Teck Coal
Environment Office
Bag Service 2000, 421 Pine Avenue
Sparwood, B.C. Canada V0B 2G0

+1 250 425 3352 Tel
www.teck.com

Technical Report Overview

Report: Upper Fording River Westslope Cutthroat Trout Population Monitoring 2020

Overview: This report presents the 2020 population monitoring results for spawning activity, juvenile and adult abundance, and recruitment of isolated populations of Westslope Cutthroat Trout in the Upper Fording River using data from current and previous sampling programs to look at trends and precision of estimates.

This report was prepared for Teck by Poisson Consulting Ltd., Grylloblatta Consulting, and Lotic Environmental Ltd.

For More Information

If you have questions regarding this report, please:

- Phone toll-free to 1.855.806.6854
- Email **feedbackteckcoal@teck.com**

Future studies will be made available at **teck.com/elkvalley**

UPPER FORDING RIVER WESTSLOPE CUTTHROAT TROUT POPULATION MONITORING 2020

July 15, 2021

Prepared for: Teck Coal Ltd., Sparwood, BC

Prepared by: Thorley, J.L.[1], Kortello, A.K.[2], Robinson, M.[3]

1. Poisson Consulting Ltd., Nelson, BC
2. Grylloblatta Consulting, Nelson, BC
3. Lotic Environmental Ltd., Cranbrook, BC

The **suggested citation** for this interpretive report is:

Thorley, J.L., Kortello, A.K. & M. Robinson. (2021) Upper Fording River Westslope Cutthroat Trout Population Monitoring 2020. A Poisson Consulting, Grylloblatta Consulting and Lotic Environmental report prepared for Teck Coal Ltd., Sparwood, BC.

EXECUTIVE SUMMARY

The upper Fording River is mine-influenced system that contains genetically pure Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi*) above a natural barrier, Josephine Falls. The goal of the 2020 monitoring program was to determine the abundance and recruitment success of this population. Redd surveys were used to monitor spawning activity, while snorkel surveys, and backpack electroshocking methods were used to estimate abundance.

Redd numbers and distribution were highest in 2015 although effort was not consistent across years. In 2020, spawning activity was more similar to 2012 and 2013 in the numbers of redds and locations. Data from snorkel surveys and electrofishing on the upper Fording River collected between 2013 and 2020 were analyzed using hierarchical Bayesian models to estimate fish population abundance and recruitment. All life stages showed a peak in abundance near 2017 and lower estimates thereafter.

Estimated numbers of age-1 fish, an indicator for population recruitment, have declined by 49% to approximately 11,100 (95% CI 4,360-48,500) fish in 2020 from a peak of 21,700 (95% CI 8,890-93,500) fish in 2017 but are within the range of variability of earlier years. Age-2+ juvenile fish populations were estimated at 13,100 fish (95% CI 5,570-54,900) in 2020. The abundance of age-2+ juveniles peaked in 2017 at approximately 27,200 fish (95% CI 11,700-115,000) but 2020 exceeded previous population estimates for 2013, 2014 and 2019. The snorkel based adult abundance estimates declined by 94% from 5,240 in 2017 to 330 in 2019 before increasing slightly to 440 in 2020. These numbers are well below 2012-2014 values of 2,580-3,670 adult fish. Confidence intervals are not provided for adult abundance estimates because the uncertainty in the observer efficiency is unknown.

Recruitment was further assessed from changes in body condition, fecundity and egg to age-1 survival. Fish size and condition and by inference fecundity have all increased since 2015. Most recent egg to age-1 survival rates substantially exceed the threshold of 5% required for population replacement. This high survival has resulted in an annual productivity rate of around 10 lifetime spawners per spawner, an order of magnitude above the level required for population replacement. The results suggest that the population is undergoing a positive compensatory response to the decline in population abundance between 2017 and 2019. Changes to the monitoring program design will be needed to decrease uncertainty in some of the estimates for future analysis

ACKNOWLEDGEMENTS

The organizations and individuals whose contributions have made this analysis report possible include Bronwen Lewis, Lindsay Watson and Carla Fraser of Teck Coal Limited, Scott Cope and Angela Cope of Westslope Fisheries Ltd., Nate Medinski and Isabelle Larocque of Lotic Environmental Ltd., Josh Korman of Ecometric Research, Maggie Branton of Branton Environmental Consulting, Beth Power and Sarah Gutzmann of Azimuth Consulting Group Inc., Cynthia Russel of Minnow Aquatic Environmental Services, Ron Ptolemy of the BC Ministry of Environment, Herb Tepper, Matt Neufeld and Josef MacLeod of BC Ministry of Forests, Lands and Natural Resource Operations, Jim Clarricoates, Heather McMahon, Kamila Baranowska of Ktunaxa Nation Council, Brian Ma of ESSA Technologies Ltd., Todd Hatfield of Ecofish Research Ltd. and Evan Amies-Galonski of Poisson Consulting Ltd.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPENDICES

The analytic appendix, which includes tables of numbers for plots, model templates, parameter descriptions and parameter coefficient tables is available online from:

Thorley, J.L. (2021) East Kootenay Westslope Cutthroat Trout Population Dynamics 2020. A Poisson Consulting Analysis Appendix. URL: https://www.poissonconsulting.ca/f/36113815.

Cleaned raw data for 2020 will be available in the Upper Fording River Westslope Cutthroat Trout Population Monitoring 2021 report.

INTRODUCTION

The Fording River is a tributary of the Elk River in the southeast corner of British Columbia (BC). Teck Coal Limited (Teck) operates three coal mines within the upper Fording River (UFR) watershed: Fording River Operations (FRO), Greenhills Operations (GHO) and Line Creek Operations (LCO). The watershed supports an isolated population of genetically pure (Rubidge and Taylor 2005) Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi*) above Josephine Falls, a natural barrier to upstream fish movement (Cope 2020b). Teck has been monitoring Westslope Cutthroat Trout (WCT) in the UFR watershed since 2013.

Westslope Cutthroat Trout are a species of Special Concern both provincially and federally. Identified threats include genetic introgression from Rainbow Trout, restricted fish passage associated with roads, forest harvest, angling mortalities, climate change and mining (Fisheries and Oceans Canada 2017).

Coal mining impacts on WCT can include habitat loss and fragmentation and changes in the physical and chemical attributes of fish habitat, such as riparian clearing, the bioaccumulation of selenium (Se), and leached minerals such as calcite from waste rock (Fisheries and Oceans Canada 2017). Other potential anthropogenic impacts to WCT in the UFR include poaching and broad scale landscape factors related to forestry, recreation, roads, railways, and natural gas wells, pipelines and infrastructure. Recreational angling is prohibited in the UFR (MFLNRORD 2019).

Fish populations are also subject to variation through stochastic effects and climatic influences such as floods. Although Kennedy and Meyer (2015) found that bioclimatic indices such as mean annual air temperature and mean winter stream flow generally explained little of the variation in WCT abundance, recruitment failure can occur at low water temperatures (Coleman and Fausch 2007), survival declines sharply at temperatures above 19ºC (Bear et al. 2007) and ice conditions can limit available habitat in winter (Brown and Mackay 1995). A detailed account of potential driving mechanisms for population dynamics will be found in the UFR Evaluation of Cause Report (Report pending - Evaluation of Cause Team 2021).

Cope (2020b), reporting on data from 2012 to 2019, estimated an increasing trend for the UFR WCT population until 2017, but between 2017 and 2019 he estimated that the numbers of juvenile (< 200 mm) and adult (>= 200 mm) WCT declined by 74% and 88% respectively. To reduce the uncertainty around these estimates, sampling efforts were repeated in 2020 and all of the data (2012 to 2020) were analyzed using a hierarchical Bayesian framework.

Hierarchical models allow the separation of stochastic, site, population, mining and regional effects and explicitly account for problematic sources of variation, such as observer efficiency (Kéry and Royle 2015). Bayesian methods readily handle missing values, do not require minimum sample sizes, allow the incorporation of prior information and facilitate intuitive probabilistic statements about derived parameters (Wyatt 2002). To increase understanding about the magnitude and consequences of the apparent decline, two questions were addressed in this report:

1. What are the juvenile and adult abundances for the UFR Westslope Cutthroat Trout population?
2. What is the recruitment to the population?

This report is not intended to assess the potential mechanisms associated with population dynamics.

METHODS

STUDY DURATION

The 2020 field program consisted of redd surveys that supplemented previous surveys conducted between 2013-2015 (Cope 2020b). Two snorkel surveys extended the adult population trend monitoring data to a 6-year data set (2012, 2013, 2014, 2017, 2019, and 2020). Backpack electrofishing also extended the age-1 and age-2+ juvenile monitoring dataset to 6-years (2013, 2014, 2015, 2017, 2019, 2020; Cope 2020).

2020 STUDY TIMING

The redd surveys took place between May 15 and July 15, 2020. Snorkel surveys occurred between July 20 and 25, 2020 (early summer survey) and again from September 7 to 12, 2020 (late summer survey). Backpack electrofishing surveys were conducted between September 14 and 19, 2020. With the exception of an additional early summer snorkel survey, the timing of all surveys was completed in a consistent manner with those in previous years.

STUDY AREA

The spatial boundary of the monitoring program was defined as the UFR watershed; the portion of the Fording River (including tributaries) located upstream of Josephine Falls, which forms a barrier to upstream fish movement (Figure 1). The UFR mainstem was stratified into 11 river segments, and Henretta Creek was stratified into an additional three river segments to facilitate population monitoring and distribution assessment (Cope 2020b; Figure 1; Table 1). These 5 km long segments do not correspond to geomorphological reaches.

The WCT population of concern is restricted to approximately 52 km of the mainstem upper Fording River (Cope 2020b), extending upstream between Josephine Falls at 1,400 m elevation (20.5 rkm) to the limit of fish distribution in the headwaters at approximately 2,740 m elevation (between 73.0 and 78.0 rkm). The population also occupies at least 32 km of fish bearing habitat in the tributaries.

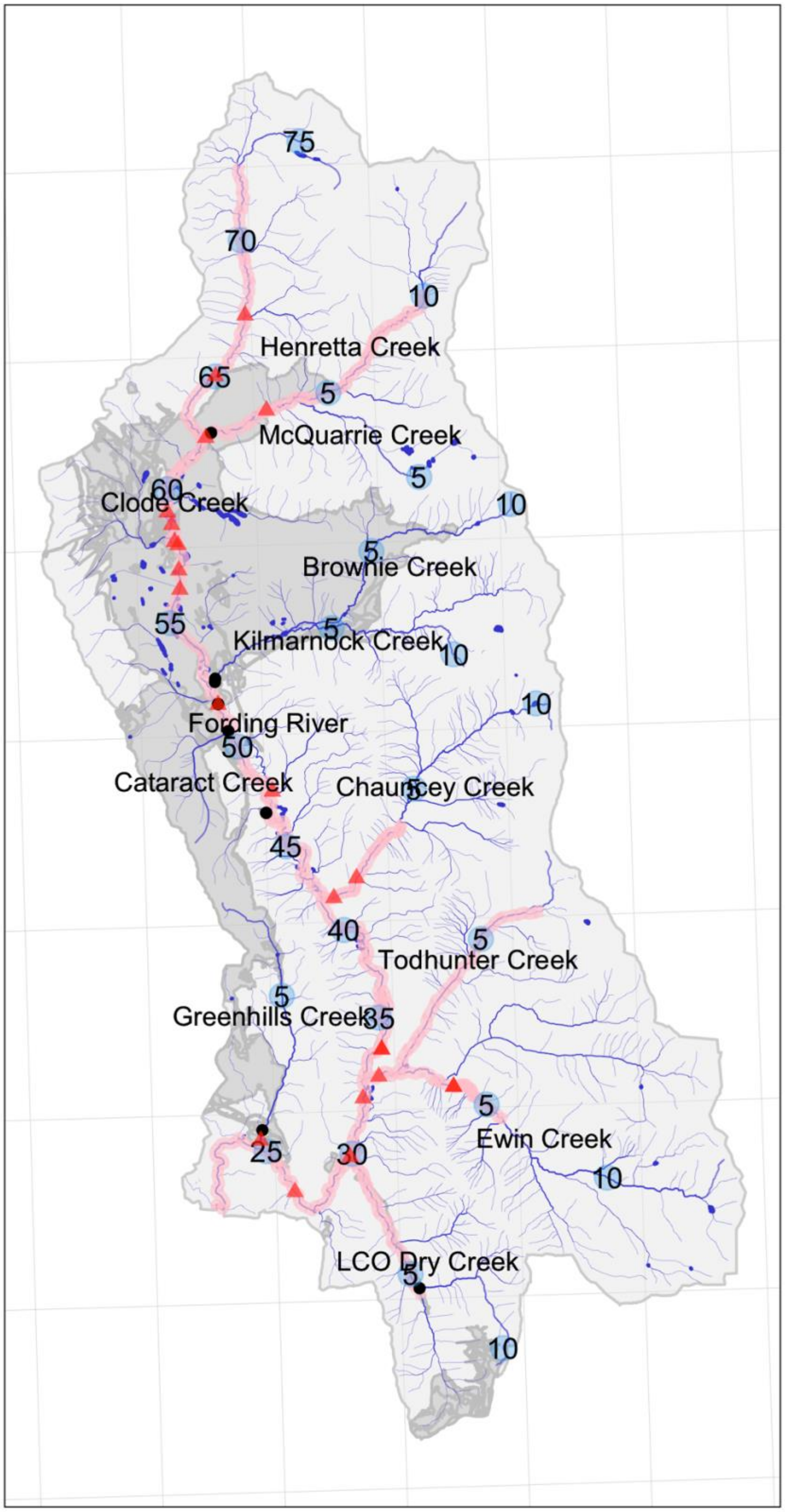

Figure 1. Upper Fording River watershed with confirmed fish bearing sections (indicated by pink), river kilometres (indicated by blue circles), electrofishing locations (indicated by red triangles) and non-culvert barriers (indicated by black circles).

Table 1. Upper Fording River segments. River kilometers (rkm) indicate the distance upstream of the Elk River confluence (adapted from Cope 2020). For tributaries, rkm indicates the distance upstream from the confluence with the UFR.

River Segment	River Km	Length (km)	Location
1	20.51–25.00	2.5	Josephine Falls to GHO
2	25.00-29.00	4.00	GHO to above Fording Bridge
3	29.00-33.16	4.16	Above Fording Br. To Ewin Creek
4	33.16-37.59	4.40	Ewin Cr. To S-bends
5	37.56-41.96	4.40	S-bends to Chauncey Creek
6	41.96-48.96	7.00	Chauncey Cr. to F2 side road
7	48.96-54.00	5.04	F2 side road to Diversion Reach
8	54.00-59.75	5.75	Diversion reach to Turnbull Br.
9	59.75-63.40	3.65	Turnbull Br. to above Henretta
10	63.40-67.75	4.35	Above Henretta Creek
11	67.75-78.00	10.25	Headwaters
H1	0.00-1.00	1.00	Henretta Creek Below Henretta Lake
H2	1.00-1.50	0.50	Henretta Lake
H3	1.50-4.00	2.50	Henretta Creek above Henretta Lake

POPULATION MONITORING

REDD SURVEYS

Redd surveys count fish nests and are used to assess spawning activity. The core areas identified in Cope et al. (2016) were surveyed again in 2020. Surveys included but were not limited to the following previously recorded spawning areas:

1) UFR in the area of the Segment S8/S9 break (historically called "Clode Flats") and associated tributary habitat (Clode Creek, West Exfiltration Ditch, Fish Pond Creek),
2) UFR in Segment S6 groundwater upwelling area and side-channels (also named "Fording River Oxbows"),
3) UFR around the mid-river log jams in Segment S4,
4) LCO Dry Creek Reach 1 and confluence with UFR in Segment S3/S2, and
5) Greenhills Creek Reaches 1 and 2.

Five separate surveys were conducted between May 15 and July 15, 2020. The Dry Creek tributary was surveyed on June 30 and July 7, 2020 by Nupqu (2021). Surveys are conducted using two crew members walking the stream or shoreline wearing polarized glasses. Redd locations were recorded using GPS and the length of each redd was measured. Surveying effort in the watershed outside the core areas was variable and directed by experience and expertise. Distribution of effort was modified by environmental conditions, such as water temperature and spawning activity distribution, if water levels and visibility/water clarity was poor (i.e., observers could not see river bottom), effort was redirected to other areas, such as Henretta Creek, Fish Pond Creek, Chauncey Creek and Greenhills Creek. Areas within the watershed that have been identified historically with very little activity were also checked, however the extent of the search area is undocumented.

ELECTROFISHING SURVEY

Populations of age-1 and age 2+ juvenile (referring to fish from the age of 2 until maturity) Westslope Cutthroat Trout in the UFR were assessed through density estimates generated by removal-depletion electrofishing. Monitoring was conducted at sites within five primary strata previously delineated within the upper Fording River watershed, these are: the Lower Mainstem (approximate rkm 20-40), Mid-Mainstem (approximate rkm 40-61) and Upper Mainstem (approximate rkm 61-78), and both Lower Tributary and Upper Tributary (Cope 2020b). Onsite FRO includes UFR rkm 51-66 and Henretta Creek (rkm 0-6). Onsite GHO includes Greenhills creek and LCO includes Dry Creek (Table 2).

Sampling generally followed methods and locations from previous monitoring (Table 2). At each location, three sites each belonging to one of the five possible mesohabitat units (e.g., pool, run, glide, riffle, cascade) were sampled. Run mesohabitat was used by Cope et al (2016) but is not a habitat unit included in Fish Habitat Assessment Procedures (Johnston and Slaney 1996). Each site covered approximately 100 m^2 of habitat. Prior to 2020, each site was sampled using a three-pass methodology. However, in response to fish handling concerns from the Elk Valley Fish and Fish Habitat Committee, in 2020 the number of passes was reduced at a subset of locations. Crews targeted single pass electrofishing at ~50% of the locations, two pass electrofishing at ~25% of the locations and three pass electrofishing at ~25% of the locations. This resulted in one-pass electrofishing conducted at 10 locations, two-pass at 5 locations and, three-pass at 4 locations (Table 2).

Sampling was completed by three-person crews, using a backpack electrofishing unit (Smith-Root LR24). Wadeable habitat (*i.e.*, < 1.5 m deep) within a selected site was sampled. Closed site conditions were achieved by installing upstream and downstream stop nets spanning the entire wetted width of the stream channel in smaller units (*i.e.*, wetted widths < 8.0 m). In larger units, upstream and downstream stop nets were placed perpendicular to the shore, while an off-shore net was set parallel to shore to enclose the stream habitat between the upstream and downstream stop nets. Nets were configured into stable position with ropes, bipod stays, and anchors. The lead line was adjoined to stream bed contours with boulders placed as weights.

Electrofishing was initiated at the downstream net and proceeded upstream in a systematic bank to bank sweep, followed by a sweep back towards the downstream net at the completion of each pass. Similar search patterns were repeated in each successive electrofishing pass. Electrofishing effort (seconds) were recorded at the end of each pass. Both the upstream and downstream nets were also monitored for drifting fish.

All fish captured during electrofishing were weighed (g), measured (fork length; mm), examined for any signs of deformities (including shortened opercula) or injuries, and scanned for PIT tags. PIT tag numbers were recorded on datasheets when detected.

Table 2. Upper Fording River electrofishing locations and number of electrofishing (EF) passes conducted in 2020.

Stream	Segment	Strata	Location	# Passes
Henretta Creek	1	Lower Tributary (FRO Onsite)	HEN1	3
Henretta Creek	3	Upper Tributary	HEN3	1
Fish Pond Creek	1	Lower Tributary (FRO Onsite)	FPC1	3
Fish Pond Tributary	1	Lower Tributary (FRO Onsite)	FPC2	1
Chauncey Creek	1	Lower Tributary	CHA1	2
Chauncey Creek	2	Upper Tributary	CHA2	2
Ewin Creek	2	Upper Tributary	EWI2	1
LCO Dry Creek	1	Lower Tributary	DRY1	1
Greenhills Creek	1	Lower Tributary (GHO Onsite)	GRE1	3
Fording River	2	Lower Mainstem	FOR2	3
Fording River	3	Lower Mainstem	FOR3	1
Fording River	6	Mid-Mainstem	FOR6	2
Fording River	8b	Mid-Mainstem (FRO Onsite)	FOR8b	1
Fording River	8a	Mid-Mainstem (FRO Onsite)	FOR8a	1
Fording-UFR47-1	8	Mid-Mainstem (FRO Onsite)	UFR47-1	2
Fording-UFR47-2	8	Mid-Mainstem (FRO Onsite)	UFR47-2	1
Fording-UFR49-2	8	Mid-Mainstem (FRO Onsite)	UFR49-2	2
Fording River	10	Upper Mainstem Headwaters	FOR10	1
Fording River	11	Upper Mainstem Headwaters	FOR11	1

SNORKEL SURVEY

In 2020, two separate snorkel surveys (early and late summer surveys) were conducted. Snorkel counts of WCT were replicated within 12 river segments (see Cope et al. 2016 for detailed description) These include 11 mainstem upper Fording River segments plus one tributary segment: Henretta Lake including lower Henretta Creek to the confluence with the upper Fording River (Table 1). From 2017 onwards, river segments where habitat offsetting work was conducted were further sub-divided into a total of 23 treatment and control sub-sections to facilitate more detailed fish distribution, habitat utilization and trend monitoring data for offsetting effectiveness evaluation.

The following areas have not been snorkelled in any of the surveys since 2012 (Cope 2020).

- The uppermost headwater river segment (S11) representing 11 km of headwater stream channel habitat. This area was not snorkeled due to the low water volume and high gradients,
- The lowermost 370 m of river Segment S1 above Josephine Falls was not snorkeled due to obvious safety concerns, and
- Other potential fish bearing tributaries (*i.e.*, Chauncey, Ewin, and Dry Creeks) were not snorkeled due to low water volume and small stream size. These tributaries are sampled as juvenile rearing tributaries using removal- depletion electrofishing techniques.

Snorkel surveys were conducted using a team of two to four observers with the exception of Henretta Lake where four or five observers were employed. In 2020, an experienced crew was used and several of these had surveyed the system previously (Cope pers. comm). Each snorkeler was assigned to a "lane" in the stream channel, incorporating an approximately 3 – 5 m width from the center of the channel to nearest streambank. In narrow channels (<15 m width) a single snorkeler was used with a second observer on shore. Crew members frequently stopped to discuss observations, compare length estimates, and to discuss whether duplication in observations had occurred.

Water clarity was assessed daily prior to commencing surveys. A horizontal Secchi distance was recorded by the snorkel team. Additionally, in 2020, water clarity was also recorded with a turbidity meter measuring nephelometric turbidity units (NTU). Spot water temperatures were taken from each snorkeled reach. Hydrometric data was acquired from Water Survey Canada Station 08NK018 (Fording River at the mouth) for the survey period to compare minimum and maximum stream discharge measured in 2020 with surveys conducted in 2012, 2013, 2014, 2017 and 2019. Minimum and maximum stream discharge during the 2020 survey period was within the range of those documented in previous years surveys (Table 3).

Estimates of observer efficiency relied on the mark-recapture program of previous years (2012, 2013, 2014; see Cope 2020b). Observer efficiencies are affected by water clarity however in 2020 these conditions were consistent with previous years. Observer efficiencies also decline with fish size (Cope et al. 2016), and have been calculated for adults (>= 200 mm) but not juveniles (<200 mm). Juvenile counts are recorded for completeness, not as an index of population size.

Table 3. Upper Fording River minimum and maximum stream discharge (m3/second) during snorkel surveys conducted between 2012 and 2020.

Year	Survey Date	Min - Max Discharge (m3/second)
2012	Sept 16 - 22, 2012	3.9 – 4.3
2013	Sept 4 - 9, 2013	5.2 – 6.0
2014	Sept 2 - 8, 2014	5.6 – 10.0
2017	Sept 5 - 12, 2017	3.5 – 3.7
2019	Sept 4 - 11, 2019	4.3 – 4.8
2020	Sept 7 - 12, 2020	3.6 – 4.0

DATA PREPARATION

The historical data were provided by Teck as an assortment of Excel spreadsheets and shape files. The 2020 field data were provided by Westslope Fisheries Ltd., Nupqu, and Lotic Environmental Ltd. The watershed, stream, lake and anthropogenic waterbodies were downloaded from the BC Freshwater Atlas. The data were extracted and cleaned and tidied (Wickham 2014) before being stored in a purpose built SQLite database using R version 4.0.3 (R Core Team 2020).

STATISTICAL ANALYSIS

Parameters represent key variable of interest for the population, like abundance or survival. The uncertainty in the parameters was estimated from the data using Bayesian methods. The estimates were produced using JAGS (Plummer 2015). For additional information on Bayesian estimation the reader is referred to McElreath (2016).

Unless stated otherwise, the Bayesian analyses used weakly informative normal and half-normal prior distributions (Gelman et al. 2017). The posterior distributions were estimated from 1,500 Markov Chain

Monte Carlo (MCMC) samples thinned from the second halves of three chains (Kery and Schaub 2011). Model convergence was confirmed by ensuring that the potential scale reduction factor $\hat{R} \leq 1.05$ (Kery and Schaub 2011) and the effective sample size (Brooks et al. 2011) ESS ≥ 150 for each of the monitored parameters (Kery and Schaub 2011).

The parameters are summarised in terms of the point *estimate*, *lower* and *upper* 95% credible limits (CLs) and the surprisal *s-value* (Greenland 2019). The estimate is the median (50th percentile) of the MCMC samples while the 95% CLs are the 2.5th and 97.5th percentiles. The s-value can be considered a test of directionality. More specifically it indicates how surprising (in bits) it would be to discover that the true value of the parameter is in the opposite direction to the estimate. An s-value of 4.3 bits, which is equivalent to a p-value (Kery and Schaub 2011; Greenland and Poole 2013) of 0.05, indicates that the surprise would be equivalent to throwing 4.3 heads in a row in a coin toss. The condition that non-essential explanatory variables have s-values ≥ 4.3 bits provides a useful model selection heuristic (Kery and Schaub 2011).

The results are displayed graphically by plotting the modeled relationships between particular variables and the response(s) with the remaining variables held constant. In general, continuous and discrete fixed variables are held constant at their mean and first level values, respectively, while random variables are held constant at their typical values (expected values of the underlying hyperdistributions) (Kery and Schaub 2011). When informative, the influence of particular variables is expressed in terms of the *effect size* (i.e., percent change in the response variable) with 95% credible intervals (CIs, Bradford et al. 2005). Credible intervals are the Bayesian equivalent of the confidence intervals used in frequentist statistics.

The analyses were implemented using R version 3.6.1 (R Core Team 2019) and the mbr family of packages. Some analyses include parameters from a second watershed, Grave Creek, to provide further context to the results.

MODEL DESCRIPTIONS

The following sections describe the variables and their relationships in the models.

FORK LENGTH

Distinguishing fish life stages is essential for evaluating recruitment to the population. Fish were classified into the following lifestages: fry (age-0 juveniles), age-1 juveniles, age-2+ juveniles and adults based on visual examination of fork length-frequency plots and previous research (Cope 2020).

ELECTROFISHING DENSITY

Calculating the density of WCT in electrofished habitats was the basis for extrapolating system-wide abundance. The single and multipass juvenile electrofishing data for the UFR population were analysed by life-stage using a hierarchical Bayesian removal model (Wyatt 2002). Young-of-year fish (fry) were excluded due to the high temporal and spatial variability associated with their late emergence from clustered redds as well as their low capture efficiency. They were also excluded because the fact that their numbers have yet to be reduced by density-dependent mortality means that their density is a poor indicator of recruitment (Johnston and Post 2009; Dauwalter et al. 2009).

Key assumptions of the single and multipass removal model include:

- Lineal density varies randomly by year within habitat type (mainstem vs tributary) and location.
- The number of fish at each site in each year is described by an over-dispersed Poisson distribution.
- The catch on each pass is binomially distributed, where the number of fish actually present in the river at the beginning of the pass represents the number of trials and the number of fish caught is the number of successful trials (Wyatt 2002).

Preliminary analysis indicated that mesohabitat (cascade, run, riffle, pool, glide) type was not an informative predictor of density and was not included in further analysis. The model could not discern an effect of mesohabitat on fish capture.

SNORKEL COUNT

The snorkel counts for the UFR population were plotted by year and segment and life stage (<200 vs 200-500+). To be conservative, adult abundance (200-500+) from 2017 to 2019 was calculated assuming the median previously recorded observer efficiency of 32% (range: 23%-42%; Cope 2020b).

The number of juvenile fish (0-200 mm) observed while snorkeling was divided by the age-1 and age-2+ juvenile electrofishing-based population abundance estimates for the mainstem for each year to estimate the snorkel observer efficiency.

BODY CONDITION

Body condition is related to nutritional status, survival and recruitment (Reimers 1963; Morgan 2004; Brosset et al. 2020) . The electrofishing length and mass data for fish from the UFR were analysed using a mass-length model to calculate body condition for the UFR population (He et al. 2008). The model was based on the allometric relationship

$$W = \alpha L^{\beta}$$

where W is the mass, α is the coefficent, β is the exponent and L is the length.

To improve chain mixing the relation was log-transformed, i.e.

$$\log(W) = \log(\alpha) + \beta \cdot \log(L)$$

Key assumptions of the condition model include:

- α can vary randomly by year.
- The residual variation in mass is log-normally distributed.

FECUNDITY

Fecundity, the mean number of eggs produced per female, is a critical measure of population growth potential. Following Ma and Thompson (2021) the fecundity was calculated assuming the following allometric relationship from Corsi et al. (2013).

$$E = \exp_{10}(-4.265 + 2.876 \cdot \log_{10}(\frac{L - 1.69}{1.040}))$$

The annual fecundity for the UFR population was estimated by taking the length of each adult observed by snorkeling and then calculating the number of eggs for that individual if it was female from the fecundity relationship. Assuming a 1:1 sex ratio in the population, each adult was also assumed to have a length equivalent to the mid-point of its size category up to a maximum of 400 mm. This was necessary because fish lengths in all years were binned into length categories with the largest category being 400+ mm in some years.

RECRUITMENT

Recruitment is the process whereby new individuals are added to the population. To assess recruitment, the total annual egg deposition was calculated from the annual fecundity (eggs per female) and the estimate of adults, assuming a 1:1 sex ratio and repeat spawning every other year (Liknes and Graham 1998), so that 50% of the adults are female and only 50% of females deposit eggs. The egg to age-1 survival (Pulkkinen et al. 2013) was then calculated by dividing the estimate of the age-1 individuals by the estimated total egg deposition the previous year (or the same year if the previous year's egg deposition was unavailable). The egg deposition was plotted in terms of the number of eggs per 100 m of habitat to allow comparisons among systems.

The egg-to-age-1 survival required for population replacement was taken from the Excel workbook (Table 4) provided by Ma and Thompson (2021) with one modification. The proportion mature by age (P_{age}) was calculated using the following equation (as opposed to a lookup table to allow the uncertainty in the maturation schedule to be quantified through a single parameter - see below). A is the age at which 50% of fish are mature and age^{12} is age to the 12$^{\text{th}}$ power, to produce a maturation curve equivalent to Ma and Thompson (2021).

$$P_{\text{age}} = \frac{\text{age}^{12}}{A_s^{12} + \text{age}^{12}}$$

The uncertainty in the egg-to-age-1 survival required for population replacement was quantified by independently sampling from the uncertainty for each parameter (Table 4) assuming a truncated normal distribution of the form

$$N(\text{estimate}, \frac{\text{upper} - \text{lower}}{3.92})\text{T}(\text{lower,upper})$$

Table 4. The life-history parameter estimates for the upper Fording river population from Ma and Thompson (2021).

Parameter	Estimate	Lower	Upper	Description
S_J	0.3835	0.20	0.574	Juvenile Survival (age-1 and -2)
S_A	0.7330	0.68	0.790	Adult Survival (age-3+)
A_max	14	12	16	Maximum age (yr)
L_inf	462	270	464	Mean maximum fork length (mm)
k	0.15	0.11	0.195	Growth rate (yr-1)
a0	-0.45	-0.10	0.212	Age at zero length (yr)
As	3.9	2.9	5	Age at 50% maturity

POPULATION PRODUCTIVITY

Productivity refers to the capacity of the population to produce new individuals, a measure of the potential for population recovery. The expected lifetime number of spawners per spawner (Myers 1999) (rho) was calculated by dividing the estimated egg to age-1 survival by the estimated egg to age-1 survival required for population replacement in each year.

RESULTS

REDD SURVEY

The year-to-year distribution of documented redds was highly variable, with the most widespread number of redds observed in 2015. In 2020, redds were less widely distributed than 2015, but not dissimilar to 2014 (Figure 2).

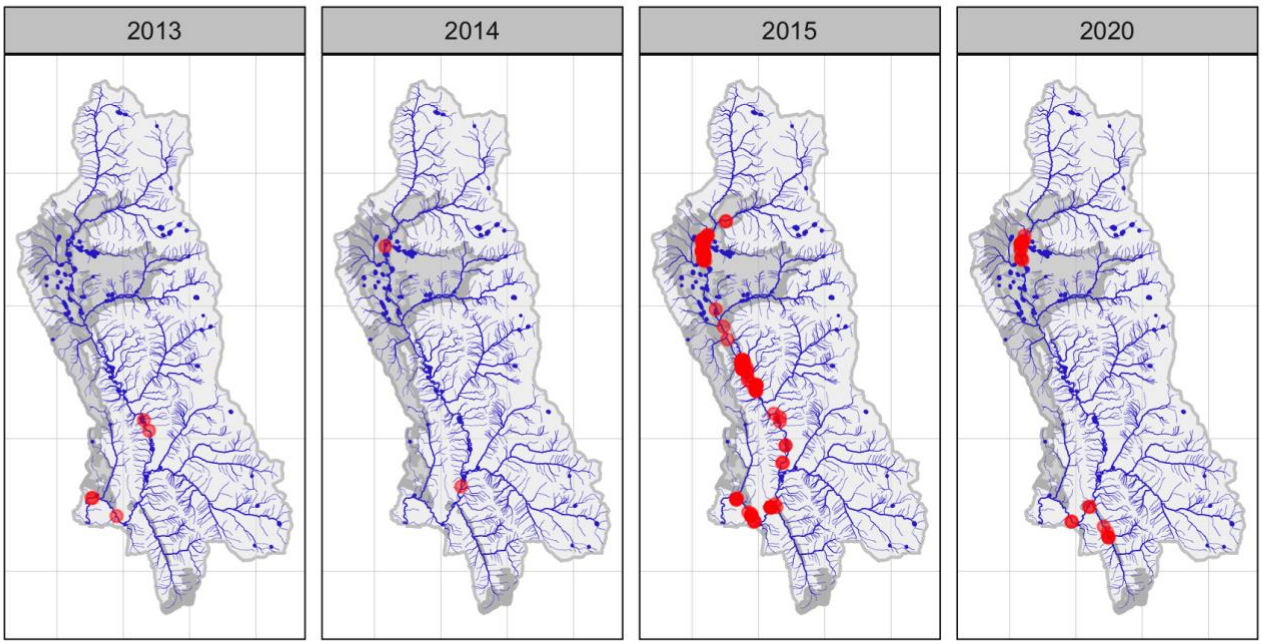

Figure 2. The spatial distribution of recorded Westslope Cutthroat Trout redds by year in the upper Fording River during redd surveys in 2013, 2014, 2015, and 2020.

FORK LENGTH

Based on visual examination of length-frequency plots for the UFR population, age-0 individuals were considered to be those less than 60 mm, age-1 individuals those between 60 and 109 mm (Figure 3). Adults were considered to be individuals >= 200 mm. Age-2+ juveniles are those individuals that are too big to be age-1 but too small to be adults (Figure 3). The number of age-0 was highly variable among years and was not consistently related to the number of age-1 the following year, e.g. compare 2019 and 2020 (Table 5, Figure 3).

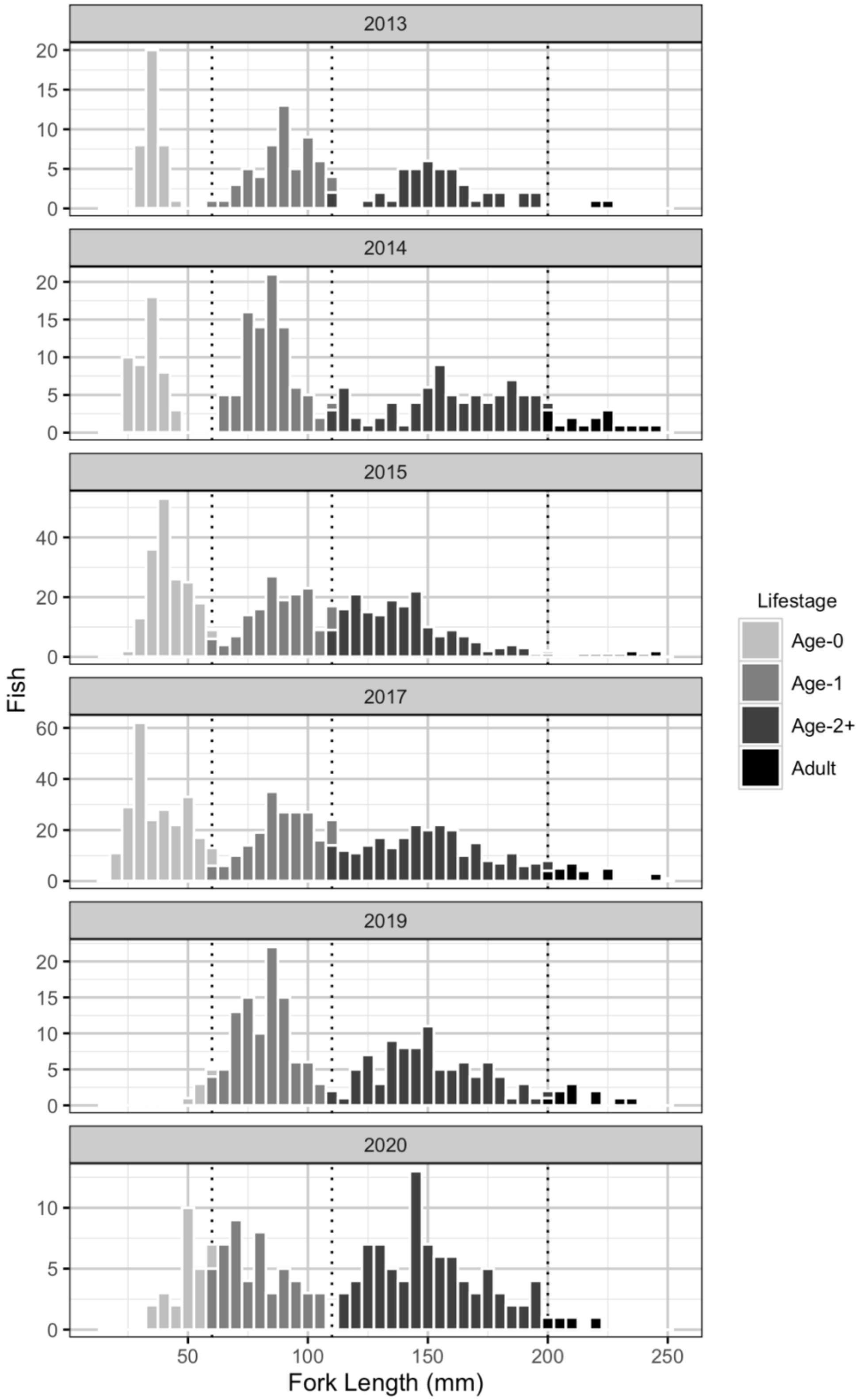

Figure 3. Number of WCT captured by fork length, year and presumed lifestage. Adults: ≥200 mm, age-2+ juveniles: >109 to <200 mm, age-1+: 60-109 mm, age-0: <60 mm.

ELECTROFISHING

The electrofishing surveys covered 1.02 km in 2020, covering over 1% of the fish-bearing length of the watershed. This was a similar effort to previous years (Table 5).

Table 5. The total length of habitat electrofished at least once and the number of fish caught on the first pass by age-class, year and population. Only the first pass was used to enable comparisons with previous years and variable numbers of passes.

Year	Population	Length (m)	Age-0	Age-1	Age-2+	Adult
2013	upper Fording	980	20	36	34	2
2014	upper Fording	896	28	46	49	13
2015	upper Fording	877	95	101	126	13
2017	upper Fording	905	104	122	181	30
2019	upper Fording	1278	4	57	65	9
2020	upper Fording	1021	11	32	59	4

Electrofishing results show high variability both between locations and within locations by year (Figure 4). Electrofishing capture efficiency for age-1 fish was 51% (95% CI 45%-56%). Age-2+ juveniles had a capture efficiency of 66% (95% CI 61%-70%) (Figure 5).

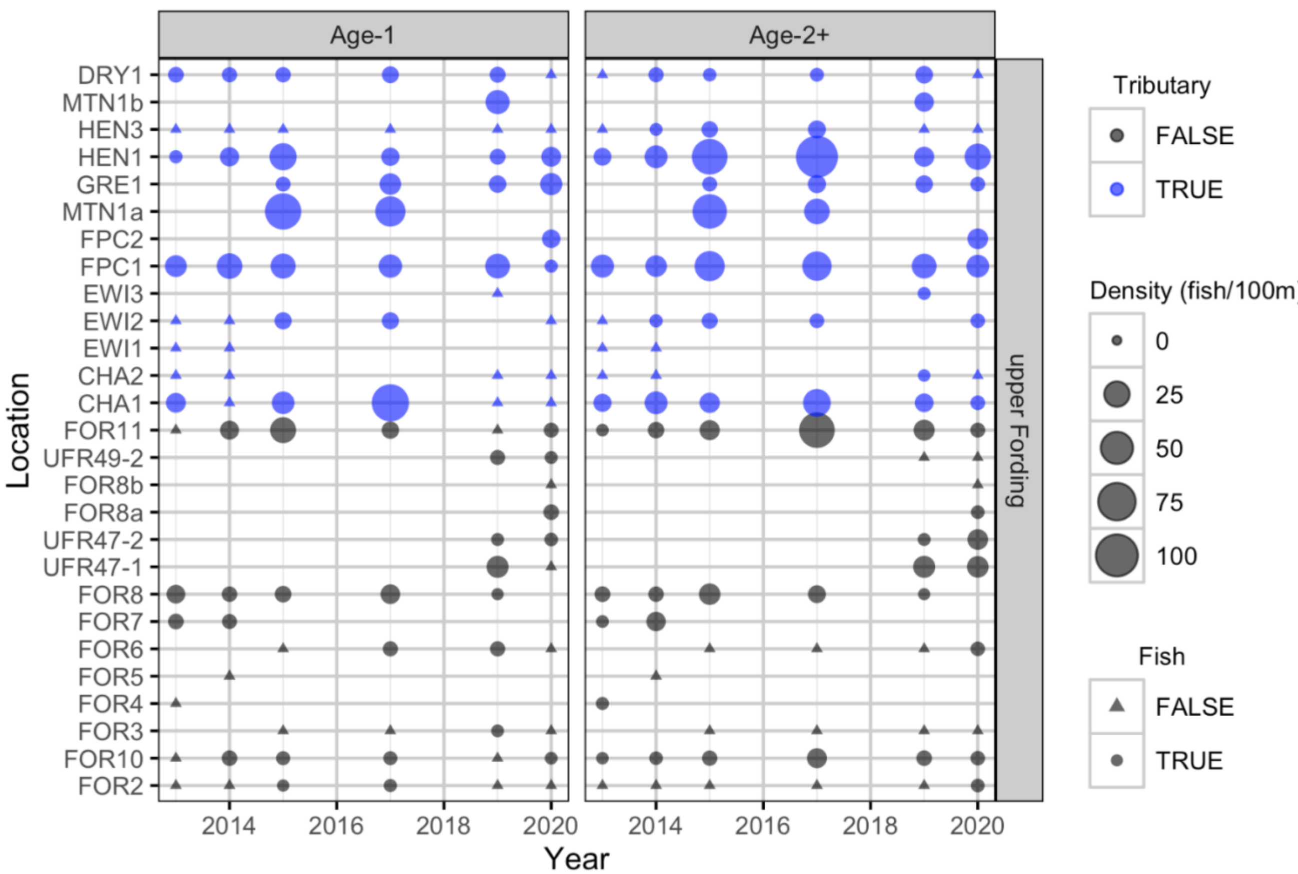

Figure 4. The electrofishing capture density on the first pass by year, location and life-stage in the upper Fording River watershed. Triangles indicate no fish were captured, grey indicates mainstem site, and blue indicates tributary site.

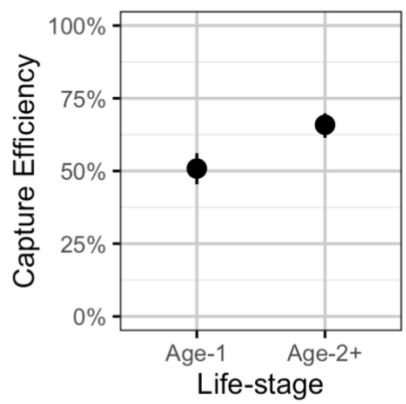

Figure 5. The estimated electrofishing capture efficiency of Age-1 and Age-2 lifestages (with 95% CIs).

AGE-1 DENSITY AND ABUNDANCE

The density variation among sites is higher in tributary habitat than in the mainstem (Figure 6). In 2020, age-1 WCT density at typical site was 11.3 fish/100 m (95% CI 3.43-58.7) in the mainstem and 15.7 fish/100 m (95% CI 5.67-66.1) in the tributaries. Overall densities were also similar between the mainstem and tributary habitat in previous years (Figure 7).

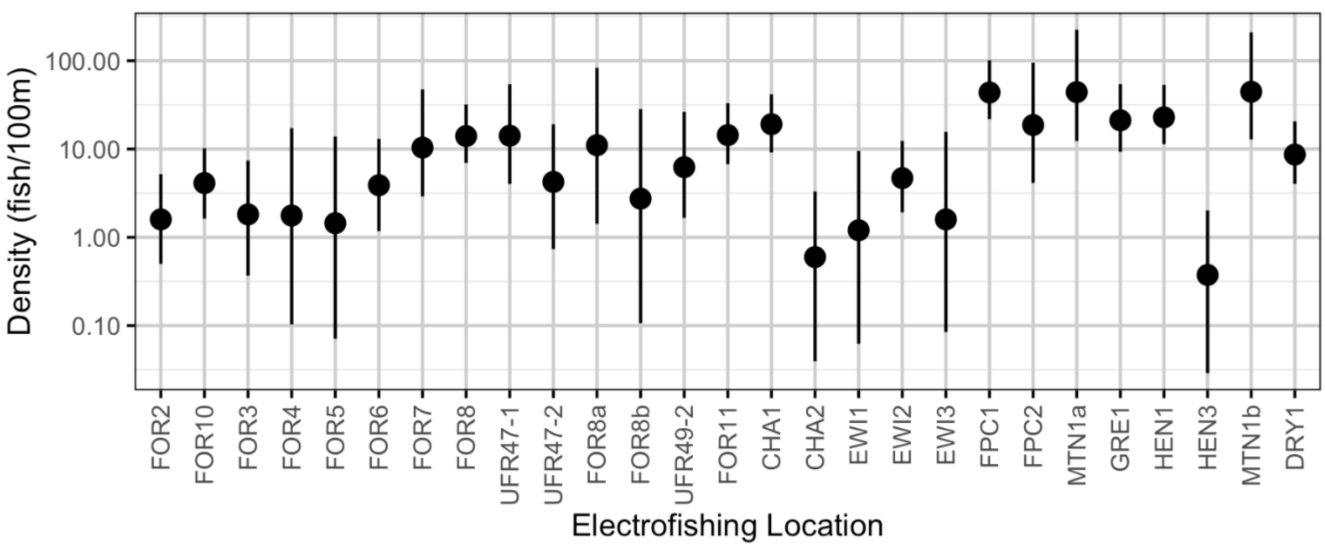

Figure 6. The estimated age-1 density by location in a typical year (combined 2013 to 2020 data set, with 95% CIs) on a log scale, mainstem location names start with FOR or UFR.

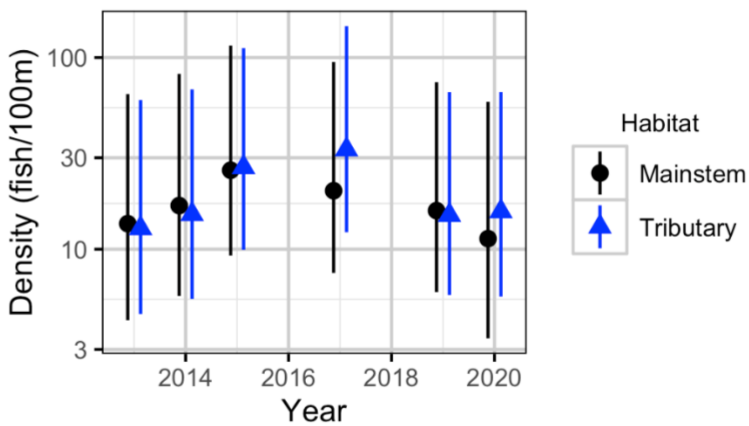

Figure 7. The estimated age-1 lineal density (fish/100m of stream) on a log scale at a typical site by year and habitat type (with 95% CIs).

The total abundance of age-1 WCT in the UFR watershed in 2020 was estimated to be 11,100 fish (95% CI 4,360-48,500). Mean abundance of age-1 WCT peaked in 2015 and 2017 at approximately 22,000 fish (2015: 22,400 fish; 95% CI 8,980-93,100 and 2017: 21,700 fish; 95% CI 8,890-93,500) The 2020 numbers are comparable to 2013 which was estimated to have been 11,300 age-1 fish (95% CI 4,360-52,900; Figure 8).

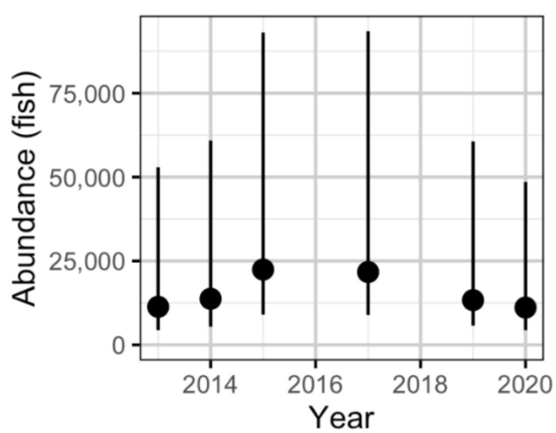

Figure 8. The combined (mainstem and tributary) estimated abundance of age-1 Westslope Cutthroat Trout in the upper Fording River watershed by year (with 95% CIs).

AGE-2+ DENSITY AND ABUNDANCE

Age-2+ juvenile densities were highly variable among locations, both in mainstem and tributary habitats (Figure 9). As in most previous years, the overall 2020 density for age-2+ juvenile WCT in the mainstem and tributaries was very similar, at 15.3 fish/100 m (95% CI 5.15-69.6) and 15.1 (95% CI 6.07-67.4), respectively (Figure 10).

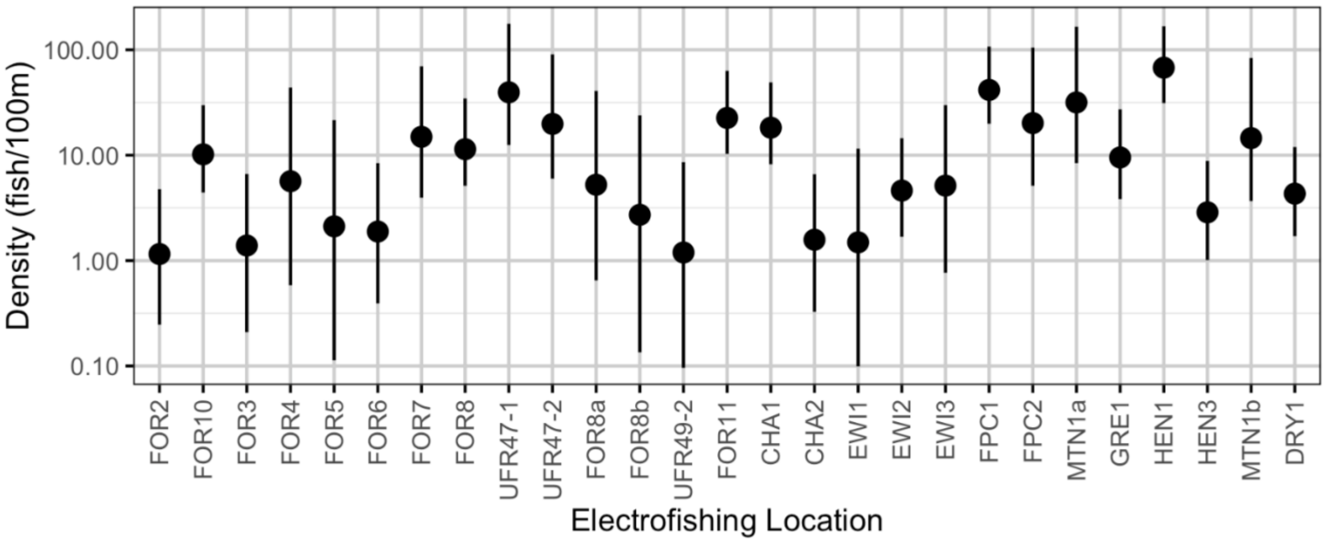

Figure 9. The estimated age-2+ juvenile lineal density by location in a typical year (combined 2013 to 2020 data set, with 95% CIs) on a log scale, mainstem location names start with F or UFR.

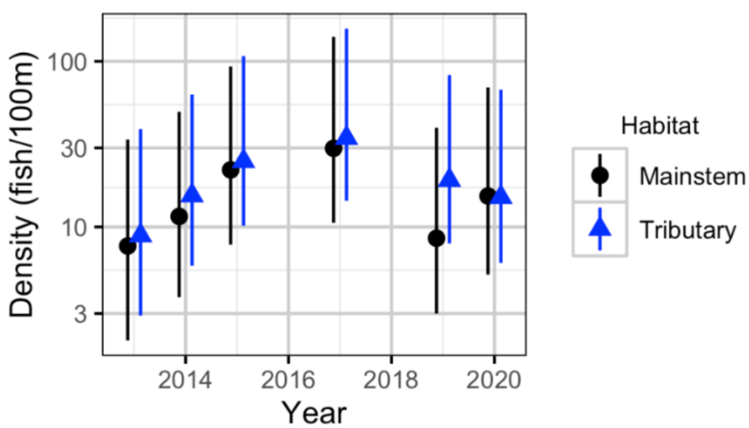

Figure 10. The estimated age-2+ juvenile lineal density (fish/100m of stream) on a log scale at a typical site by year and habitat type (with 95% CIs).

In 2020, the combined (mainstem and tributary) abundance of age-2+ juvenile WCT in the UFR watershed was estimated to 13,100 fish (95% CI 5,570-54,900). The abundance of age-2+ juveniles peaked in 2017 at approximately 27,200 fish (95% CI 11,700-115,000) with 2020 representing the third highest value and exceeding the estimates for 2013, 2014 and 2019.

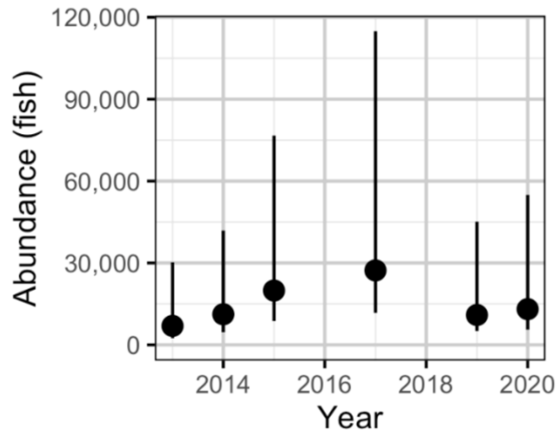

Figure 11. The combined (mainstem and tributary) estimated abundance of age-2+ juvenile Westslope Cutthroat Trout in the upper Fording River watershed by year (with 95% CIs).

SNORKEL

Snorkel counts covered approximately 48 km or 84% of the mainstem UFR and included the lower 4 km of Henretta Creek. Counts for juveniles (all fish <200 mm) and adults in the UFR are shown in Figure 12. 2017 appears to have been a year of unusually high counts, particularly for juveniles (all fish<200 mm; Figure 12, Figure 13). Total counts for these younger age class fish in the snorkel surveys (Figure 13) demonstrated much higher variability and steeper declines than the results from electrofishing (Figure 8, Figure 11) varying by two orders of magnitude from 205 fish (<200 mm) in 2012 to 2187 fish (<200 mm) in 2017 then dropping to 24 fish (<200 mm) in 2020. Compared to the estimates of the number of age-1 and age-2+ juveniles from mainstem electrofishing in 2020 and other years, the inferred snorkel observer efficiency for juvenile fish is very low and highly variable (Figure 14).

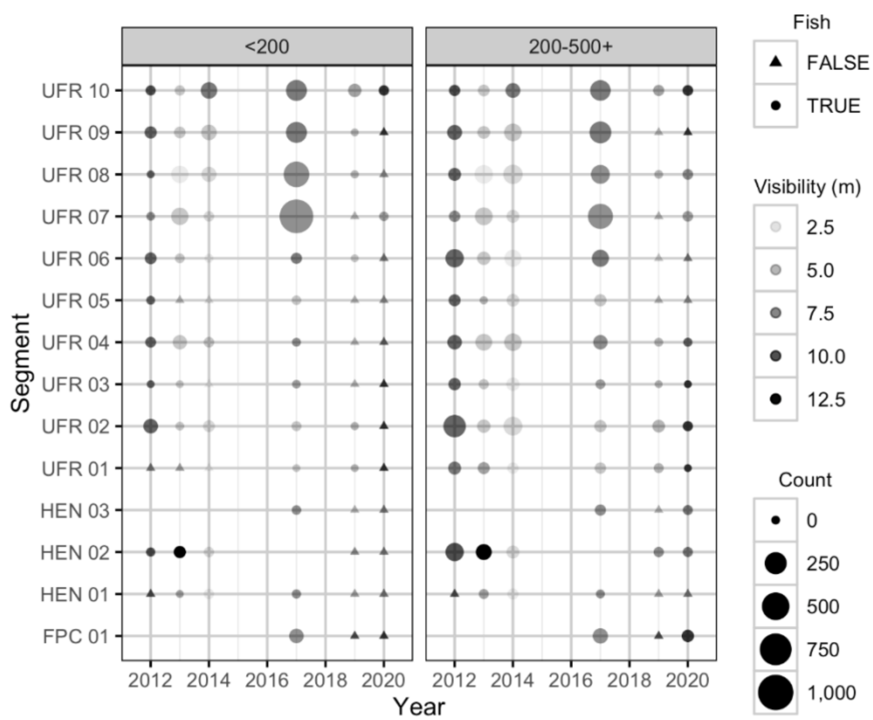

Figure 12. Raw fall snorkel counts in the upper Fording River by year, segment, size class and visibility. Triangles indicate no fish observed

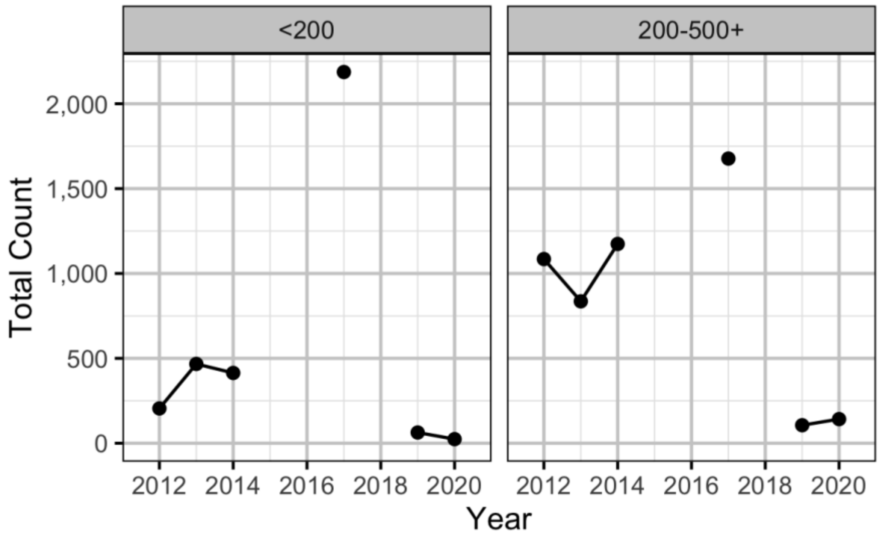

Figure 13. Total fall snorkel counts for Westslope Cutthroat Trout in the fall (September) in the upper Fording River by year and size class.

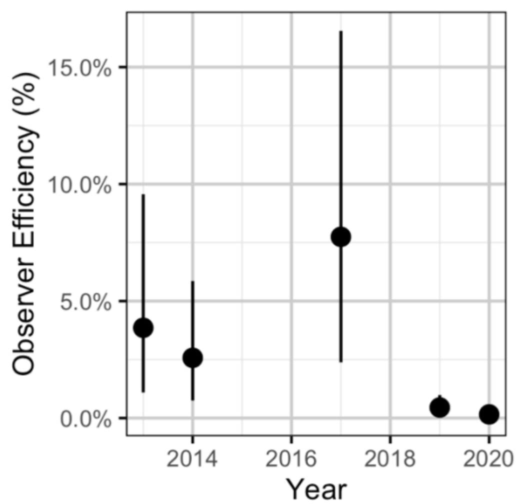

Figure 14.The implied observer efficiency of 0-200 mm fish in the mainstem while conducting daytime snorkel surveys for adult fish estimate by comparison with the electrofishing-based density estimates by year (with 95% CIs).

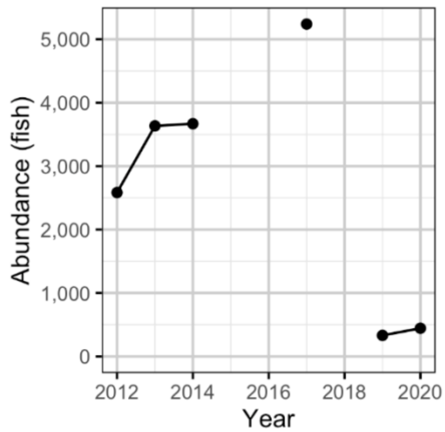

Figure 15. The estimated fall adult (200-500+ mm) Westslope Cutthroat Trout abundance by year on the upper Fording River, assuming an efficiency of 32% for 2017-2020. Credibility intervals are not provided because the distribution of the response variable is unknown.

Adult abundance in the UFR nearly doubled between 2012 and 2017 from 2,583 fish to 5,241. Adult abundance then showed a 94% decline between 2017 and 2019, from 5,241 to 331 fish (Figure 15). The adult population abundance estimate increased in 2020, to an estimated 440 adult fish.

BODY CONDITION

The mass-length data for electrofished WCT are plotted in Figure 16. The data for 2017 was not included in the analysis as the mass measurements were very imprecise (Figure 16), taken in 5 g increments.

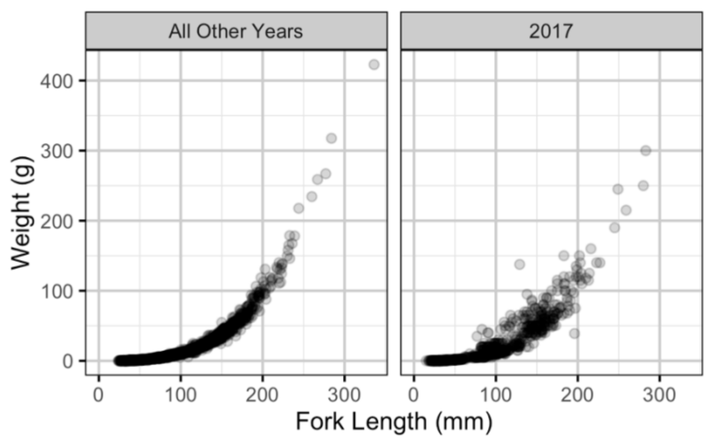

Figure 16. Mass by length. The masses for 2017 are plotted separately to illustrate the unreliability of the data as indicated by the imprecise mass measurements.

The body condition of an average length (103 mm) fish was above that of a typical year for 2019 and 2020 (Figure 17) at 0.8% (95% CI -3.0%-4.5%) and 1.9% (95% CI -1.4-6.2%), respectively. In 2015, during the upward trend in fish abundance, fish body condition was substantially lower than average (for the years analyzed; 2013-2020) at -3.2% (95% CI -7.1%- -0.02%).

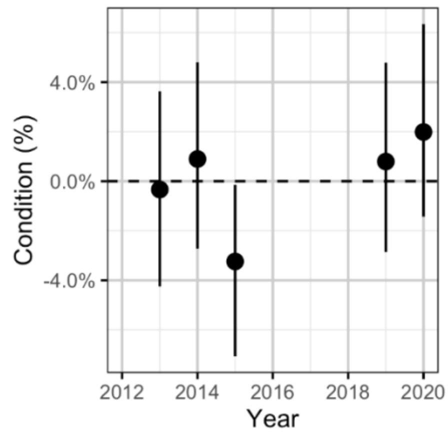

Figure 17.The percent change in the body condition for an average length fish relative to a typical year by year (with 95% CRIs).

FECUNDITY

Following Ma and Thompson (2021) the fecundity was calculated from the fork length using the same equation as Corsi et al. (2013). The relationship between fork length and fecundity is plotted together with those from other studies in Figure 18.

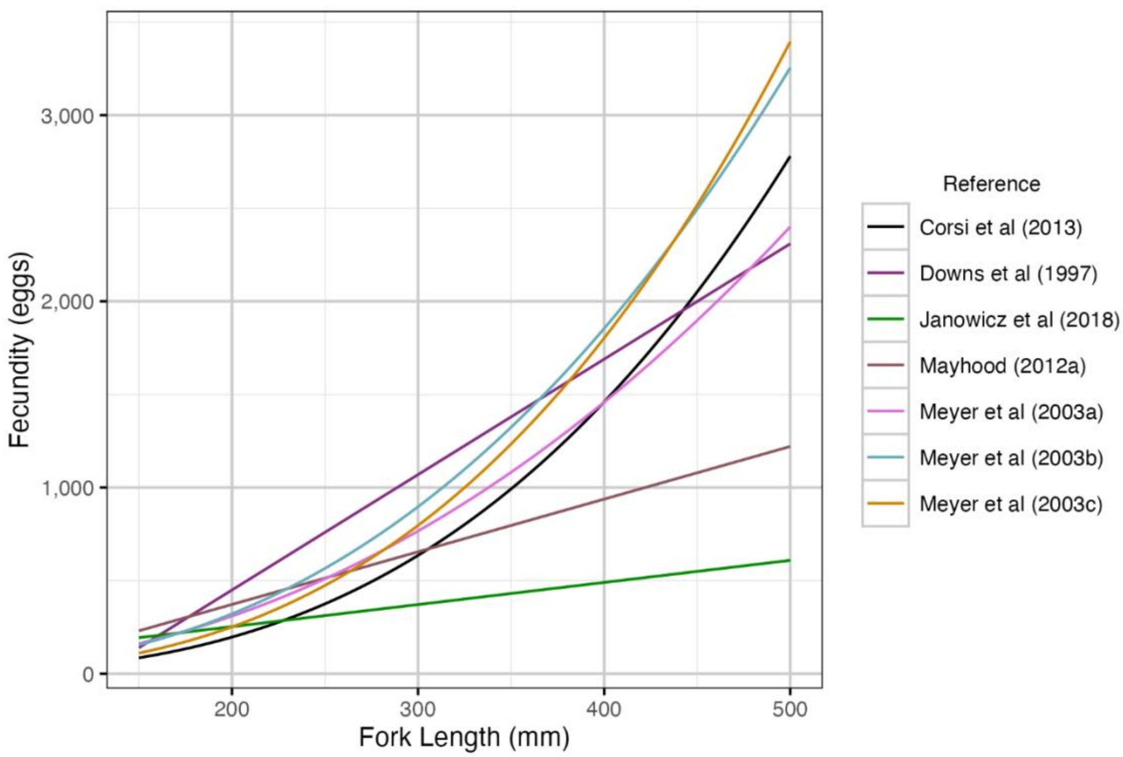

Figure 18. Examples of WCT fecundity-fork length relationships derived from literature.

Since 2012, the estimated fecundity has varied between 560 and 780 eggs/female. In recent years, estimated fecundity increased from 2017 and 2019 values of ~560 eggs/ female to 670 eggs/female in 2020 (Figure 19).

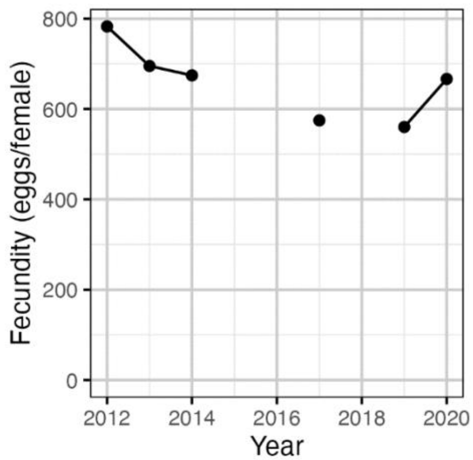

Figure 19. The estimated fecundity by year.

RECRUITMENT

Since the 2018 spawn year, the egg to age-1 survival (Figure 20) has substantially exceeded the threshold of 5% required for population replacement based on the literature (Brian Ma, pers comm.). The egg to age-1 survival rates, which take into account differences in the amount of habitat and size of the fish, are comparable to those for the neighboring Grave Creek population. Additionally, using life history parameter estimates specific to the UFR, a 3% replacement rate for the population was calculated, somewhat less than the 5% literature values (Table 6). Egg to age-1 survival for the years 2012-2016 was close to this value.

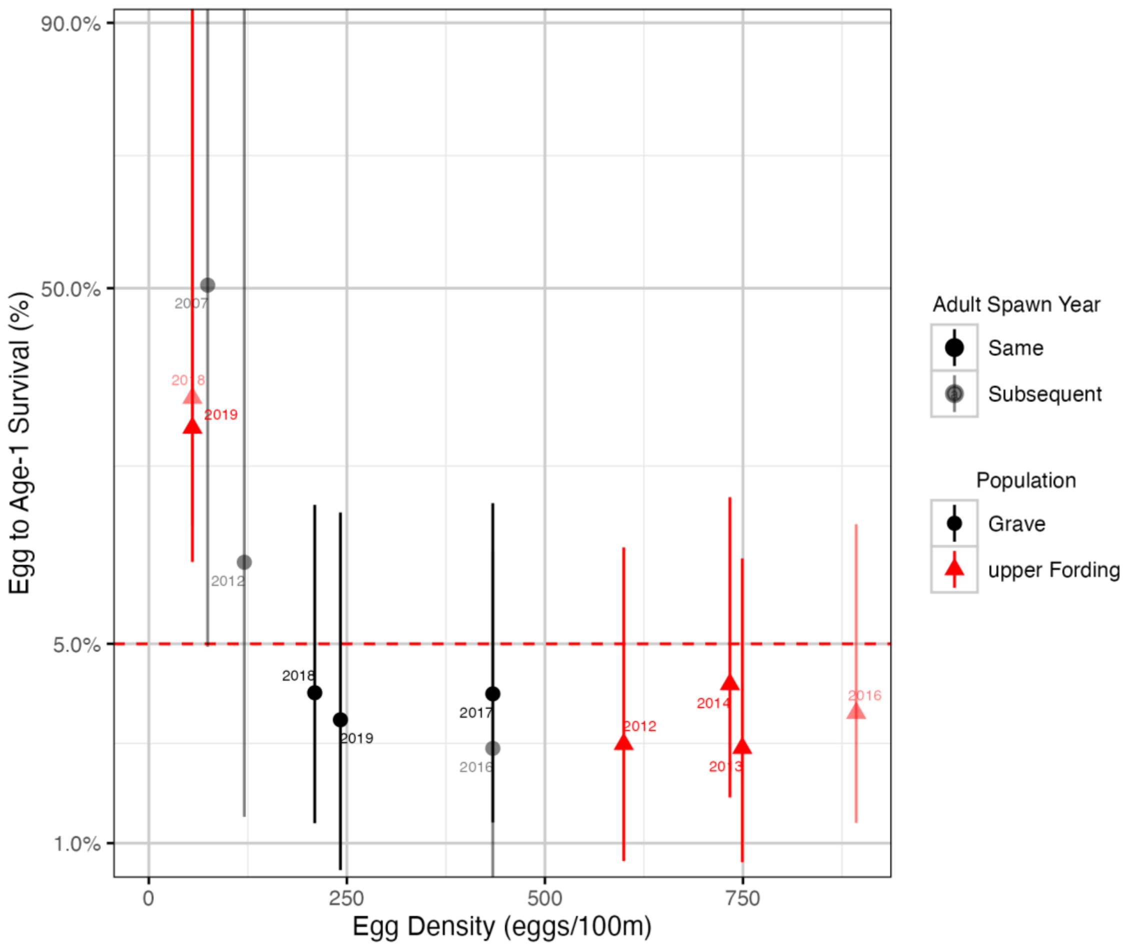

Figure 20. The egg to age-1 survival by total egg deposition, population and spawn year. The dashed red line indicates the egg-to-fry survival required for replacement based on the literature.

Table 6. The calculated egg to age-1 survival required for replacement (with 95% CIs) based on the parameter values provided by Ma and Thompson (2021).

Population	Estimate	95% lower	95% upper
upper Fording	0.03	0.01	0.08

POPULATION PRODUCTIVITY

For the UFR the estimated population productivity was around the replacement rate of 1 lifetime spawner produced per spawner until the 2018 and 2019 spawn years when following the drop in egg density the productivity increased to around 10 spawners per spawner (Figure 21).

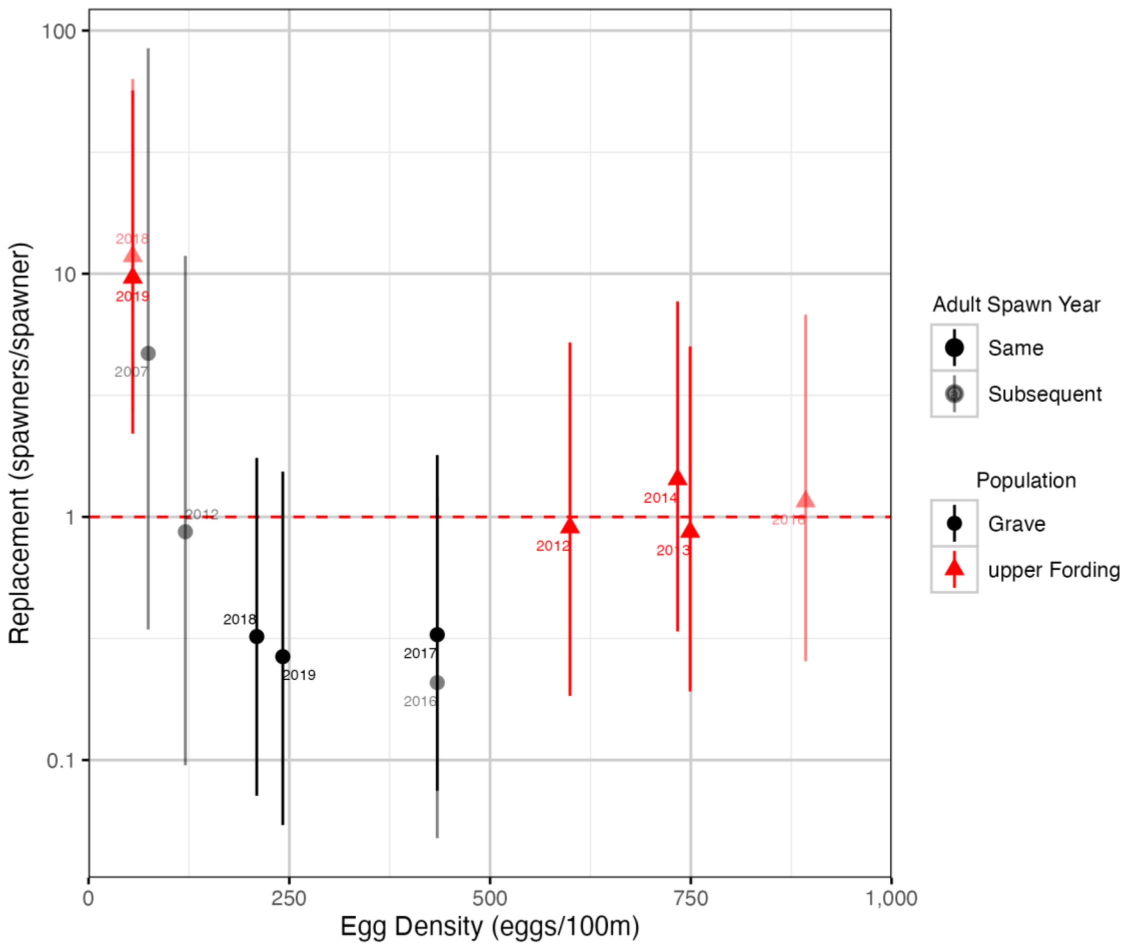

Figure 21. The calculated expected lifetime spawners per spawner on a log scale, by egg density, population and spawn year (with 95% CIs representing the uncertainty in the age-1 abundance and subsequent survival terms). Lower and upper CIs are truncated at 0.001 and 100 respectively. The dashed red line indicates replacement.

DISCUSSION

Determining population abundance estimates with sufficient accuracy and precision is essential for tracking changes in at-risk populations potentially impacted by industrial activities. In the last five years, substantial fluctuations were reported in the UFR WCT population estimates. For many salmonid populations high levels of uncertainty make the determination of the magnitude of trends difficult. In particular, large, biologically important declines may be occurring in the population but may be unable to be discerned with any confidence (Dauwalter et al. 2009). The current report used a hierarchical Bayesian approach to maximize the use of the available information and to draw easy to interpret probabilistic conclusions.

The occurrence and distribution of WCT redds testifies to the continued presence of spawning activity in the UFR. However, due to the lack of complete information on survey coverage the current redd count data does not represent a reliable index of adult abundance or even the total amount of spawning activity.

The electrofishing catches of age-0 juvenile (fry) densities were not analyzed as the large inter-annual variation in emergence timing and the high temporal and spatial variation in densities combined with the low capture efficiency makes any population estimates highly uncertain (Shepherd and Cushing 1980; Yant et al. 1984; Meyer et al. 2006). Furthermore, fry counts are a poor indication of recruitment success as this age class may be experiencing density-dependent mortality.

Age-1 and age-2+ juvenile WCT abundance estimates from electrofishing both declined from 2017 but have remained within the range of values observed in previous years. Although the number of juveniles (all fish <200 mm) observed during the daytime mainstem snorkels surveys for adults exhibited a much more extreme and ongoing decline they do not currently represent cause for concern. Daytime snorkel surveys for juvenile salmonids are highly inefficient because small fish are harder to detect and may be concealed (Thurow et al. 2006). Indeed, comparison of the age-1 and age-2+ population abundance estimates to the juvenile snorkel counts indicate that the daytime snorkelers typically observe less than 5% of the juveniles in the mainstem and observer efficiency increases with the estimated population abundance. Compare this to the calculated observer efficiency for adults, which varied between 42% and 25%, depending on visibility conditions. Consequently, low counts in the juvenile snorkel counts can be explained by relatively small changes in observer efficiency.

There was a substantial decline in the number of adults in the UFR between 2017 and 2019 but no evidence of further decline between 2019 and 2020. This suggests that the high adult mortality between 2017 and 2019 may have been due to an acute (short-term) event as opposed to chronic conditions. While adult population abundance would not be expected to recover immediately from an acute event, recovery is possible if juveniles successfully reach adulthood and are able to successfully spawn.

Compensatory density dependence is important to fisheries management because it operates to offset the losses of individuals. Population compensation occurs when survival, growth or fecundity increase at lower densities, thereby promoting population growth (Rose et al. 2001). Alternately, density dependent mortality is typically strongest during the earliest life stages, i.e. from egg to age-1 survival (Shepherd and Cushing 1980; Yant et al. 1984; Elliott 1989; Johnston and Post 2009). The high egg to age-1 survival rate (~25%) in the upper Fording River for the 2019 spawn year suggests a strong compensatory response may be occurring. For comparison, 5% is considered sufficient for replacement in a typical Westslope Cutthroat Trout population and Peterson et al. (2008) estimated egg to age-1 survival rates of 13% for cutthroat trout in the absence of competition from non-native trout. In addition to higher survival of juveniles, we recorded higher than average fish body condition after the population decline that also suggests a compensatory growth response likely due to less competition for resources.

Population productivity is directly related to egg survival. By definition, productivity (lifetime spawners per spawner) must equal 1 for a stable population while a value > 1 indicates a growing population and a value < 1 indicates a decreasing population. Myers (1999) calculated a lifetime reproductive rate, at low population densities, of between 4-27 spawners per spawner for 7 different salmonid species. The UFR WCT population falls within this range at ~10 spawners/spawner in 2020.

Following the peak in adult WCT density in 2017 and substantial decline in 2019, WCT body condition and egg to age-1 survival have improved and recruitment is well above the levels required for replacement. Taken together these findings suggest a resilient population with the capacity to compensate for acute mortality events. If the cause of high adult mortality can be identified and rectified or if this was a unique extreme event, the prognosis for a population recovery appears to be good.

The study design of the current program suffers from a number of limitations including underestimation of abundance from depletion-removal electrofishing (Meyer and High 2011), bias due to the non-random selection of electrofishing sites at the mesohabitat scale and the limited electrofishing coverage of the available habitat (Korman et al. 2016). There is also uncertainty surrounding the distribution of fish within the tributaries. There is also some uncertainty regarding observer efficiencies during most recent snorkel surveys. Nonetheless, the general conclusion that the population is undergoing a positive compensatory response to the decline in population abundance between 2017 and 2019 is considered robust.

The current report does not address the question of whether or to what degree habitat degradation from regional anthropogenic causes has occurred, or how many fish would be present in the absence of anthropogenic effects. The causal relationships responsible for the observed decline from 2017 to 2019, primarily in adult WCT, have yet to be determined (UFR Evaluation of Cause Report, report pending - Evaluation of Cause Team 2021).

RECOMMENDATIONS

- Continue annual monitoring efforts using snorkeling and electrofishing to assess population recovery or determine if there are further declines in the population. Specific recommendations for modified data collection will be provided in the 2021 UFR Study Design.
- Model UFR WCT population dynamics with potential anthropogenic and climactic variables in conjunction with reference WCT populations to evaluate the relative contributions of key factors.

REFERENCES

Bear, E.A., McMahon, T.E., and Zale, A.V. 2007. Comparative Thermal Requirements of Westslope Cutthroat Trout and Rainbow Trout: Implications for Species Interactions and Development of Thermal Protection Standards. Trans. Am. Fish. Soc. **136**(4): 1113–1121. doi:10.1577/T06-072.1.

Bradford, M.J., Korman, J., and Higgins, P.S. 2005. Using confidence intervals to estimate the response of salmon populations (Oncorhynchus spp.) to experimental habitat alterations. Can. J. Fish. Aquat. Sci. **62**(12): 2716–2726. doi:10.1139/f05-179.

Brooks, S., Gelman, A., Jones, G.L., and Meng, X.-L. (*Editors*). 2011. Handbook for Markov Chain Monte Carlo. Taylor & Francis, Boca Raton.

Brosset, P., Smith, A.D., Plourde, S., Castonguay, M., Lehoux, C., and Van Beveren, E. 2020. A fine-scale multi-step approach to understand fish recruitment variability. Sci. Rep. **10**(1): 16064. doi:10.1038/s41598-020-73025-z.

Brown, R.S., and Mackay, W.C. 1995. Fall and Winter Movements of and Habitat Use by Cutthroat Trout in the Ram River, Alberta. Trans. Am. Fish. Soc. **124**(6): 873–885. Taylor & Francis. doi:10.1577/1548-8659(1995)124<0873:FAWMOA>2.3.CO;2.

Coleman, M.A., and Fausch, K.D. 2007. Cold Summer Temperature Limits Recruitment of Age-0 Cutthroat Trout in High-Elevation Colorado Streams. Trans. Am. Fish. Soc. **136**(5): 1231–1244. doi:https://doi.org/10.1577/T05-244.1.

Cope, S. 2020. Upper Fording River Westslope Cutthroat Trout Population Monitoring Project: 2019. A Westslope Fisheries Ltd. report, Teck Coal Limited, Sparwood, BC.

Cope, S., Schwarz, C., Prince, A., and Bisset, J. 2016. Upper Fording River Westslope Cutthroat Trout Population Assessment and Telemetry Project: Final Repor. A Westslope Fisheries Ltd. report, Tech Coal Limited, Sparwood, BC.

Corsi, M.P., Eby, L.A., Barfoot, C.A., and Fleming, I. 2013. Hybridization with rainbow trout alters life history traits of native westslope cutthroat trout. Can. J. Fish. Aquat. Sci. **70**(6): 895–904. doi:10.1139/cjfas-2012-0312.

Dauwalter, D., Rahel, F., and Gerow, K. 2009. Temporal Variation in Trout Populations: Implications for Monitoring and Trend Detection. Trans. Am. Fish. Soc. - TRANS AMER FISH SOC **138**: 38–51. doi:10.1577/T07-154.1.

Elliott, J.M. 1989. Mechanisms Responsible for Population Regulation in Young Migratory Trout, Salmo trutta. I. The Critical Time for Survival. J. Anim. Ecol. **58**(3): 987–1001. [Wiley, British Ecological Society]. doi:10.2307/5137.

Elphick, J., Bailey, H., Lo, B.K., Sword, G., and Berdusco, J. 2009. Effect of selenium on early life-stage development of westslope cutthroat trout.

Evaluation of Cause Team. 2021. Upper Fording River Evaluation of Cause Report. Teck Coal Limited, Sparwood, BC.

Canada Department of Fisheries and Oceans. 2017. Management plan for the westslope cutthroat trout (Oncorhynchus clarkii lewisi), British Columbia population, in Canada. Available from http://publications.gc.ca/collections/collection_2017/mpo-dfo/En3-5-75-2016-eng.pdf [accessed 20 July 2020].

Gelman, A., Simpson, D., and Betancourt, M. 2017. The Prior Can Often Only Be Understood in the Context of the Likelihood. Entropy **19**(10): 555. doi:10.3390/e19100555.

Greenland, S. 2019. Valid P-Values Behave Exactly as They Should: Some Misleading Criticisms of P-Values and Their Resolution With S-Values. Am. Stat. **73**(sup1): 106–114. Taylor & Francis. doi:10.1080/00031305.2018.1529625.

Greenland, S., and Poole, C. 2013. Living with P Values: Resurrecting a Bayesian Perspective on Frequentist Statistics. Epidemiology **24**(1): 62–68. doi:10.1097/EDE.0b013e3182785741.

He, J.X., Bence, J.R., Johnson, J.E., Clapp, D.F., and Ebener, M.P. 2008. Modeling Variation in Mass-Length Relations and Condition Indices of Lake Trout and Chinook Salmon in Lake Huron: A Hierarchical Bayesian Approach. Trans. Am. Fish. Soc. **137**(3): 801–817. doi:https://doi.org/10.1577/T07-012.1.

Johnston, F.D., and Post, J.R. 2009. Density-dependent life-history compensation of an iteroparous salmonid. Ecol. Appl. **19**(2): 449–467. doi:https://doi.org/10.1890/07-1507.1.

Johnston, N.T., and Slaney, P.A. 1996. Fish Habitat Assessment Procedures. Ministry of Environment, Lands and Parks and Ministry of Forests, Vancouver, BC. Available from http://a100.gov.bc.ca/appsdata/acat/documents/r15711/Fish_Habitat_Assessment_Procedures_1229454360370_60d06fb366d66d9a96f0f58ea082db1abc58c0fc1e3805cd799cd37fc0143bdb.pdf.

Kennedy, C.J., McDonald, L.E., Loveridge, R., and Strosher, M.M. 2000. The Effect of Bioaccumulated Selenium on Mortalities and Deformities in the Eggs, Larvae, and Fry of a Wild Population of Cutthroat Trout (Oncorhynchus clarki lewisi). Arch. Environ. Contam. Toxicol. **39**(1): 46–52. doi:10.1007/s002440010078.

Kennedy, P., and Meyer, K.A. 2015. Trends in Abundance and the Influence of Bioclimatic Factors on Westslope Cutthroat Trout in Idaho. J. Fish Wildl. Manag. **6**(2): 305–317. Allen Press. doi:10.3996/012015-JFWM-001.

Kéry, M., and Royle, J. andrew. 2015. Applied Hierarchical Modeling in Ecology: Analysis of distribution, abundance and species richness in R and BUGS.

Kery, M., and Schaub, M. 2011. Bayesian population analysis using WinBUGS : a hierarchical perspective. Academic Press, Boston. Available from http://www.vogelwarte.ch/bpa.html.

Korman, J., Schick, J., and Mossop, B. 2016. Estimating Riverwide Abundance of Juvenile Fish Populations: How Much Sampling is Enough? North Am. J. Fish. Manag. **36**(2): 213–229. doi:https://doi.org/10.1080/02755947.2015.1114542.

Liknes, G., and Graham, P. 1998. Westslope cutthroat trout in Montana: life history, status, and management. Am. Fish. Soc. Symp. **4**: 53–60.

Ma, B.O., and Thompson, A. 2021. Tool to Estimate Egg-to-Age-1 Survial Required for Population Replacement Prepared as part of the WCT Population Model development for Teck Coal Ltd. Excel Spreadsheet, ESSA Technologies Ltd.

McElreath, R. 2016. Statistical rethinking: a Bayesian course with examples in R and Stan. CRC Press/Taylor & Francis Group, Boca Raton.

MFLNRORD. 2019. 2019-2021 Freshwater Fishing Regulations Synopsis. Available from https://www2.gov.bc.ca/assets/gov/sports-recreation-arts-and-culture/outdoor-recreation/fishing-and-hunting/freshwater-fishing/fishing_synopsis.pdf [accessed 22 March 2021].

Morgan, M.J. 2004. The relationship between fish condition and the probability of being mature in American plaice (Hippoglossoides platessoides). ICES J. Mar. Sci. **61**(1): 64–70. doi:10.1016/j.icesjms.2003.09.001.

Myers, R.A., Bowen, K.G., and Barrowman, N.J. 1999. Maximum reproductive rate of fish at low population sizes. Can. J. Fish. Aquat. Sci. NRC Research Press Ottawa, Canada. doi:10.1139/f99-201.

Nupqu. 2021. Dry Creek Fish and Fish Habitat Monitoring Program 2020. A Nupqu Limited Partnership Report, Teck Coal Limited - Line Creek Operations, Sparwood, BC.

Peterson, D.P., Fausch, K.D., Watmough, J., and Cunjak, R.A. 2008. When Eradication is not an Option: Modeling Strategies for Electrofishing Suppression of Nonnative Brook Trout to Foster Persistence of Sympatric Native Cutthroat Trout in Small Streams. North Am. J. Fish. Manag. **28**(6): 1847–1867. doi:10.1577/M07-174.1.

Pilgrim, N.L. 2012. Multigenerational effects of selenium in rainbow trout, brook trout, and cutthroat trout. Thesis, Lethbridge, Alta. : University of Lethbridge, Dept. of Biological Sciences, c2012. Available from https://opus.uleth.ca/handle/10133/3299 [accessed 9 December 2020].

Plummer, M. 2015, October 1. JAGS version 4.0.1 user manual. Available from http://sourceforge.net/projects/mcmc-jags/files/Manuals/4.x/jags_user_manual.pdf.

Pulkkinen, H., Mäntyniemi, S., and Chen, Y. 2013. Maximum survival of eggs as the key parameter of stock–recruit meta-analysis: accounting for parameter and structural uncertainty. Can. J. Fish. Aquat. Sci. **70**(4): 527–533. doi:10.1139/cjfas-2012-0268.

R Core Team. 2019. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. Available from https://www.R-project.org/.

Reimers, N. 1963. Body Condition, Water Temperature, and Over-winter Survival of Hatchery-reared Trout in Convict Creek, California. Trans. Am. Fish. Soc. **92**(1): 39–46. Taylor & Francis. doi:10.1577/1548-8659(1963)92[39:BCWTAO]2.0.CO;2.

Rose, K., Cowan, J., Winemiller, K., Myers, R., and Hilborn, R. 2001. Compensatory density dependence in fish populations: Importance, controversy, understanding and prognosis. Fish Fish. **2**: 293–327. doi:10.1046/j.1467-2960.2001.00056.x.

Rubidge, E.M., and Taylor, E.B. 2005. An analysis of spatial and environmental factors influencing hybridization between native westslope cutthroat trout (Oncorhynchus clarki lewisi) and introduced rainbow trout (O. mykiss) in the upper Kootenay River drainage, British Columbia. Conserv. Genet. **6**(3): 369–384. doi:10.1007/s10592-005-4972-4.

Shepherd, J.G., and Cushing, D.H. 1980. A mechanism for density-dependent survival of larval fish as the basis of a stock-recruitment relationship. ICES J. Mar. Sci. **39**(2): 160–167. doi:10.1093/icesjms/39.2.160.

Thurow, R., Peterson, J., and Guzevich, J. 2006. Utility and Validation of Day and Night Snorkel Counts for Estimating Bull Trout Abundance in First to Third-Order Streams. North Am. J. Fish. Manag. - NORTH AM J FISH MANAGE **26**: 217–232. doi:10.1577/M05-054.1.

Wickham, H. 2014. Tidy Data. J. Stat. Softw. **59**(10): 1–22.

Wyatt, R.J. 2002. Estimating riverine fish population size from single- and multiple-pass removal sampling using a hierarchical model. Can. J. Fish. Aquat. Sci. **59**(4): 695–706. doi:10.1139/f02-041.

Yant, P.R., Karr, J.R., and Angermeier, P.L. 1984. Stochasticity in Stream Fish Communities: An Alternative Interpretation. Am. Nat. **124**(4): 573–582. [University of Chicago Press, American Society of Naturalists].