16	0	39	5	28	0	0	26	39	98	0.40
2017-05-19	0	74	5	44	0	4	33	74	160	0.46
2017-05-22	1	861	3	132	0	8	168	862	1173	0.73
2017-05-25	5	729	14	587	1	9	716	734	2061	0.36
2017-05-28	213	2207	258	603	36	10	1103	2420	4430	0.55
2017-06-01	838	1758	646	432	173	9	1145	2596	5001	0.52
2017-06-04	692	333	408	-62	140	7	1235	1025	2753	0.37
2017-06-07	1644	1927	137	167	302	206	2018	3571	6401	0.56
2017-06-10	392	518	-29	618	297	129	1810	910	3735	0.24
2017-06-13	212	415	125	-619	181	44	502	627	860	0.73
2017-06-16	573	1062	-249	-67	563	150	95	1635	2127	0.77
2017-06-19	1748	3687	525	-310	1650	688	2240	5435	10228	0.53
2017-06-22	2165	2652	723	447	3428	1146	3492	4817	14053	0.34

2017-06-25	4364	2648	3628	-41	3254	201	5919	7012	19973	0.35
2017-06-28	2433	1320	5866	657	804	33	12552	3753	23665	0.16
2017-07-01	4514	1141	3412	2681	3074	58	14760	5655	29640	0.19
2017-07-04	3371	1507	3426	1160	1721	99	10117	4878	21401	0.23
2017-07-07	2390	2014	2127	2548	1375	31	4538	4404	15023	0.29
2017-07-10	1803	1782	1945	2561	1427	2	3921	3585	13441	0.27
2017-07-13	2616	1374	1044	1849	922	1	4199	3990	12005	0.33
2017-07-16	1810	1928	1713	1841	742	1	1935	3738	9970	0.37
2017-07-19	1103	1348	2440	1355	669	0	1343	2451	8258	0.30
2017-07-22	1592	1011	1762	2492	461	2	1226	2603	8546	0.30
2017-07-25	1292	627	2357	2055	574	5	1218	1919	8128	0.24
2017-07-28	1550	1185	5104	3484	529	2	921	2735	12775	0.21
2017-08-01	947	1418	2578	1650	401	0	992	2365	7986	0.30
2017-08-04	575	1056	2437	1587	233	15	1430	1631	7333	0.22
2017-08-07	278	699	1448	1153	294	6	1687	977	5565	0.18
2017-08-10	432	559	1105	1620	379	9	1095	991	5199	0.19
2017-08-13	494	640	1947	1095	513	2	863	1134	5554	0.20
2017-08-16	470	252	506	496	735	2	379	722	2840	0.25
2017-08-19	231	375	816	648	756	13	779	606	3618	0.17
2017-08-22	236	386	849	398	537	64	1007	622	3477	0.18
2017-08-25	77	190	90	370	704	39	853	267	2323	0.11
2017-08-28	117	191	-209	169	653	14	1203	308	2138	0.14
2017-09-01	84	197	465	502	574	13	608	281	2443	0.12
2017-09-07	37	473	351	369	249	1	362	510	1842	0.28
2017-09-10	36	113	55	-48	83	0	493	149	732	0.20
2017-09-13	17	102	54	142	71	1	278	119	665	0.18

2017-09-16	7	62	141	273	57	1	129	69	670	0.10
2017-09-19	15	33	152	127	13	0	51	48	391	0.12
2017-09-22	3	19	37	20	8	0	38	22	125	0.18
2017-09-25	3	42	8	77	9	0	48	45	187	0.24
2017-09-28	2	31	82	93	11	0	29	33	248	0.13
2017-10-01	3	11	0	0	6	0	1	14	21	0.67
2019-05-19	1	50	1	59	0	0	8	51	119	0.43
2019-05-22	0	3	1	19	0	0	9	3	32	0.09
2019-05-25	2	32	3	40	0	0	23	34	100	0.34
2019-05-28	21	137	40	270	7	11	98	158	584	0.27
2019-06-01	140	519	280	361	67	301	298	659	1966	0.34
2019-06-04	201	263	214	76	173	123	538	464	1588	0.29
2019-06-07	195	141	415	-25	208	22	535	336	1491	0.23
2019-06-10	270	184	800	338	682	28	807	454	3109	0.15
2019-06-13	713	233	1311	310	916	17	746	946	4246	0.22
2019-06-16	511	241	1619	1056	965	52	691	752	5135	0.15
2019-06-19	313	208	750	463	472	74	610	521	2890	0.18
2019-06-22	330	169	672	208	407	19	423	499	2228	0.22
2019-06-25	479	222	1017	496	105	10	762	701	3091	0.23
2019-06-28	480	264	636	468	105	9	514	744	2476	0.30
2019-07-01	475	280	287	523	99	11	626	755	2301	0.33
2019-07-04	244	263	286	852	65	0	319	507	2029	0.25
2019-07-07	201	599	409	1471	41	6	335	800	3062	0.26
2019-07-10	505	895	425	565	163	1	753	1400	3307	0.42
2019-07-13	665	765	508	1465	264	1	1447	1430	5115	0.28
2019-07-16	362	612	445	-53	244	7	867	974	2484	0.39

2019-07-19	347	404	497	1026	86	5	217	751	2582	0.29
2019-07-22	592	540	881	1069	81	2	214	1132	3379	0.34
2019-07-25	550	454	843	417	138	2	238	1004	2642	0.38
2019-07-28	225	206	426	87	225	3	158	431	1330	0.32
2019-08-01	385	165	788	52	59	4	469	550	1922	0.29
2019-08-04	255	130	301	117	109	22	358	385	1292	0.30
2019-08-07	278	154	468	-4	88	15	194	432	1193	0.36
2019-08-10	175	126	474	86	76	1	107	301	1045	0.29
2019-08-13	851	501	1216	123	180	16	488	1352	3375	0.40
2019-08-16	93	82	455	147	136	5	187	175	1105	0.16
2019-08-19	60	14	321	128	75	5	70	74	673	0.11
2019-08-22	50	88	359	68	99	5	90	138	759	0.18
2019-08-25	62	30	148	28	36	1	133	92	438	0.21
2019-08-28	86	41	148	196	35	1	123	127	630	0.20
2019-09-01	48	111	72	46	36	8	176	159	497	0.32
2019-09-04	13	23	46	56	26	0	89	36	253	0.14
2019-09-07	1	9	4	-3	13	0	49	10	73	0.14
2019-09-10	8	24	10	22	13	0	20	32	97	0.33
2019-09-13	9	25	12	24	15	0	0	34	85	0.40
2019-09-16	3	9	9	-9	18	0	8	12	38	0.32
2019-09-19	3	5	1	6	5	0	13	8	33	0.24

Table S6. Gastro-intestinal data of 107 euthanized California sea lions collected at 46 time points. The time window start and end correspond to the 3-day time window surrounding the date of CSL euthanasia used to calculate the abundance of passed fish through Bonneville dam.

Euthanasia date	Chinook consumed (F^S)	Lamprey consumed (F^L)	Time window start	Time window end
2017-04-19	1	0	2017-04-18	2017-04-20
2017-04-25	3	0	2017-04-24	2017-04-26
2017-04-25	0	0	2017-04-24	2017-04-26
2017-04-25	1	0	2017-04-24	2017-04-26
2017-04-25	2	0	2017-04-24	2017-04-26
2017-04-25	6	3	2017-04-24	2017-04-26
2017-04-25	1	0	2017-04-24	2017-04-26
2017-04-27	2	0	2017-04-26	2017-04-28
2017-05-02	1	0	2017-05-01	2017-05-03
2017-05-02	8	0	2017-05-01	2017-05-03
2017-05-02	1	0	2017-05-01	2017-05-03
2017-05-02	4	0	2017-05-01	2017-05-03
2017-05-03	3	0	2017-05-02	2017-05-04
2017-05-04	2	0	2017-05-03	2017-05-05
2017-05-09	5	0	2017-05-08	2017-05-10
2017-05-09	2	1	2017-05-08	2017-05-10
2017-05-09	3	7	2017-05-08	2017-05-10
2017-05-09	1	0	2017-05-08	2017-05-10
2017-05-10	1	0	2017-05-09	2017-05-11
2017-05-10	1	0	2017-05-09	2017-05-11
2017-05-11	3	0	2017-05-10	2017-05-12
2017-05-16	2	0	2017-05-15	2017-05-17
2017-05-17	4	1	2017-05-16	2017-05-18

2017-05-17	2	0	2017-05-16	2017-05-18
2018-04-10	1	2	2018-04-09	2018-04-11
2018-04-11	1	0	2018-04-10	2018-04-12
2018-04-11	1	0	2018-04-10	2018-04-12
2018-04-11	1	0	2018-04-10	2018-04-12
2018-04-11	1	0	2018-04-10	2018-04-12
2018-04-17	1	0	2018-04-16	2018-04-18
2018-04-17	1	1	2018-04-16	2018-04-18
2018-04-18	0	0	2018-04-17	2018-04-19
2018-04-18	3	0	2018-04-17	2018-04-19
2018-04-19	0	0	2018-04-18	2018-04-20
2018-04-19	2	0	2018-04-18	2018-04-20
2018-04-24	2	0	2018-04-23	2018-04-25
2018-04-24	3	0	2018-04-23	2018-04-25
2018-04-24	1	1	2018-04-23	2018-04-25
2018-04-24	1	0	2018-04-23	2018-04-25
2018-04-24	4	0	2018-04-23	2018-04-25
2018-04-25	1	0	2018-04-24	2018-04-26
2018-05-01	1	0	2018-04-30	2018-05-02
2018-05-01	1	0	2018-04-30	2018-05-02
2018-05-03	7	1	2018-05-02	2018-05-04
2018-05-03	1	1	2018-05-02	2018-05-04
2018-05-08	7	0	2018-05-07	2018-05-09
2018-05-08	3	0	2018-05-07	2018-05-09
2018-05-08	6	2	2018-05-07	2018-05-09
2018-05-08	3	2	2018-05-07	2018-05-09

2018-05-08	11	0	2018-05-07	2018-05-09
2018-05-09	0	0	2018-05-08	2018-05-10
2018-05-15	1	0	2018-05-14	2018-05-16
2019-04-30	5	0	2019-04-29	2019-05-01
2019-05-01	1	0	2019-04-30	2019-05-02
2019-05-01	4	0	2019-04-30	2019-05-02
2019-05-01	1	1	2019-04-30	2019-05-02
2019-05-01	4	1	2019-04-30	2019-05-02
2019-05-01	1	0	2019-04-30	2019-05-02
2019-05-02	4	1	2019-05-01	2019-05-03
2019-05-02	2	0	2019-05-01	2019-05-03
2019-05-02	2	0	2019-05-01	2019-05-03
2019-05-02	5	1	2019-05-01	2019-05-03
2019-05-07	1	0	2019-05-06	2019-05-08
2019-05-08	1	0	2019-05-07	2019-05-09
2019-05-14	5	1	2019-05-13	2019-05-15
2019-05-14	3	0	2019-05-13	2019-05-15
2019-05-14	3	0	2019-05-13	2019-05-15
2019-05-15	5	2	2019-05-14	2019-05-16
2019-05-15	2	0	2019-05-14	2019-05-16
2019-05-15	1	0	2019-05-14	2019-05-16
2019-05-15	1	0	2019-05-14	2019-05-16
2022-04-20	1	0	2022-04-19	2022-04-21
2022-04-26	7	0	2022-04-25	2022-04-27
2022-04-26	1	0	2022-04-25	2022-04-27
2022-04-26	6	0	2022-04-25	2022-04-27

2022-04-28	3	0	2022-04-27	2022-04-29
2022-05-03	7	0	2022-05-02	2022-05-04
2022-05-03	11	0	2022-05-02	2022-05-04
2022-05-03	5	0	2022-05-02	2022-05-04
2022-05-03	3	0	2022-05-02	2022-05-04
2022-05-04	3	0	2022-05-03	2022-05-05
2022-05-05	5	0	2022-05-04	2022-05-06
2022-05-10	7	0	2022-05-09	2022-05-11
2022-05-11	1	0	2022-05-10	2022-05-12
2022-05-11	2	0	2022-05-10	2022-05-12
2023-04-19	1	1	2023-04-18	2023-04-20
2023-04-19	3	0	2023-04-18	2023-04-20
2023-05-02	1	0	2023-05-01	2023-05-03
2023-05-02	1	0	2023-05-01	2023-05-03
2023-05-03	1	0	2023-05-02	2023-05-04
2023-05-03	5	0	2023-05-02	2023-05-04
2023-05-04	1	0	2023-05-03	2023-05-05
2023-05-04	0	0	2023-05-03	2023-05-05
2023-05-04	1	0	2023-05-03	2023-05-05
2023-05-04	5	0	2023-05-03	2023-05-05
2023-05-09	2	0	2023-05-08	2023-05-10
2023-05-10	4	0	2023-05-09	2023-05-11
2023-05-10	4	1	2023-05-09	2023-05-11
2023-05-10	3	2	2023-05-09	2023-05-11
2023-05-11	0	0	2023-05-10	2023-05-12
2023-05-11	3	3	2023-05-10	2023-05-12

2023-05-11	2	0	2023-05-10	2023-05-12
2023-05-16	2	0	2023-05-15	2023-05-17
2023-05-16	1	0	2023-05-15	2023-05-17
2023-05-16	6	3	2023-05-15	2023-05-17
2023-05-16	0	7	2023-05-15	2023-05-17
2023-05-16	8	1	2023-05-15	2023-05-17

Table S7. Posterior summaries, including the mean and 95% credibility interval (equal tailed interval) for multi-species functional response (MSFR) parameters (Equations 1-2) with a three-day, four-day, and five-day window.

parameter	summary (1 day)	summary (2 day)	summary (3 day)
q	-0.60 (-0.75, -0.42)	-0.62 (-0.75, -0.46)	-0.64 (-0.75, -0.48)
h_L	0.20 (0.01, 0.52)	0.17 (0.01, 0.43)	0.15 (0.01, 0.40)
h_S	0.14 (0.02, 0.25)	0.13 (0.01, 0.25)	0.12 (0.01, 0.24)
$\log(b_L)$	2.25 (0.87, 4.01)	1.87 (0.70, 3.42)	1.62 (0.58, 3.08)
$\log(b_S)$	2.04 (1.32, 3.04)	1.80 (1.17, 2.71)	1.62 (1.07, 2.49)

Figures

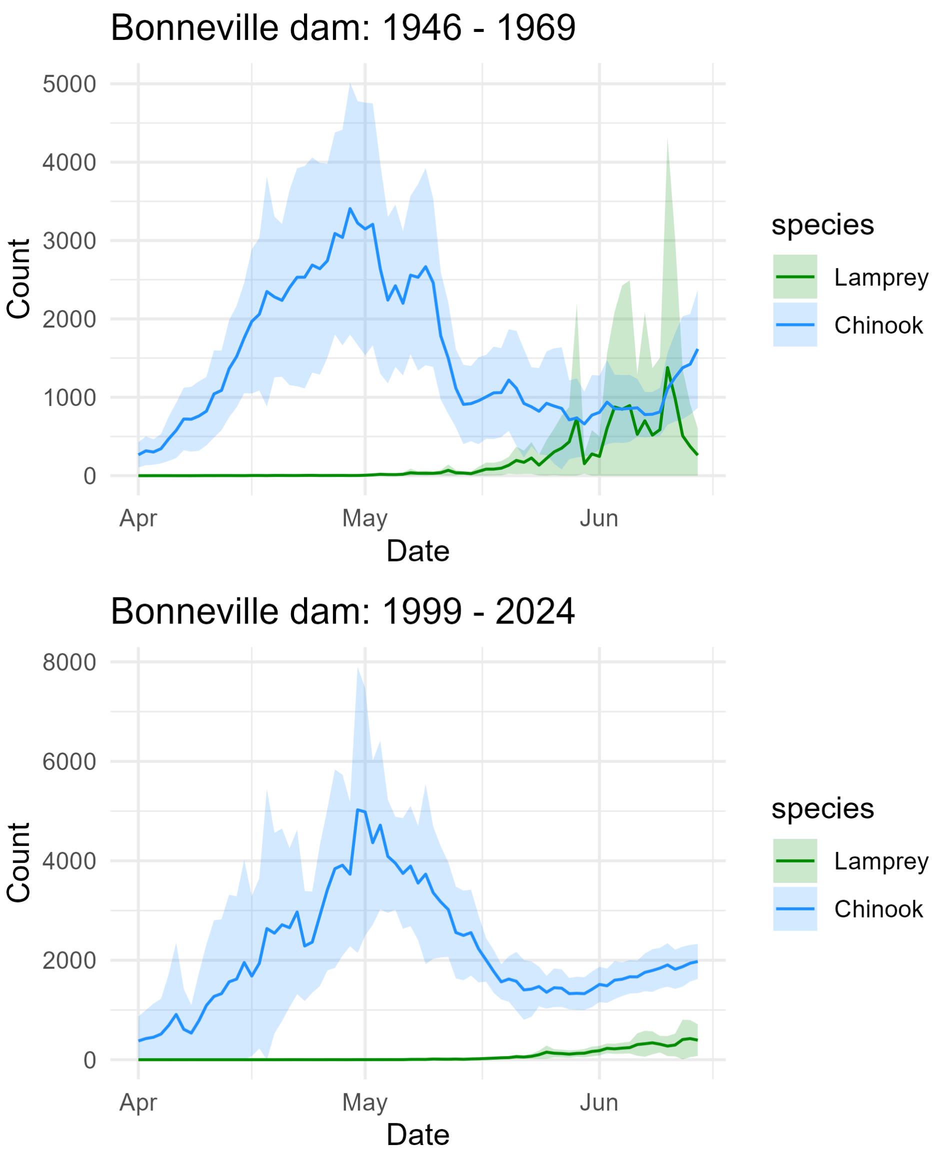

Figure S1. Count of Chinook salmon and Pacific lamprey passing through Bonneville dam fish windows in April to mid-June from **A.** 1946 - 1969 and **B.** 1999 - 2024. Pacific lamprey counts were not recorded from 1970 - 1998. Solid line indicates the mean count across years, and shaded area indicates $\pm$ 0.5 standard deviation from the mean.

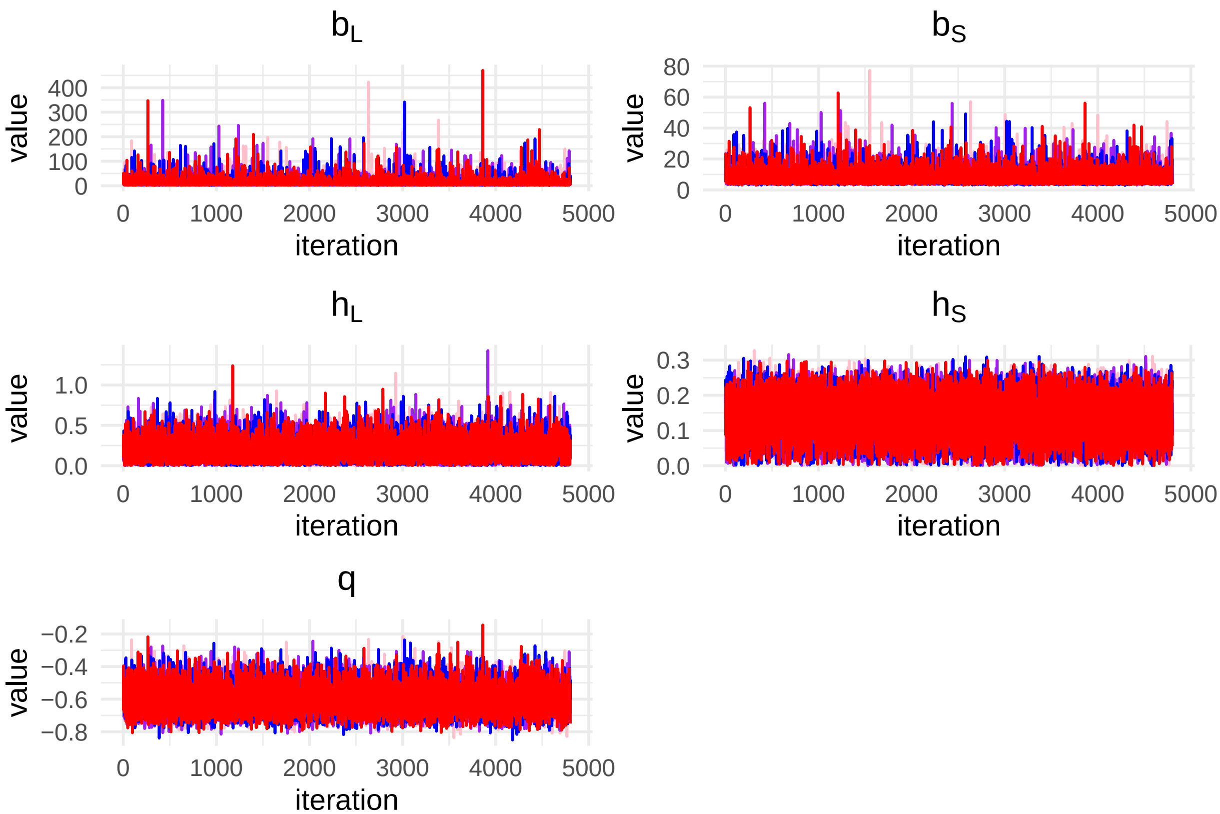

Figure S2. Trace plots of posterior samples of MSFR parameters. Colors refer to separate chains.

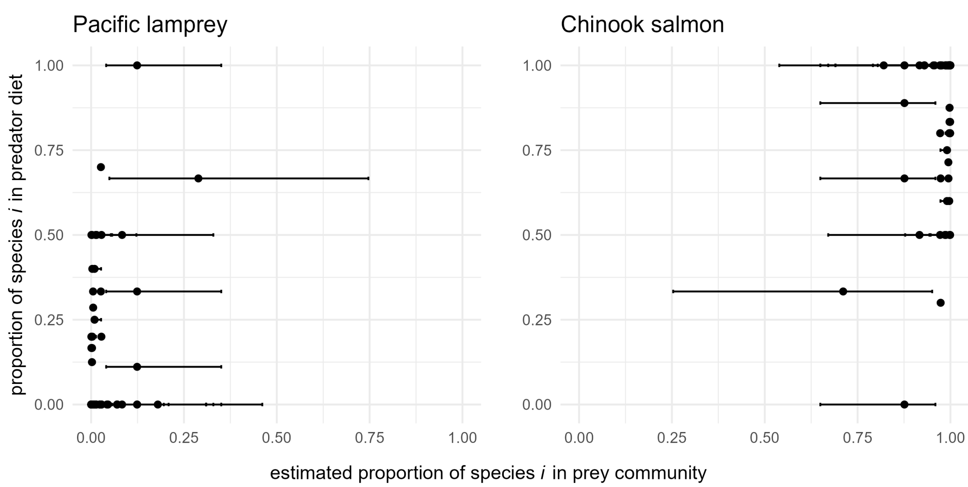

Figure S3. Relationship between the proportion of each fish species in the predator's diet and estimated proportion of each fish species in the prey community. Error bars indicate the 95% credible interval for the abundance of available lamprey and salmon, L_t^A and S_t^A, respectively.

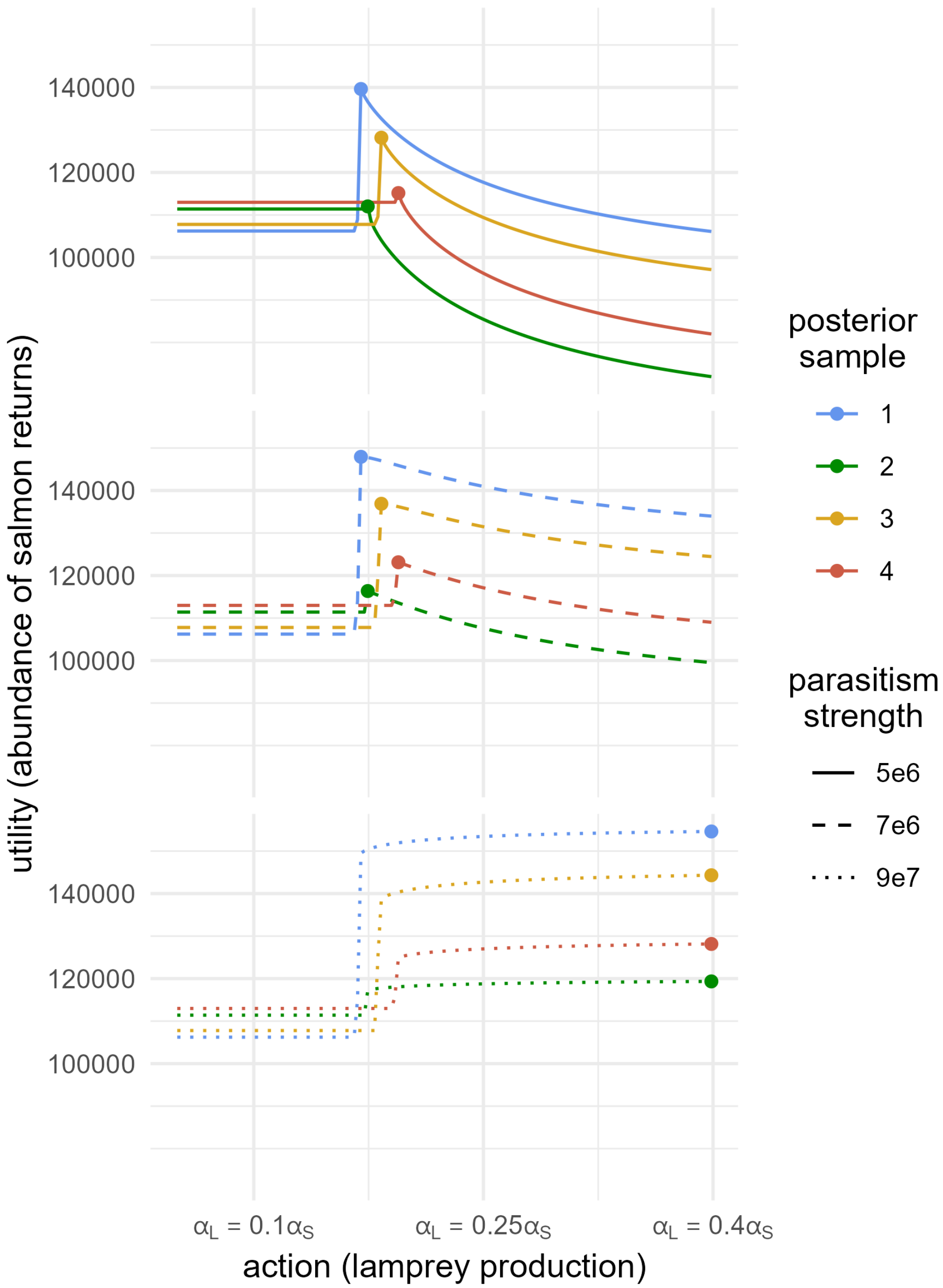

Figure S4. Decision utility as a function of a decision maker's action, or the lamprey production, α_L, relative to Chinook salmon production, α_S. Colors correspond to functional response uncertainty, and line types correspond to parasitism uncertainty. The point indicates the action that maximizes utility, $a*$.

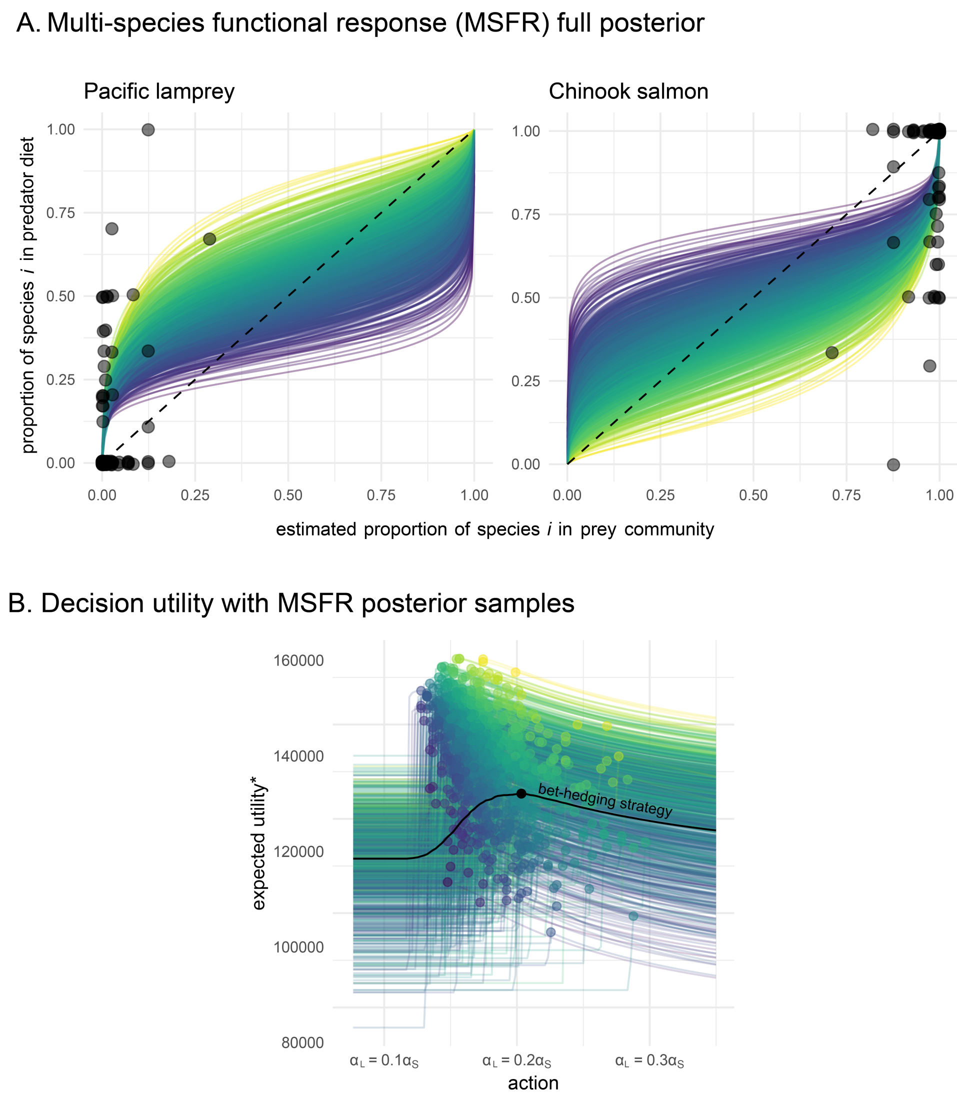

Figure S5. Relationship between functional response uncertainty and decision utility. **A.** Full posterior describing the relationship between a species' proportion in the prey community and proportion in the predator's diet for Pacific lamprey and Chinook salmon. Each line corresponds to the MSFR prediction for each posterior sample, and color corresponds to the value of each prediction when the species' proportion in the prey community equals 0.5. Dashed black line indicates the 1:1 line **B.** Decision utility calculated with each sample from the full MSFR posterior in panel A. The expected utility is calculated for each action, $a \in A$ (lamprey production parameter, α_L, relative to Chinook salmon production parameter, α_S). The asterisk indicates that the utility is calculated as an expectation over parasitism uncertainty (i.e., $E_P[U(a, f, p)]$). Points indicate the action that maximizes utility over parasitism uncertainty (i.e., $\max_a E_P[U(a, f, p)]$). Colors indicate the corresponding posterior sample from panel A. The black line indicates the utility calculated as an expectation over both parasitism and functional response uncertainty (i.e., $E_{F,P}[U(a, f, p)]$). The black point indicates the action that maximizes utility over all uncertainty, or the bet-hedging strategy (i.e., $\max_a E_{F,P}[U(a, f, p)]$).

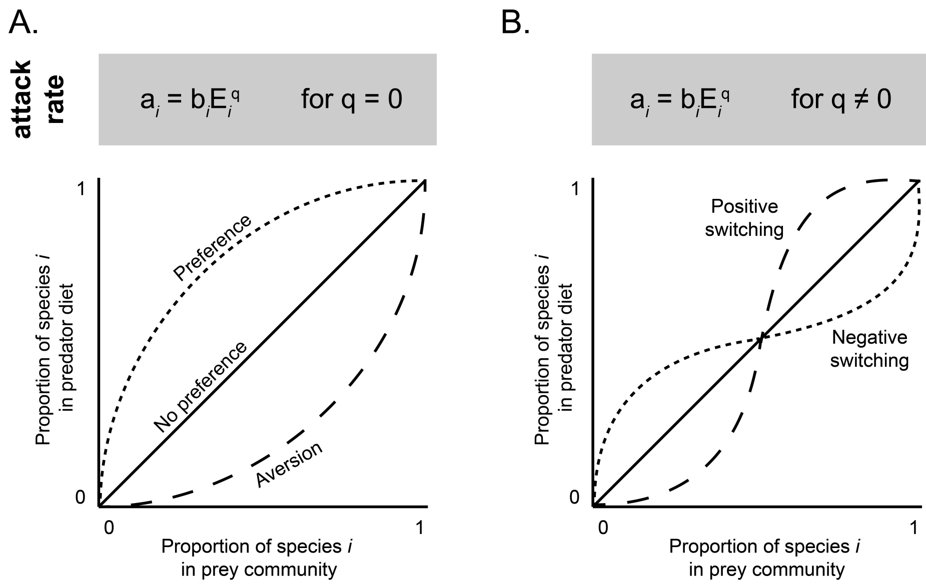

Figure S6. Conceptual diagram of density-dependent multi-species functional response (MSFR), relating the formulation of the density-dependent attack rate (Equations 1-2) to system behavior.

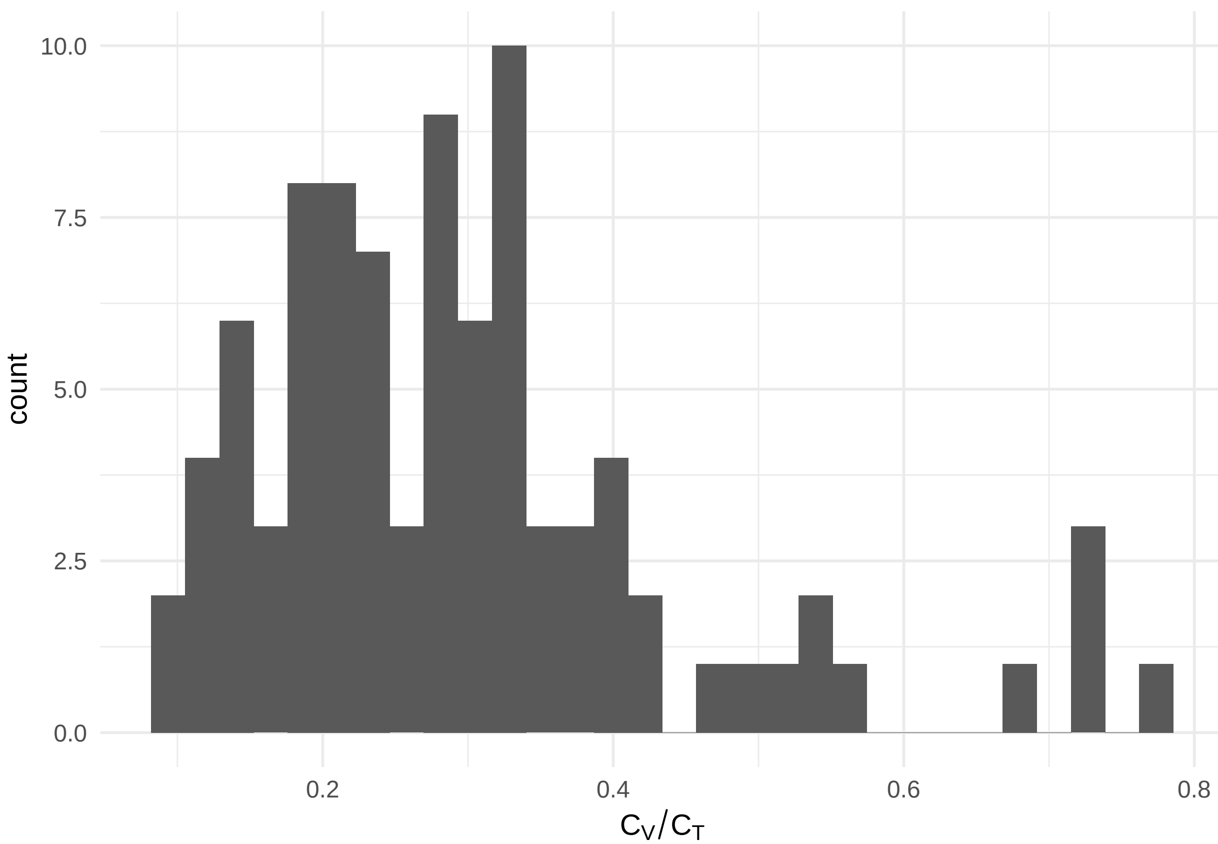

Figure S7. Histogram of the proportion of lamprey observed by visual day-time counts (C_V/C_T) is used to inform beta distribution parameters, α_D and β_D (Equation 13).

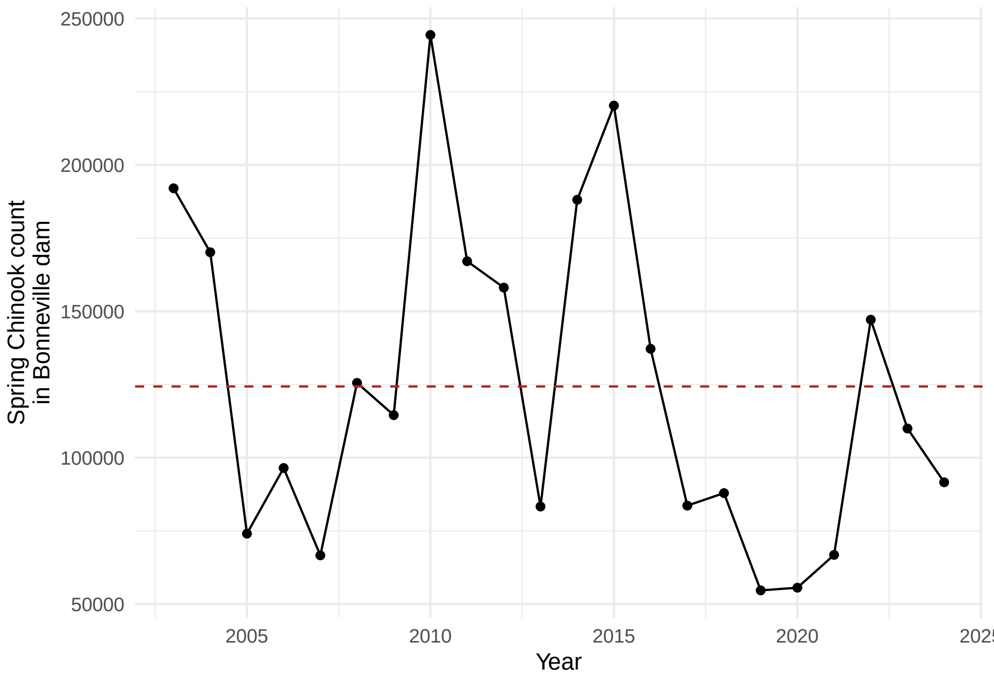

Figure S8: Total count of Spring Chinook salmon passing through Bonneville dam. Dashed red line indicates time series mean.

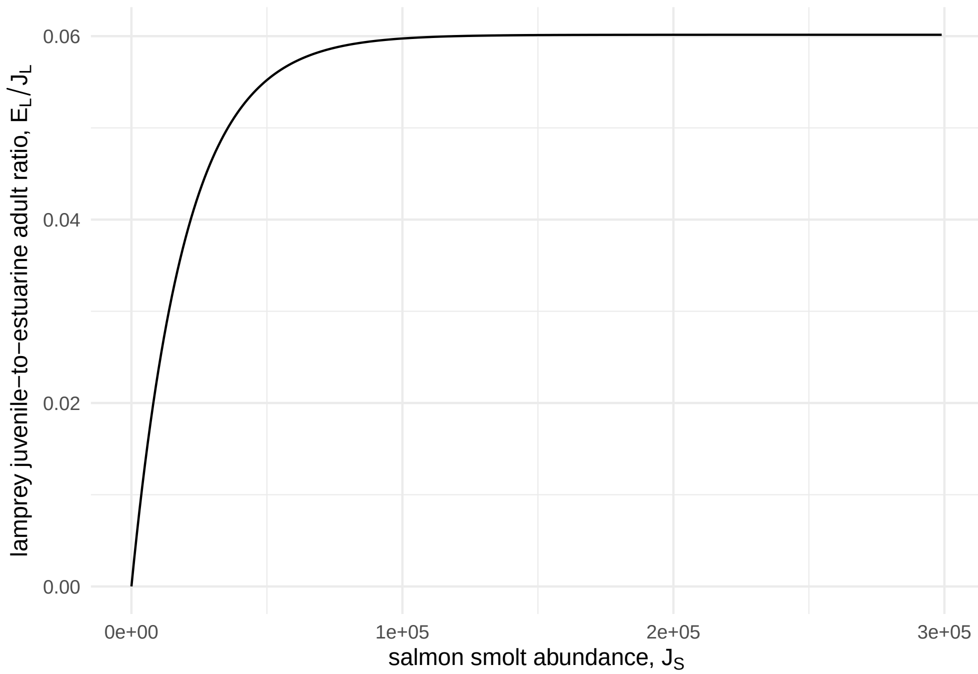

Figure S9: Relationship between salmon smolt abundance, J_S, and lamprey ocean survival (E_L/J_L), given parameter value selected for D_L, the coefficient scaling the rate at which lamprey survival increases as a function of salmon density.

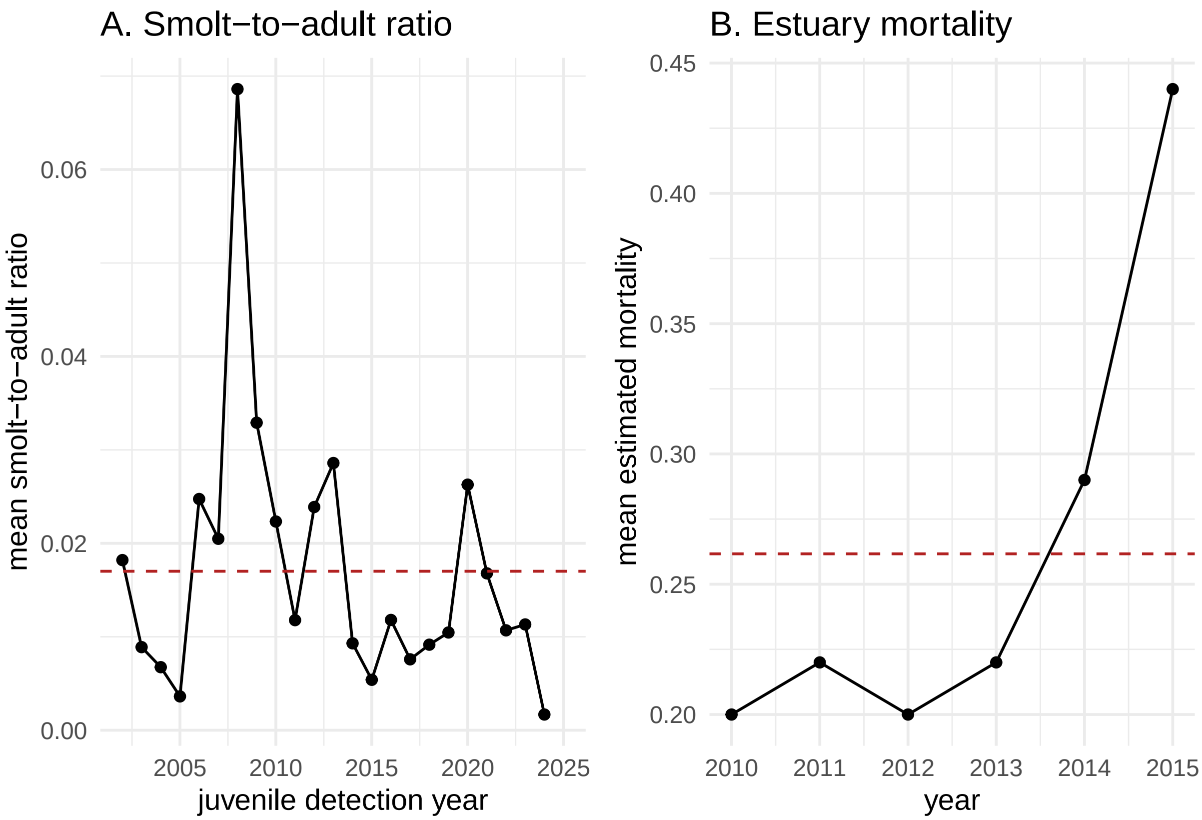

Figure S10: Data sources used to inform ocean mortality, s^o. **A.** Mean smolt-to-adult ratio (Bonneville dam juvenile to Bonneville dam adult) calculated with PIT-Tagged Snake River Spring/Summer Chinook ecologically significant unit (ESU), retrieved from the DART data base. Red dashed line indicates time series mean ($R^{\mathrm{SAR}} = 0.017$). **B.** Annual estimated number of spring run Chinook salmon lost to sources other than harvest between the Columbia River Estuary and Bonneville Dam (retrieved from Table 5 in (Wargo Rub et al. 2019)) Red dashed line indicates time series mean ($s^e = 0.26$). The value we use for mortality in the ocean, s^o is therefore: $s^o = R^{\mathrm{SAR}}/s^e = 0.06$.

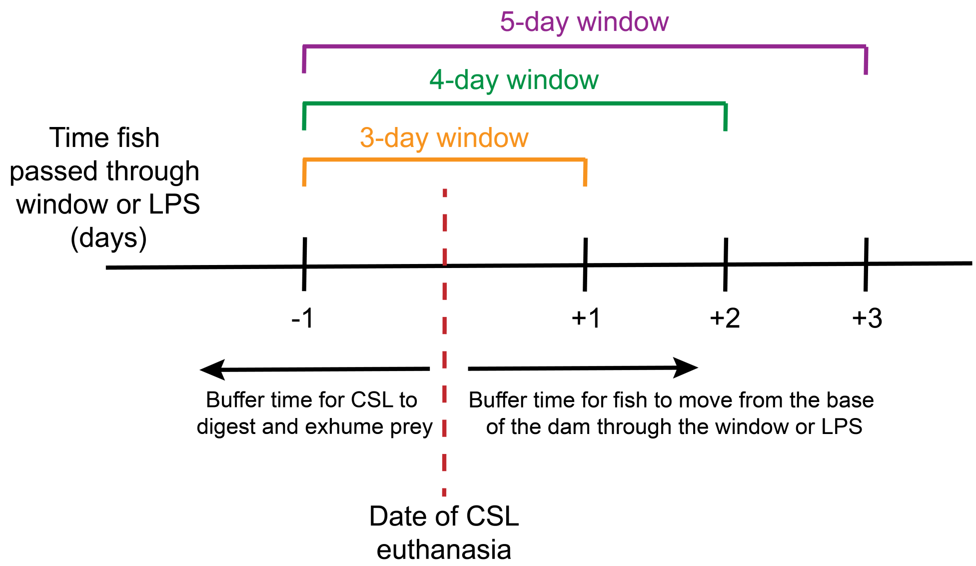

Figure S11. Conceptual diagram of time window used to find the sum of fish passing through the dam for each CSL euthanasia time point. The axis is the time fish passed through the visual fish windows or lamprey passage structures (LPS), measured in days.

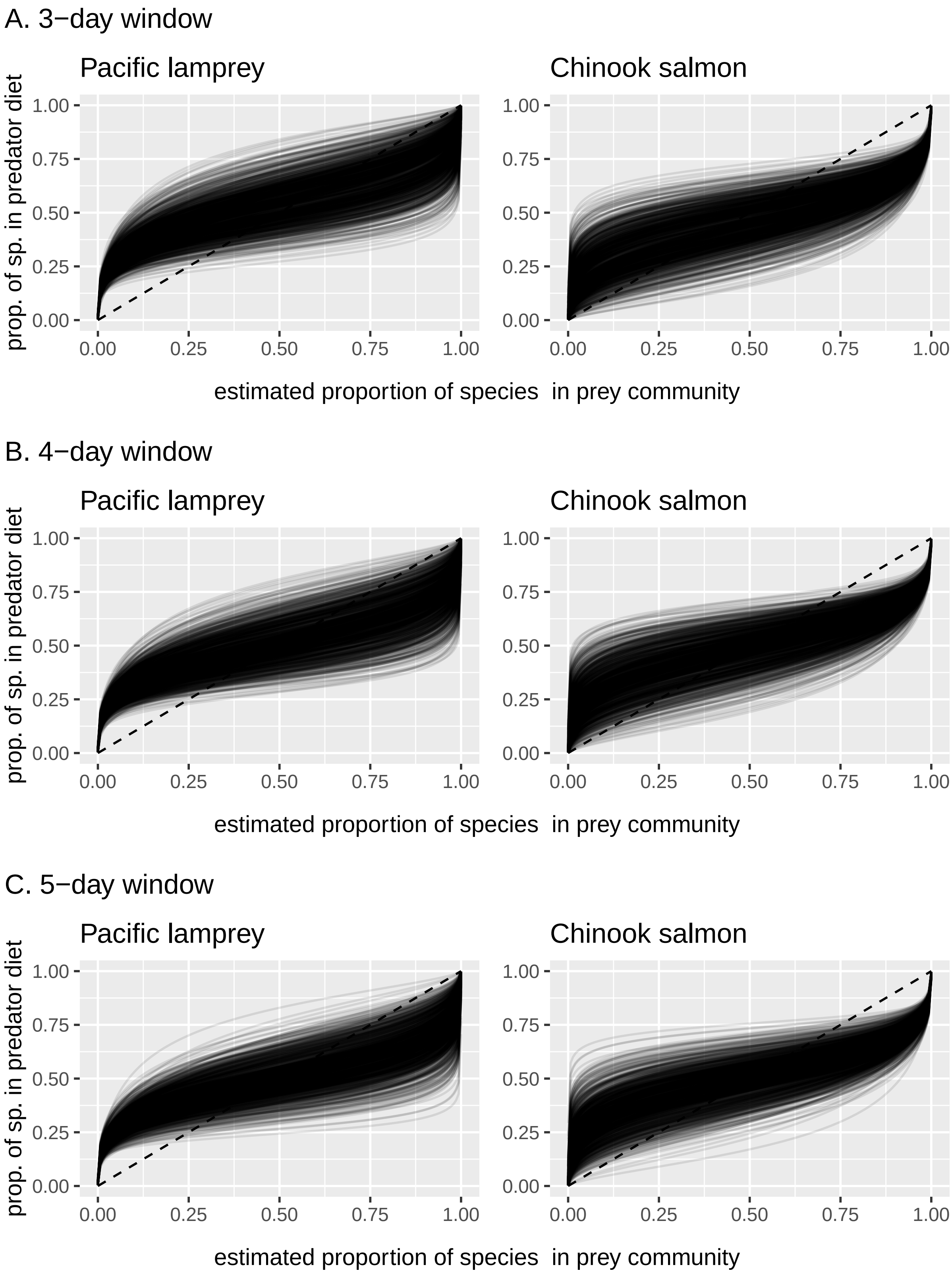

Figure S12. Multi-species functional response (MSFR) model fits of sensitivity analysis with 1000 randomly selected posterior samples using the posterior from the **A.** 3-day time window (main analysis results), **B.** 4-day time window, and **C.** 5-day time window.

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