Supplement 1

Low impact of first-time spawners on population growth in a brown trout population

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S1 Vital rates

All the vital rates required to parameterising the IPM (Table 3) were estimated from data or from literature. See Figures S1–S5 for all vital rates plotted over body size. The parameters in all the vital rate functions are either mean estimates from frequentist models or the posterior means of Bayesian models.

The functions used in the model are based on averaged environmental conditions. This was achieved by setting the random effects required to predict the vital rates to zero. For the prediction functions that includes a time trend, i.e. river growth, smolting, and maturation, we set the year to 1991, which is the median year of the study period from 1966 to 2016.

S1.1 Vital rates from literature

There is no data for the remaining vital rates, three of them related to early life history; early (egg to age 1) survival probability (S_0), juvenile survival probability (S_j), dam survival probability of smolts (S_{dam}), and the background mortality hazard rate of subadults (m_s^O). For these vital rates, we used literature values from brown trout or other salmonid species (Table S1). Note that we used literature values for annual subadult survival (S_s), and not just subadult background mortality. See details in the Supplement of Nater et al. (2019) in this special issue.

Table S1: Values of vital rates from literature review in (Nater et al. 2019) for early (S_0), juvenile (S_j), subadult (S_s), and dam passage survival (S_{dam}) of salmonids.

Vital rate	Total range	90% range	50% range	Median	Mean
S_0	0.009–0.140			0.088	0.082
S_j	0.025–0.750	0.050–0.700	0.230–0.488	0.322	0.353
S_s	0.010–0.720	0.013–0.693	0.100–0.450	0.245	0.295
S_{dam}	0.410–0.920				0.750

Note: The 90% and 50% ranges, and the median and mean values are calculated using the lower and upper bounds of reported ranges from individual studies, and thus assume equal likelihood of all values between the lower and upper range boundaries. The exception is S_{dam}, where there is only one study and the mean is the one reported in that study.

S1.2 Fecundity

In the model, fecundity is defined as the number of eggs produced by a female of a given body size and was estimated from data (Figure S1). Despite the scarcity of data on Hunder trout (15 females caught and stripped in two spawning seasons), the estimated relationship between body size and egg number falls within the range reported for other salmonid populations in the literature (e.g. L'Abee-Lund & Hindar 1990, Fleming, Ian A 1996, Jonsson & Jonsson 1999).

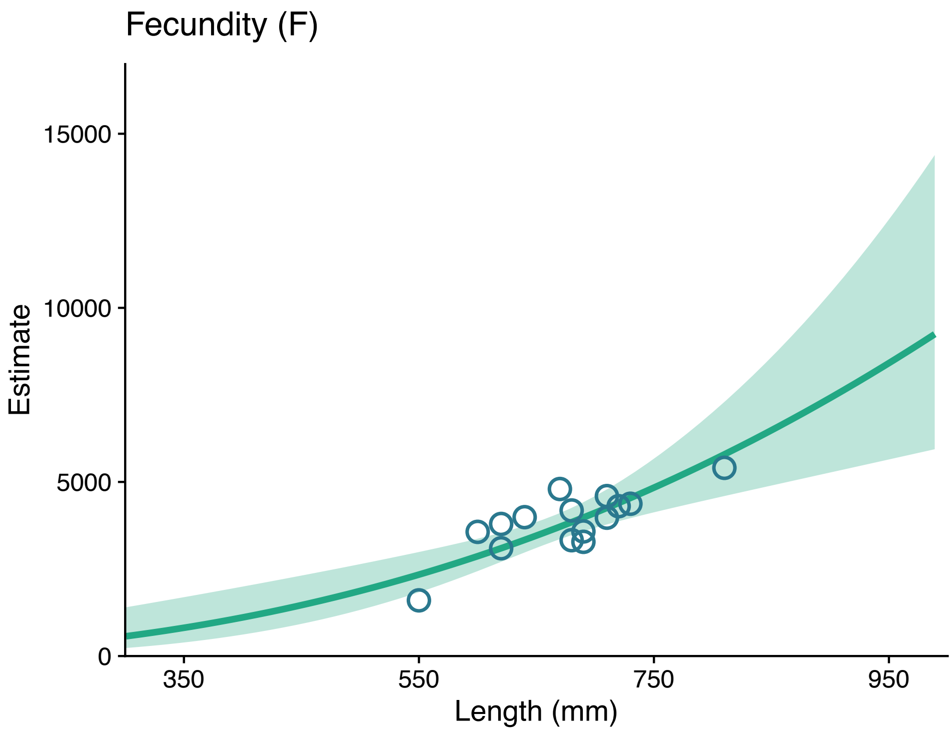

Figure S1: Fecundity function for the relevant body size range. The solid line represent mean predictions, the ribbon is the 95% confidence interval from a linear model fit, and the open circles are the egg count data points from a small sample of 15 females from the study system (see Nater et al. 2019 for details).

S1.3 Mortality and survival

All the estimates of size-dependent mortalities (Figure S2) and survival probabilities (Figure S3) are based on a Bayesian mark-recapture model from Nater et al. (2020) fitted to 50 years of data. Hunder trout are biennial spawners and the data is based on fish captured and then recaptures in the ladder during the spawning runs. The mortality rates and survival probabilities were thus estimated over two-year intervals based on body size at the beginning of the first year. Spawners in the model that transition to the non-spawning stage are assumed to experience two years' worth of mortality, and non-spawners have a survival of 1. Although this leads to a number and size-distribution of non-spawners that is partially representative, population growth rate is not affected. The subadult survival (Figure S3C) was based on the harvest mortality, but altered to depend on current size and rescaled to one-year intervals. This assumption is sound for subadults, as they grow much faster than mature adults and subadult background mortality was a free parameter in the model (for details, see Nater et al. 2020).

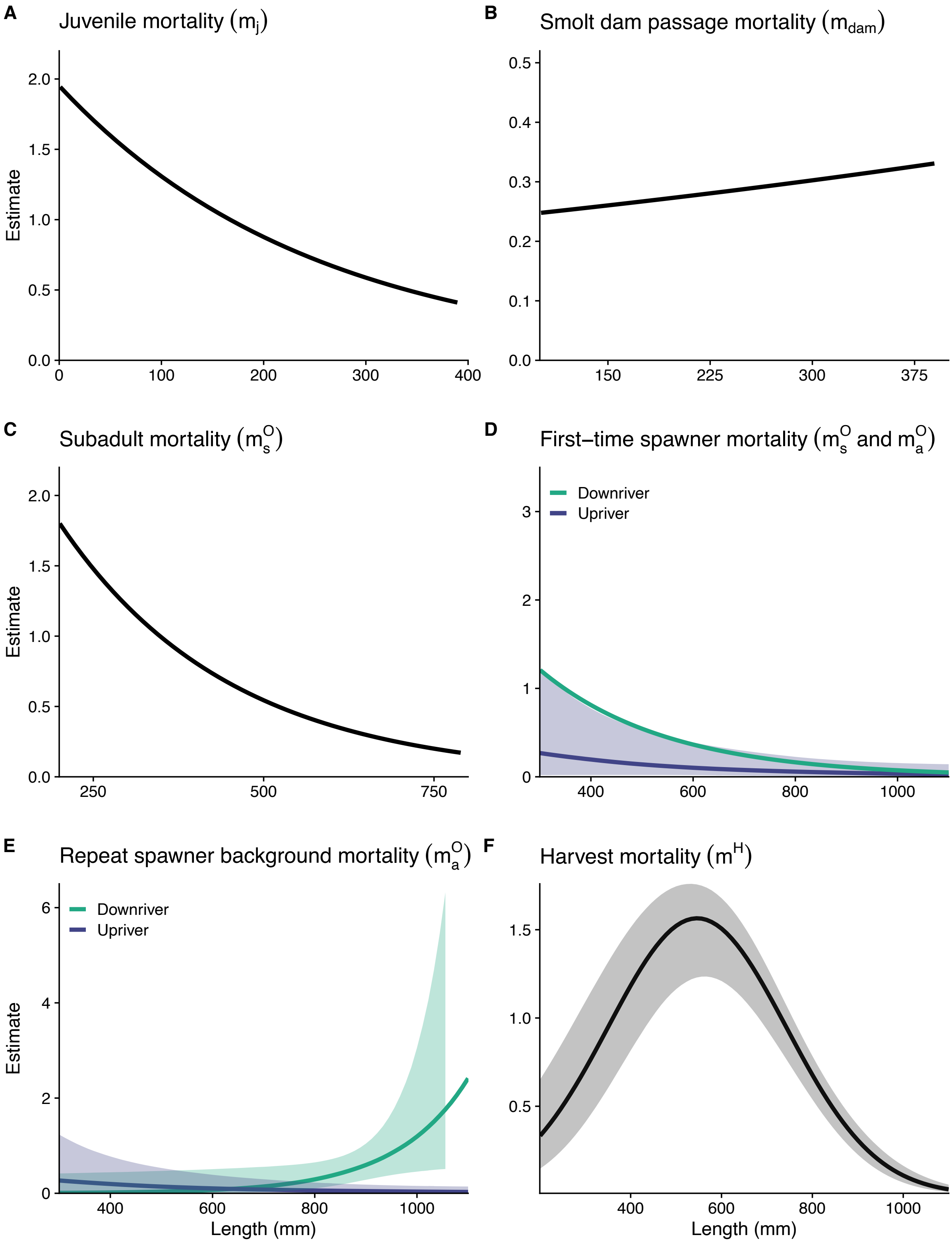

Figure S2: Mortality hazard rates for the relevant body size ranges of the different life stages. The juvenile (m_j) and smolt dam passage (m_{dam}) background mortalities in panels (A) and (B), and the subadult (m_s^O) background mortality in panels (C) and (D) are means estimated from literature and therefore plotted without uncertainty. The adult background mortality (m_a^O) in panels (D) and (E) and the harvest mortality (m^H) in panel (F), have posterior means and 95% credibility intervals from the Bayesian mark-recapture model (Nater et al. 2020).

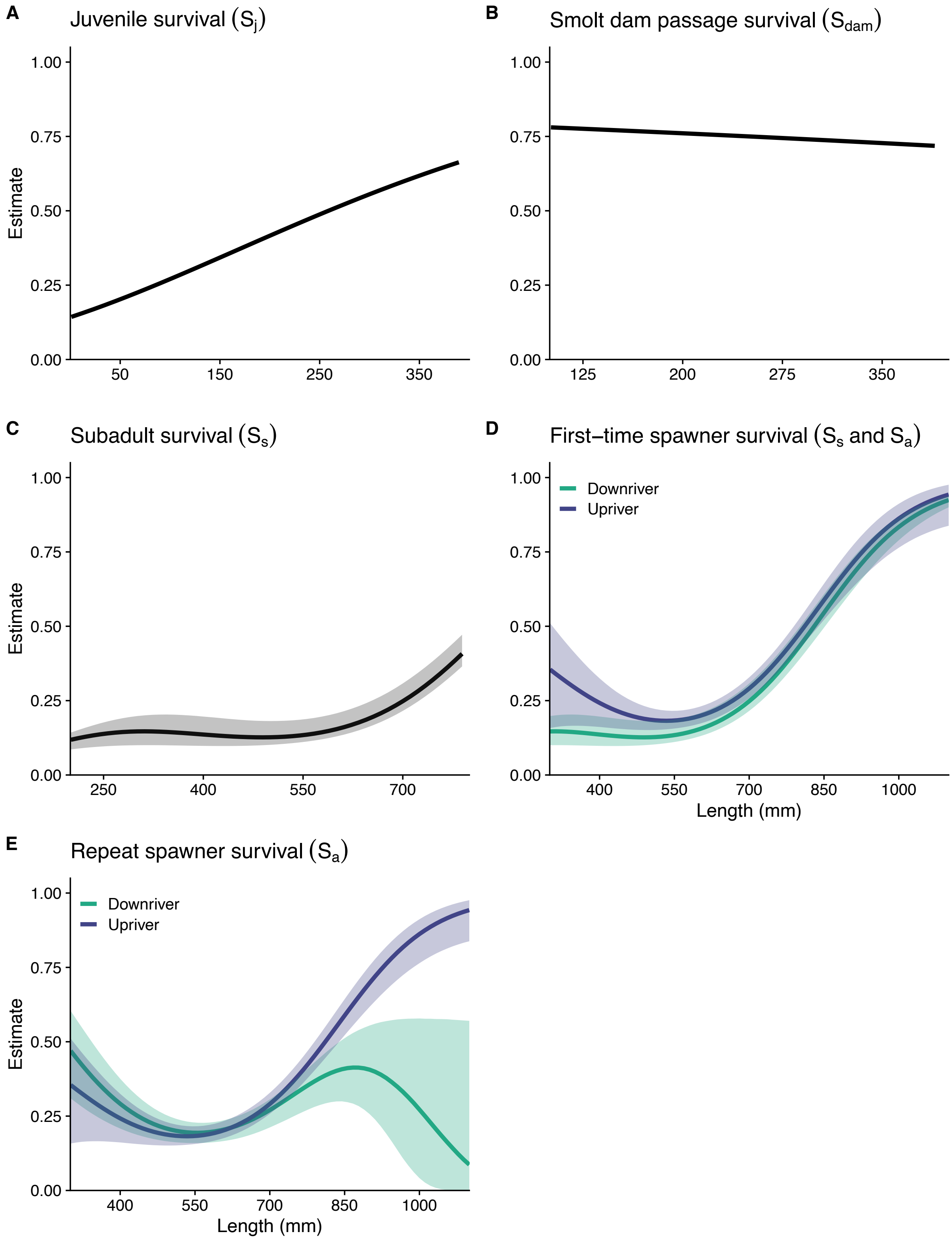

Figure S3: Survival probabilities for the relevant body size ranges of the different life stages. The juvenile (S_j) and smolt dam passage (S_{dam}) survival in panels (A) and (B) are means estimated from literature and therefore plotted without uncertainty. The subadult (S_s) and adult (S_a) survival in panels (C)–(E) have posterior means and 95% credibility intervals from the Bayesian mark-recapture model (Nater et al. 2020).

S1.4 Growth

The annual growth functions (Figure S4) were parametrised from posterior means in a Bayesian growth model fitted to the Hunder trout scale data (Nater et al. 2018, 2020). The growth is described as a linear and size-independent process in the river stage, while the lake phase is a size-dependent von Bertalanffy curve including cost of reproduction. Parameters of the river growth function was also used to describe the offspring size distribution after one year of growth. See Nater et al. (2018, 2020) for details.

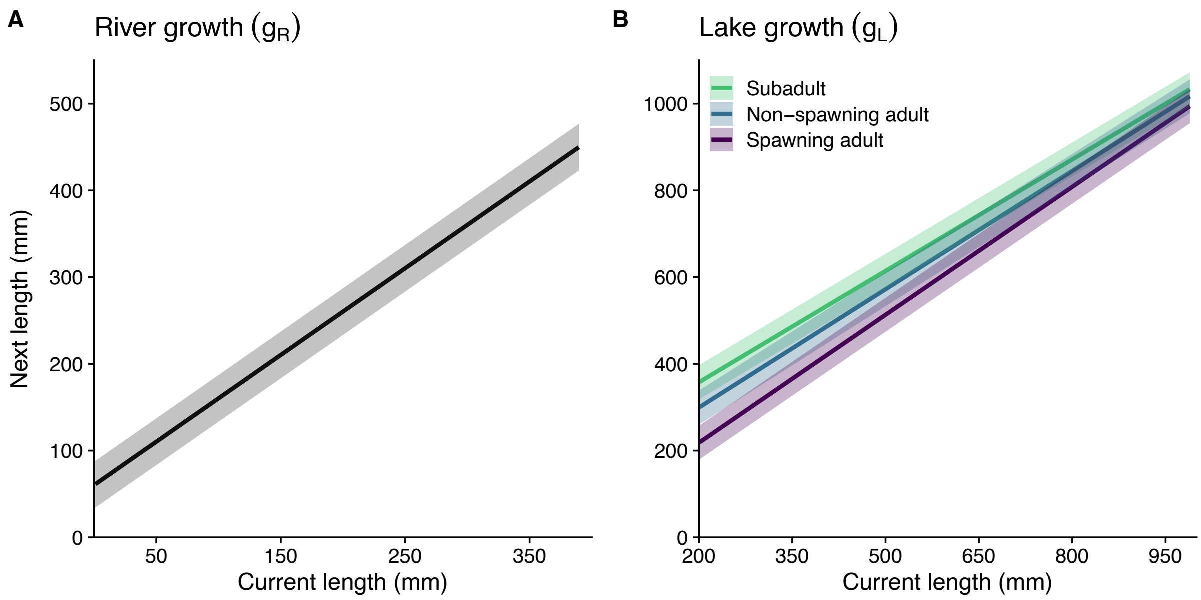

Figure S4: Growth functions without the random individual and year variations for the river and lake stages. In both panels the solid lines represent posterior means and the ribbons represent the 95% credibility intervals from the Bayesian growth model (Nater et al. 2018, 2020). In panel (B), the lake growth is plotted for subadults (green top line), non-spawning adults without cost of reproduction (blue middle line) and spawning adults with cost of reproduction (purple lower line).

S1.5 Transition probabilities

The scale data was also used to estimate smolting and maturation probabilities (Figures S5 A and B). Both probabilities were fitted by binomial generalised linear mixed-effects models with year as a random effect. We chose the most parsimonious models by looking at both AIC and BIC. For smolting probability, the model included the fixed effect of body size and the interaction between body size and year due to time trends in the data. For the maturation probability, body size, origin (wild or reared), sex, and year were included as fixed effects. To accommodate for any lasting effects of hatchery-rearing on size, origin was included as an effect on the slope as well as the intercept by adding an interaction between body size and origin. We also added an interaction for body size and sex, as females have a larger size range at maturation than males. The fish ladder usage probability (Figure S5C) is based on a Bayesian mark-recapture model from Nater et al. (2020) fitted to 50 years of data.

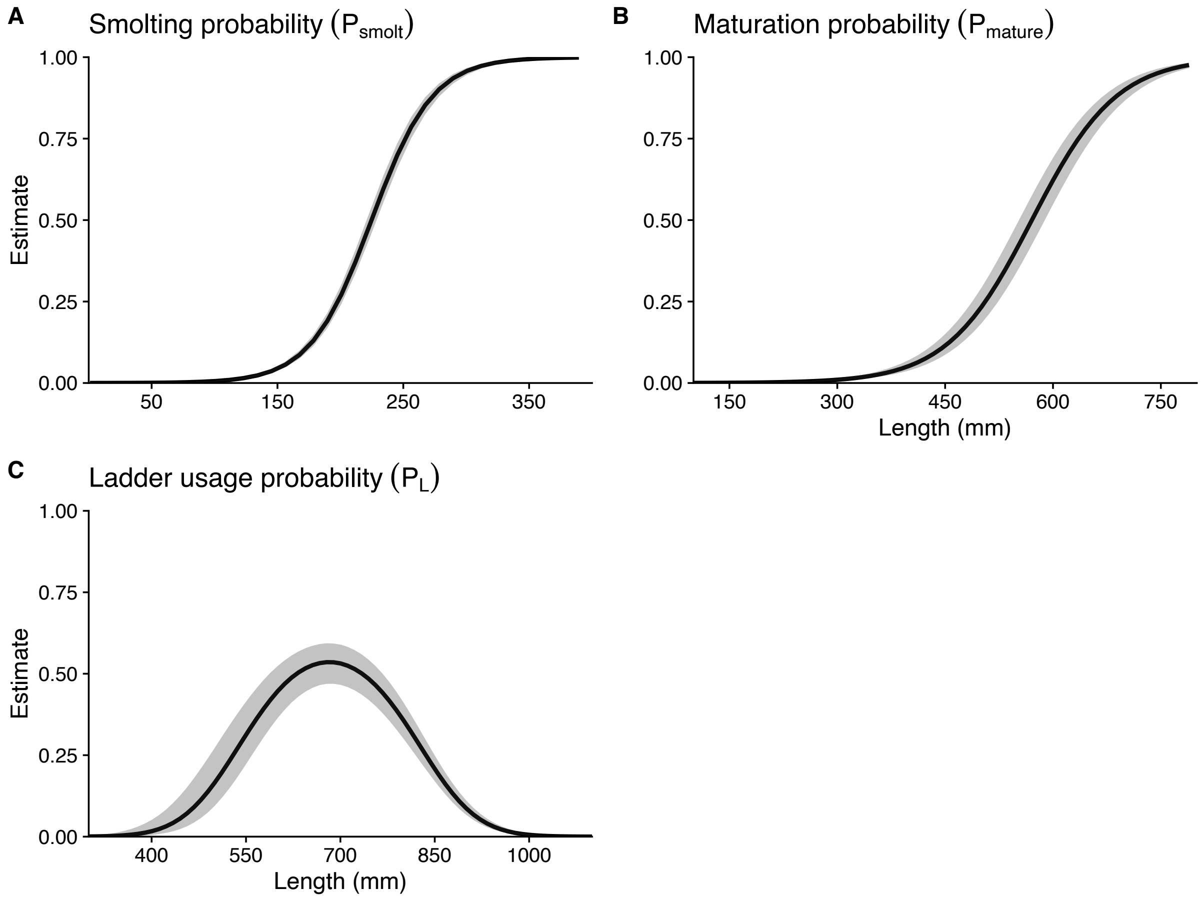

Figure S5: Stage transition probabilities for the relevant body size ranges of different life stages. The smolting (P_{smolt}) and maturation (P_{mature}) probabilities in panel (A) and (B), are plotted with mean predictions and the 95% confidence intervals from generalised linear mixed-effects model fits. The ladder usage probability (P_L) in panel (C) is based on the posterior means and 95% credibility intervals from the Bayesian mark-recapture model (Nater et al. 2020).

S2 Below-dam spawner penalty

The Hunder trout spawns in a regulated river, and the hydropower dam influences its life history. See Figure S6 for the life cycle with the dam. The dam impedes upriver migration, and reduces the water flow and the total area and quality of the spawning ground in the section between the dam and the tunnel outlet (Aass et al. 1989, and Figure 1). It is therefore likely that the reproductive success of spawners below the dam is impaired. In lack of empirical data, Nater et al. (202x, this issue) investigated this by running the population model with different levels of below-dam spawner penalties. To investigate how it affects our results, we ran the scenarios with a below-dam spawner penalty with 100% increase in early mortality of their offspring.

Adding the below-dam spawner penalty, but not harvest nor reduced reproduction (bottom left corner in Figure S7), reduce λ from 1.046 to 0.937, a 10.9% reduction. For both scenarios with the below-dam penalty, $\lambda < 1$ (Figure S7), but the slopes of the contour lines are similar to the scenarios without the below-dam penalty (Figure 4).

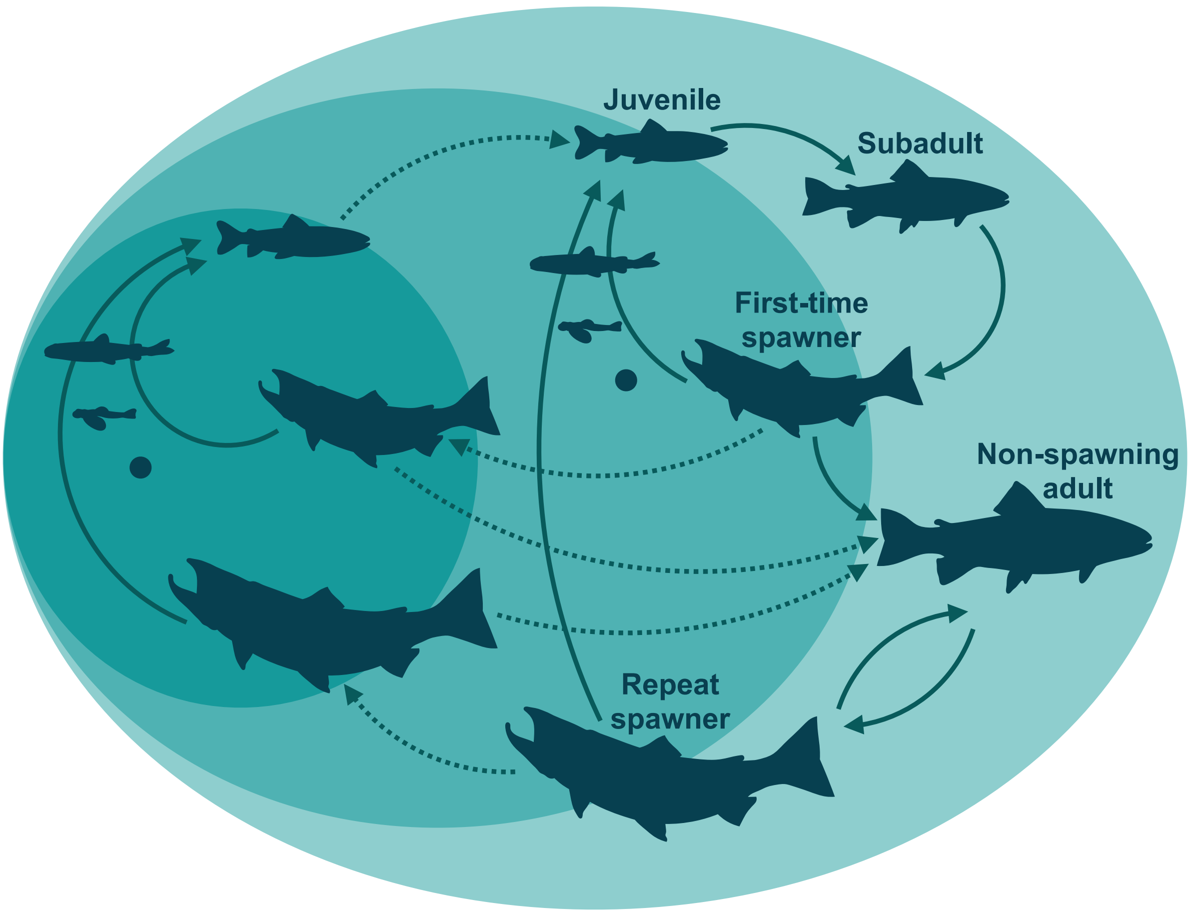

Figure S6: Life cycle of the Hunder trout with the dam. The increasingly larger circles from left to right represents the above dam river stage, the below dam river stage, and the lake stage. Fish represent life stages, and arrows are possible transitions from year t to $t + 1$. The dashed arrows includes traversing the dam on either up- or downward migration. All transitions are listed in Table 1.

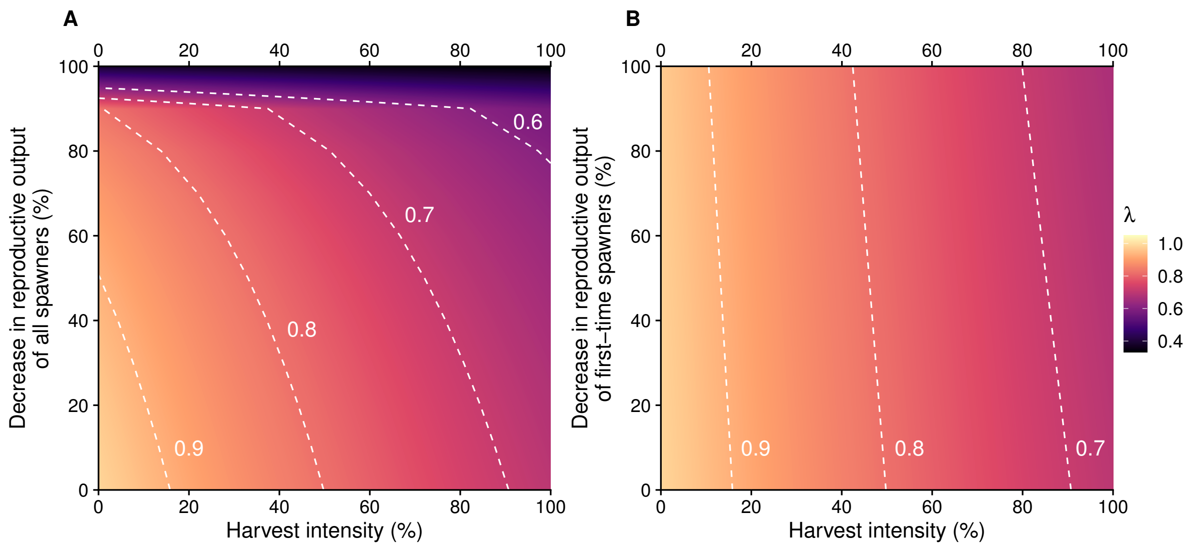

Figure S7: Long-term population growth rate (λ) calculated in model simulations, for different levels of decrease in reproductive output over harvest intensity and twice as high early mortality of juveniles below the dam. In panel (A) the reproductive output of all spawners the population is decreased, while in panel (B), only the reproductive output of first-time spawners is decreased. In both panels the dashed lines are $\lambda = 0.9$, $\lambda = 0.8$, $\lambda = 0.7$, and $\lambda = 0.6$.

S3 Proportions

The proportions of the different spawners above and below the dam and the proportion of juveniles produced by each spawner type are presented for the different scenarios below. All proportions are calculated from the stable size-by-stage distributions (SSDs). The model output does not give us juveniles produced by the different spawner types, but rather the density of juveniles above and below the dam. We distributed the juveniles age 1 to the different spawner types in the two locations by using the expected fecundity of adults given their size $F(x)$ and the SSDs of the spawners. For both juveniles and spawners, we summed up by spawner type and location separately, and divided by the sum of all to get the proportions.

S3.1 Baseline scenario

The baseline scenario assumes no decrease in reproduction and no harvesting. See Figure 5A for the stable size-by-stage distributions of the four types of spawners given their spawning experience and location relative to the dam. Because of the size-selectivity of the ladder, most of the spawners spawn below the dam. The repeat spawners make up 63% of the spawners (Figure S8A), and they produce 76% of the juveniles (Figure S8B).

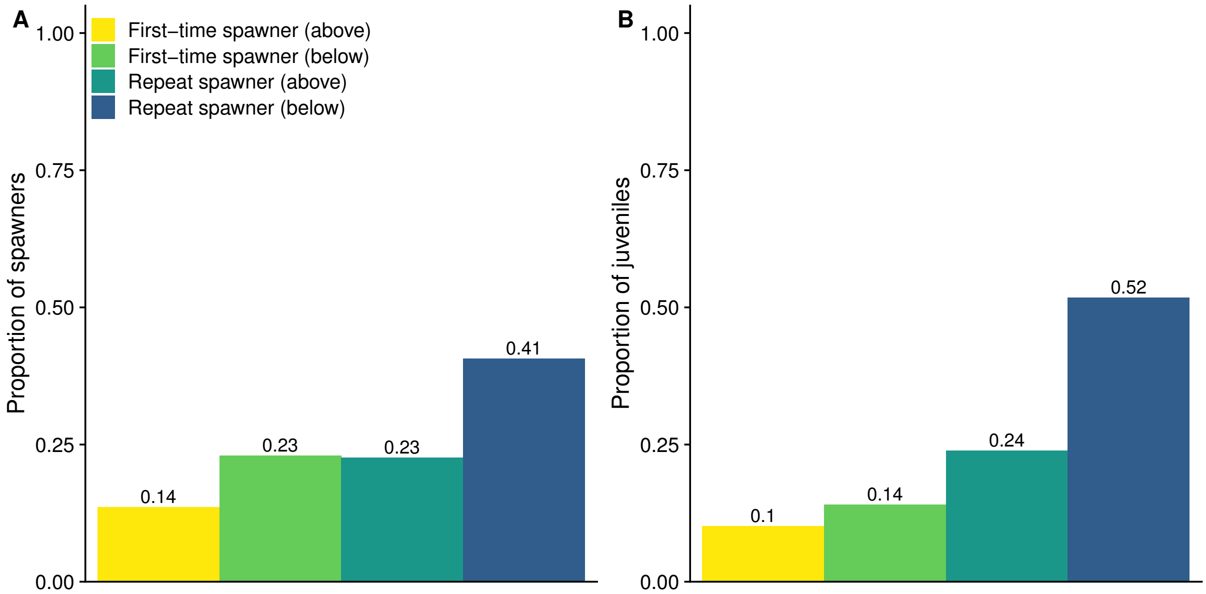

Figure S8: Proportion of spawners (A) and their juveniles (B), distributed above and below the dam in the baseline scenario without harvest nor reproductive penalties. All proportions are rounded to two decimals.

S3.2 Decreased reproductive output of all spawners

As the reproductive output of all spawners decreases, λ decreases too (y-axis in Figure 4A). Here, we show the proportions of spawners and juveniles at different levels of decrease in reproductive output for all spawners. We plot results up to a 90% decrease, since at a 100% reduction no juveniles are produced. As the reproduction of all spawners decreases, the proportion of repeat spawners increases (Figure S9A). Repeat spawners represents a terminal stage in our model, and it accumulates more individuals relative to the other stages as λ decreases (Figure 5B). It follows that as the proportion of repeat spawners in the population increases, the proportion of juveniles they produce increases too (Figure S9B).

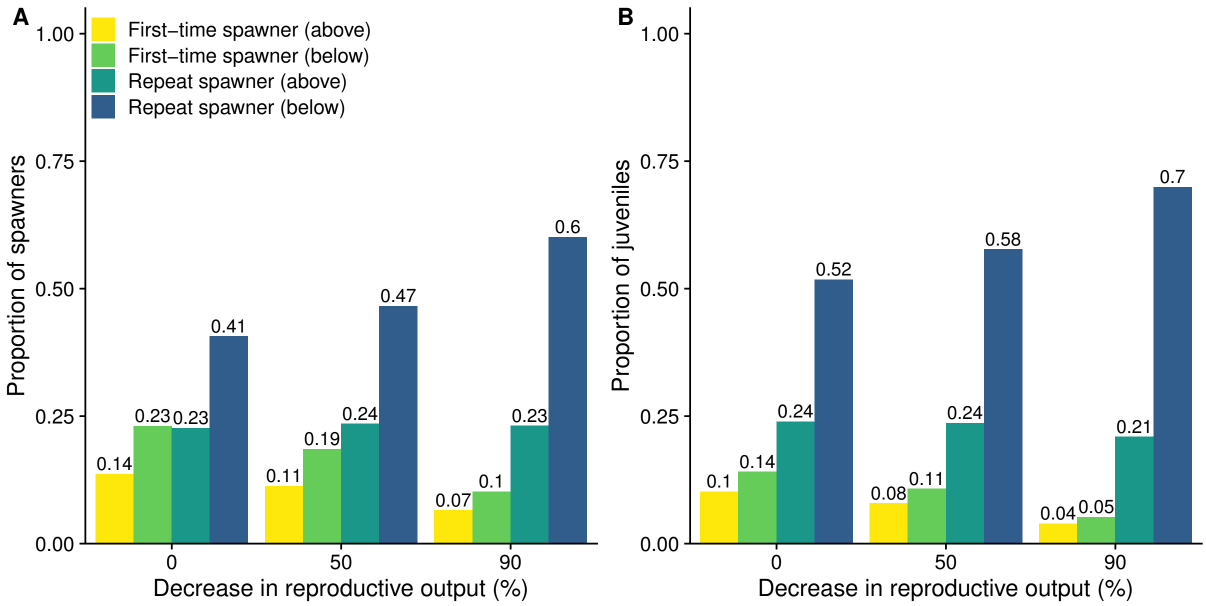

Figure S9: Proportion of spawners (A) and their juveniles (B), distributed above and below the dam for three different levels of decrease in reproductive output of all spawners in the population. The scenarios with no decrease is the baseline scenario. All proportions are rounded to two decimals.

S3.3 Decreased reproductive output of first-time spawners

As the reproductive output of first-time spawners decreases, λ only slightly decreases (y-axis in Figure 4B). The stable size-by-stage distribution also remains mostly unchanged from the baseline scenario (Figure 5C). This implies that the reproductive contribution of first-time spawners is not very important for the population growth or the population structure. The proportion of spawners in the population remains largely unchanged (Figure S10A), although the proportion of juveniles does not (Figure S10B).

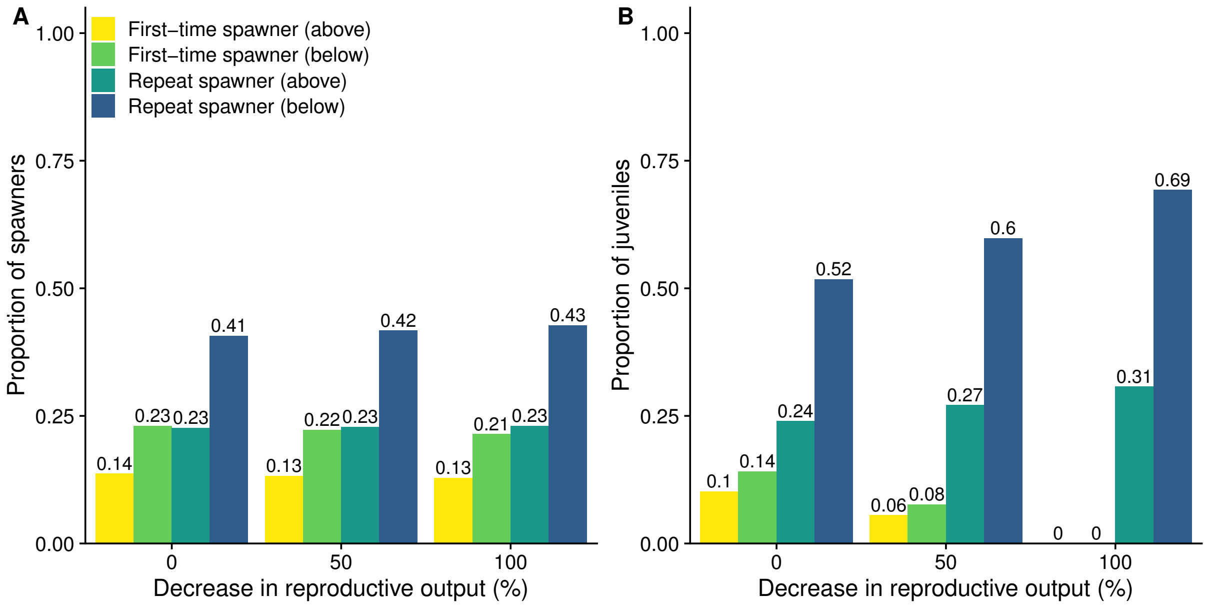

Figure S10: Proportion of spawners (A) and their juveniles (B), distributed above and below the dam for three different levels of decrease in reproductive output of first-time spawners in the population. The scenarios with no decrease is the baseline scenario. All proportions are rounded to two decimals.

S3.4 Harvest mortality

For increasing harvest intensity, λ always decreases (x-axes in Figure 4). The harvest targets mostly repeat spawners, resulting in a reduced density of larger spawners (Figure 5D). Although the proportion shifts from most repeat spawners to most first-time spawners as harvest intensity increases (Figure S11A), repeat spawners still produce more juveniles for all harvest intensities (Figure S11B).

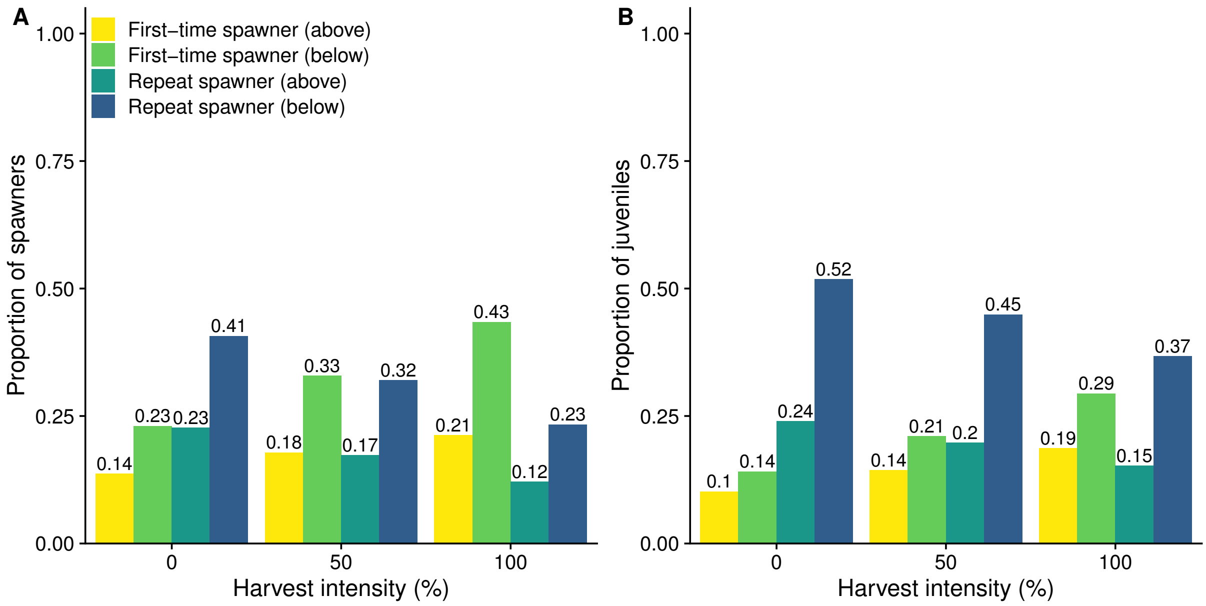

Figure S11: Proportion of spawners (A) and their juveniles (B), distributed above and below the dam for three different levels of harvest intensity. The scenarios with no harvest is the baseline scenario. All proportions are rounded to two decimals.

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