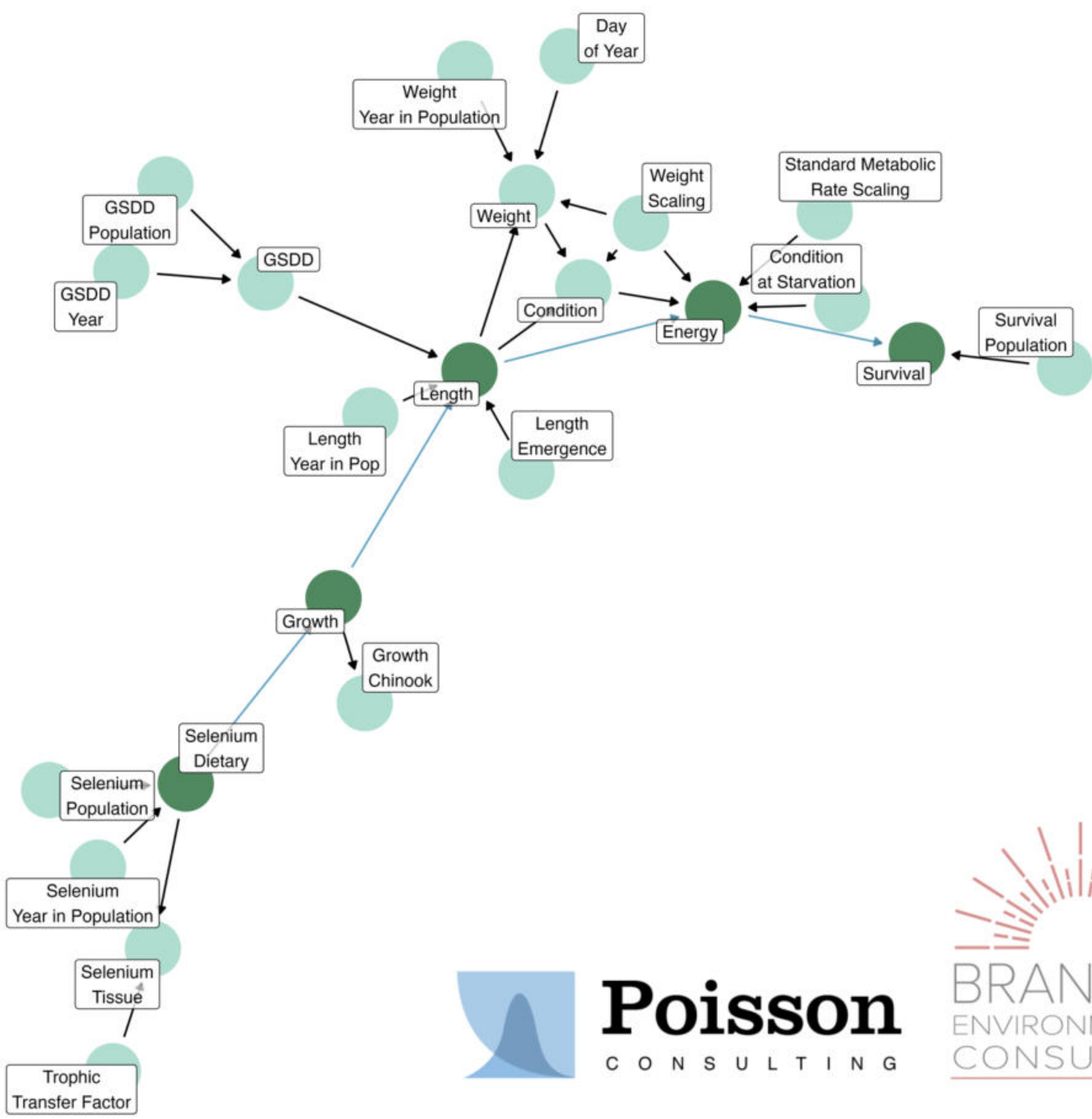
Subject Matter Expert Report: Energetic Status at the Onset of Winter Based on Fork Length and Wet Weight – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population

February 2023

Prepared for: Teck Coal Ltd., Sparwood, BC

Prepared by: Thorley, J.L.[1] & Branton, M.A.[2]

1. Poisson Consulting, Nelson, BC
2. Branton Environmental Consulting, Vancouver, BC



Poisson CONSULTING

BRANTON ENVIRONMENTAL CONSULTING

Published by Poisson Consulting Ltd., 4216 Shasheen Road, Nelson, BC V1L 6X1

For inquiries contact: reports@poissonconsulting.ca

Suggested Citation: Thorley, J.L. & Branton, M.A. (2022) *Subject Matter Expert Report: Energetic Status at the Onset of Winter Based on Fork Length and Wet Weight*. *Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population*. Report prepared for Teck Coal Limited. Prepared by Poisson Consulting Ltd and Branton Environmental Consulting.

Primary Author
Joseph L. Thorley, Ph.D., R.P.Bio.
Senior Computational Biologist

Primary Author
Maggie A. Branton, Ph.D. P.Ag.
Senior Environmental Scientist

EXECUTIVE SUMMARY

An analysis of population monitoring data collected from 2017 to 2019 in the Harmer Creek population area indicated that the abundance of juvenile Westslope Cutthroat Trout was very low and appeared to be due to recruitment failure. Teck Coal Limited assembled a team of Subject Matter Experts (SMEs) and initiated an Evaluation of Cause to evaluate and report on what may have contributed to the very low recruitment.

A strong negative relationship between the size of young of year trout and overwintering survival is well documented in the literature and likely reflects the fact that size is a key indicator of energetic status. More specifically, length indicates the efficiency of energy use while body condition is an indicator of lipid storage. Although fish can feed in winter, they must store most of the energy they require throughout the winter during the short growing season.

Several stressors that could affect the growth of fish were evaluated in SME reports and include low growing season degree days (GSDD), exposure to dietary selenium, food availability and energy use. While the scope of the SME reports was to consider each of these potential stressors individually, our analysis considers the energetic status of fish, as inferred from fish size, which allows the relative contributions of some of the various energy related stressors to changes in recruitment to be estimated.

We used a hierarchical Bayesian Integrated Network (hBIN) model to quantify the effect of energetic status on the egg to age-1 survival for the Harmer Creek and Grave Creek populations. The ratio between energy stores at the onset of winter and energy requirements was calculated as energetic status for this report. Energetic status was calculated based on length, body condition and the scaling of standard metabolic rate to the size observed in salmonids. This was used to estimate the relative contributions of GSSD, dietary selenium, fork length, body condition and energetic status to the observed recruitment patterns. The hBIN model makes multiple key assumptions including that 1) dietary selenium has the same effect on the length of age-0 Westslope Cutthroat Trout as has been observed in a study on age-0 Chinook Salmon, 2) the effect of selenium on length occurs solely via the dietary pathway and 3) selenium only affects energetic status via fish length. In addition, the model does not include other stressors which may explain some of the remaining variation in the egg to age-1 survival or interact with the effect of energetic status as their effect on any of the variables in the model could not be quantified.

The results indicate that energetic status is an important predictor of the egg to age-1 survival. More specifically the results suggest that energetic status explains 65% (29-85% 95% CI) of the difference in recruitment between the Harmer Creek and Grave Creek populations (Reduced Recruitment) and 90% (76-96% 95% CI) of the difference between Harmer Creek in 2018 compared to 2017 and 2019 (Recruitment Failure). The results also suggest that GSDD and dietary selenium explain 34% (4-58% 95% CI) and 8% (3-16% 95% CI) of the Reduced Recruitment, respectively. Growing season degree days and dietary selenium were similar in 2018 compared to 2017 and 2019 therefore did not explain the Recruitment Failure that occurred over and above the observed Reduced Recruitment.

ACKNOWLEDGEMENTS

The organizations and individuals whose contributions have made this analysis report possible include Carla Fraser, Bronwen Lewis, Marko Adzic, Mike Moore and Dayna Meredith of Teck Coal Limited; Ryan Hill, Beth Power, Sarah Gutzman and Brian Pyper of Azimuth Consulting Group Inc.; Matt Neufeld and Josef MacLeod of BC Ministry of Forests, Lands and Natural Resource Operations; Kamila Baranowska of Ktunaxa Nation Council; Bruce Kilgour of Kilgour and Associates; Mike Robinson and Jill Brooks of Lotic Environmental Ltd.; Todd Hatfield, Morgan Hocking, Joao Braga and Jason Ammerlaan of Ecofish Research Ltd.; Adrian de Bruyn of ADEPT Environmental Sciences Ltd., Sam Luoma of University of California, Davis; Trent Bollinger of TKB Ecosystem Health Services Ltd.; Kara Warner of Golder Associates Ltd. and Amy Wiebe, Jen Ings and Jeff Row of Minnow Environmental Consulting among others.

TABLE OF CONTENTS

LIST OF FIGURES

List of Tables

List of Equations

ACRONYMS

Acronym	
CI	Compatibility Intervals
FL	Fork Length
GLM	Generalized Linear Model
GSDD	Growing Season Degree Days
hBIN	Hierarchical Bayesian Integrated Network
MCMC	Monte Carlo Markov Chain
RB	Rainbow Trout
SMR	Standard Metabolic Rate
SD	Standard Deviation
TL	Total Length
TSS	Total Suspended Solids
TTF	Trophic Transfer Factor
WCT	Westslope Cutthroat Trout

READER'S NOTE

Background

The Elk Valley (Qukin ʔamaʔkis) is located in the southeast corner of British Columbia (BC), Canada. “Ktunaxa people have occupied Qukin ʔamaʔkis for over 10,000 years. . . . The value and significance of ʔa·kxamis ʼqapi qapsin (All Living Things) to the Ktunaxa Nation and in Qukin ʔamaʔkis must not be understated” (text provided by the Ktunaxa Nation Council [KNC]).

The Elk Valley contains the main stem of the Elk River, and one of the tributaries to the Elk River is Grave Creek. Grave Creek has tributaries of its own, including Harmer Creek. Harmer and Grave Creeks are upstream of a waterfall on Grave Creek, and they are home to isolated, genetically pure Westslope Cutthroat Trout (WCT; *Oncorhynchus clarkii lewisi*). This fish species is iconic, highly valued in the area and of special concern under federal and provincial legislation and policy.

In the Grave Creek watershed[1], the disturbance from logging, roads and other development is limited. The mine property belonging to Teck Coal Limited’s Elkview Operations includes an area in the southwest of the Harmer Creek subwatershed. These operations influence Harmer Creek through its tributary Dry Creek, and they influence Grave Creek below its confluence with Harmer Creek (Harmer Creek Evaluation of Cause, 2022)[2]. Westslope Cutthroat Trout populations in both Harmer and Grave Creeks are part of Teck Coal’s monitoring program.

The Evaluation of Cause Process

The Process Was Initiated

Teck Coal undertakes aquatic monitoring programs in the Elk Valley, including fish population monitoring. Using data collected as part of Teck Coal’s monitoring program, Cope & Cope (2020) reported low abundance of juvenile WCT in 2019, which appeared to be due to recruitment failure in Harmer Creek.

[1] Including Grave and Harmer Creeks and their tributaries.

[2] Harmer Creek Evaluation of Cause Team. (2022*). Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited.

Teck Coal initiated an Evaluation of Cause — a process to evaluate and report on what may have contributed to the apparent recruitment failure. Data were analyzed from annual monitoring programs in the Harmer and Grave Creek population areas[3] from 2017 to 2021 (Thorley et al. 2022; Chapter 4, Evaluation of Cause), and several patterns related to recruitment[4] were identified:

- *Reduced Recruitment*[5] occurred during the 2017, 2018 and 2019 spawn years[6] in the Harmer Creek population and in the 2018 spawn year in the Grave Creek population.
- The magnitude of Reduced Recruitment in the Harmer Creek population in the 2018 spawn year was significant enough to constitute *Recruitment Failure*[7].
- Recruitment was *Above Replacement*[8] for the 2020 spawn year in both the Harmer and Grave Creek populations.

The recruitment patterns from 2017, 2018 and 2019 in Harmer Creek are collectively referred to as Reduced Recruitment in this report. To the extent that there are specific nuances within 2017-2019 recruitment patterns that correlate with individual years, such as the 2018 Recruitment Failure, these are referenced as appropriate.

How the Evaluation of Cause Was Approached

When the Evaluation of Cause was initiated, an *Evaluation of Cause Team* (the Team) was established. It was composed of *Subject Matter Experts* (SMEs) who evaluated stressors with the potential to impact the WCT population. Further details about the Team are provided in the Evaluation of Cause report (Harmer Creek Evaluation of Cause Team, 2022).

During the Evaluation of Cause process, the Team had regularly scheduled meetings with representatives of the KNC and various agencies (the participants). These meetings included discussions about the overarching question that would be evaluated and about technical issues, such as identifying potential

[3] Grave Creek population area" includes Grave Creek upstream of the waterfall at river kilometer (rkm) 2.1 and Harmer Creek below Harmer Sedimentation Pond. "Harmer Creek population area" includes Harmer Creek and its tributaries (including Dry Creek) from Harmer Sedimentation Pond and upstream.

[4] Recruitment refers to the addition of new individuals to a population through reproduction.

[5] For the purposes of the Evaluation of Cause, Reduced Recruitment is defined as a probability of > 50% that annual recruitment is <100% of that required for population replacement (See Chapter 4, Evaluation of Cause, Harmer Creek Evaluation of Cause Team 2022).

[6] The spawn year is the year a fish egg was deposited, and fry emerged.

[7] For the purposes of the Evaluation of Cause, Recruitment Failure is defined as a probability of > 50% that annual recruitment is <10% of that required for population replacement (See Chapter 4, Evaluation of Cause, Harmer Creek Evaluation of Cause Team 2022).

[8] For the purposes of the Evaluation of Cause, Above Replacement is defined as a probability of > 50% that annual recruitment is >100% of that required for population replacement (See Chapter 4, Evaluation of Cause, Harmer Creek Evaluation of Cause Team 2022).

stressors, natural and anthropogenic, which had the potential to impact recruitment in the Harmer Creek WCT population. This was an iterative process driven largely by the Team's evolving understanding of key parameters of the WCT population, such as abundance, density, size, condition and patterns of recruitment over time. Once the approach was finalized and the data were compiled, SMEs presented methods and draft results for informal input from participants. Subject Matter Experts then revised their work to address feedback and, subsequently, participants reviewed and commented on the reports. Finally, results of the analysis of the population monitoring data and potential stressor assessments were integrated to determine the relative contribution of each potential stressor to the Reduced Recruitment in the Harmer Creek population.

The Overarching Question the Team Investigated

The Team investigated the overarching question identified for the Evaluation of Cause, which was:

> **What potential stressors can explain changes in the Harmer Creek Westslope Cutthroat Trout population over time, specifically with respect to Reduced Recruitment?**

The Team developed a systematic and objective approach to investigate the potential stressors that could have contributed to the Reduced Recruitment in the Harmer Creek population. This approach is illustrated in the figure that follows the list of deliverables, below. The approach included evaluating patterns and trends, over time, in data from fish monitoring and potential stressors within the Harmer Creek population area and comparing them with patterns and trends in the nearby Grave Creek population area, which was used as a reference. The SMEs used currently available data to investigate causal effect pathways for the stressors and to determine if the stressors were present at a magnitude and for a duration sufficient to have adversely impacted the WCT. The results of this investigation are provided in two types of deliverables:

1. Individual Subject Matter Expert reports (such as the one that follows this Note). Potential stressors were evaluated by SMEs and their co-authors using the available data. These evaluations were documented in a series of reports that describe spatial and temporal patterns associated with the potential stressors, and they focus on the period of Reduced Recruitment, including the Recruitment Failure of the 2018 spawn year where appropriate. The reports describe if and to what extent potential stressors may explain the Reduced Recruitment.

   The full list of Subject Matter Expert reports follows at the end of this Reader's Note.

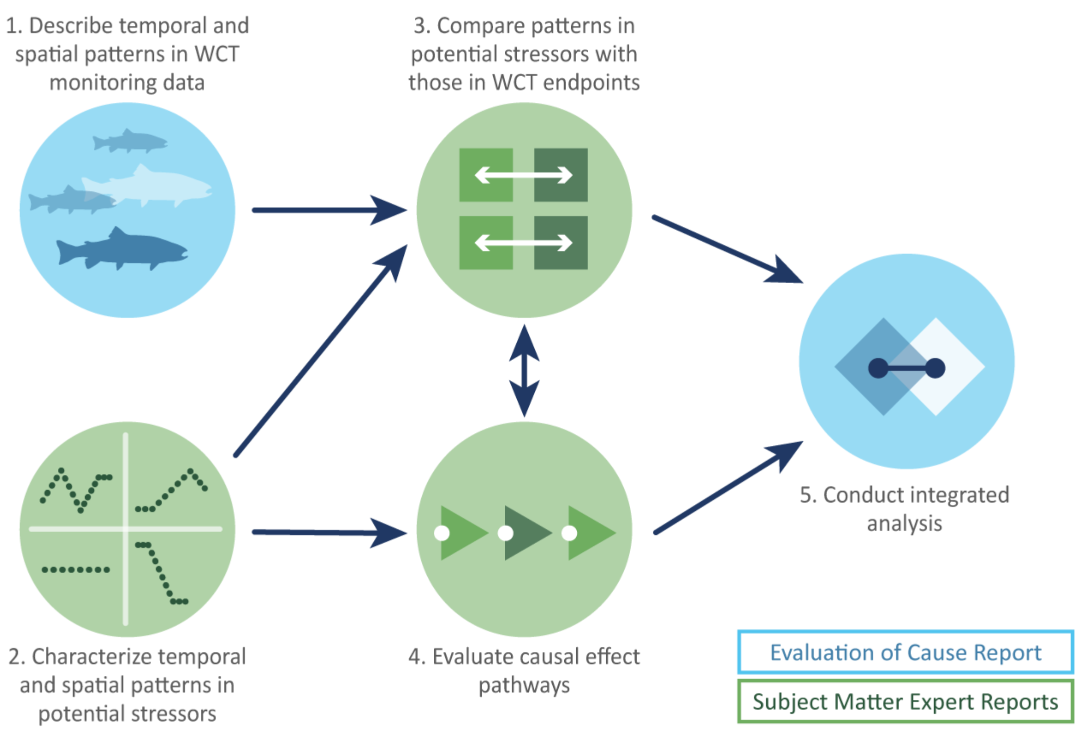
2. The Evaluation of Cause report. The SME reports provided the foundation for the Evaluation of Cause report, which was prepared by a subset of the Team and included input from SMEs.

The Evaluation of Cause report:

a. Provides readers with context for the SME reports and describes Harmer and Grave Creeks, the Grave Creek watershed, the history of development in the area and the natural history of WCT in these creeks

b. Presents fish monitoring data, which characterize the Harmer Creek and Grave Creek populations over time

c. Uses an integrated approach to assess the role of each potential stressor in contributing to Reduced Recruitment in the Harmer Creek population area.



Conceptual approach to the Evaluation of Cause for the Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout population.

Participation, Engagement & Transparency

To support transparency, the Team engaged frequently with participants throughout the Evaluation of Cause process. Participants in the Evaluation of Cause process, through various committees, included:

- Ktunaxa Nation Council

- BC Ministry of Forests,
- BC Ministry of Land, Water and Resource Stewardship
- BC Ministry Environment & Climate Change Strategy
- Ministry of Energy, Mines and Low Carbon Innovation
- Environmental Assessment Office

Citations for Evaluation of Cause Team Reports

Focus	Citation
Harmer Creek Evaluation of Cause report	Harmer Creek Evaluation of Cause Team. (2022). *Evaluation of Cause - Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited.
Calcite	Hocking, M. A., Cloutier, R. N., Braga, J., & Hatfield, T. (2022). *Subject Matter Expert Report: Calcite. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by Ecofish Research Ltd.
Dissolved oxygen	Abell, J., Yu, X., Braga, J., & Hatfield, T. (2022). *Subject Matter Expert Report: Dissolved Oxygen. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by Ecofish Research Ltd.
Energetic Status	Thorley, J.L. & Branton, M.A. (2022) *Subject Matter Expert Report: Energetic Status at the Onset of Winter Based on Fork Length and Wet Weight. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population*. Report prepared for Teck Coal Limited. Prepared by Poisson Consulting Ltd and Branton Environmental Consulting.

Focus	Citation
Food availability	Wiebe, A., Orr, P., & Ings, J. (2022). *Subject Matter Expert Report: Food Availability. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by Minnow Environmental Inc.
Groundwater	Canham, E., & Humphries, S. (2022). *Evaluation of Groundwater as a Potential Stressor to Westslope Cutthroat Trout in the Harmer and Grave Creek Watersheds.* Memo prepared for Teck Coal Limited. Prepared by SNC-Lavalin Inc.
Habitat availability (instream flow)	Wright, N., Little, P., & Hatfield, T. (2022). *Subject Matter Expert Report: Streamflow and Inferred Habitat Availability. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by Ecofish Research Ltd.
Sediment quality	Wiebe, A., Orr, P., & Ings, J. (2022). Subject Matter Expert Report: Sediment Quality. *Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population*. Report prepared for Teck Coal Limited. Prepared by Minnow Environmental Inc.
Selenium	de Bruyn, A., Bollinger, T., & Luoma, S. (2022). *Subject Matter Expert Report: Selenium. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by ADEPT Environmental Sciences Ltd, TKB Ecosystem Health Services, and SNL PhD, LLC.
Small population size	Thorley, J. L., Hussein, N., Amish, S. J. (2022). *Subject Matter Expert Report: Small Population Size. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by Poisson Consulting and Conservation Genomics Consulting, LLC.
Telemetry analysis	Akaoka, K., & Hatfield, T. (2022). *Harmer and Grave Creeks Telemetry Movement Analysis.* Memo prepared for Teck Coal Limited. Prepared by Ecofish Research Ltd.

Focus	Citation
Total suspended solids	Durston, D., & Hatfield, T. (2022). *Subject Matter Expert Report: Total Suspended Solids. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by Ecofish Research Ltd.
Water quality	Warner, K., & Lancaster, S. (2022). *Subject Matter Expert Report: Surface Water Quality. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by WSP-Golder.
Water temperature and ice	Hocking, M., Whelan, C. & Hatfield, T. (2022). *Subject Matter Expert Report: Water Temperature and Ice. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by Ecofish Research Ltd.

1. INTRODUCTION

1.1. OVERALL BACKGROUND

Teck Coal Limited (Teck Coal) undertakes aquatic monitoring programs in the Elk Valley, including fish population monitoring. Using data collected from 2017 to 2019 in Harmer and Grave Creeks, Cope & Cope (2020) reported low abundance of juvenile Westslope Cutthroat Trout (WCT; *Oncorhynchus clarkii lewisi*), which was suggestive of recruitment failure in Harmer Creek. Teck Coal initiated an Evaluation of Cause — a process to evaluate and report on what may have contributed to the apparent recruitment failure. Data were analyzed from annual monitoring programs in the Harmer and Grave Creek population areas[9] from 2017 to 2021 (Thorley et al. 2022; Chapter 4, Evaluation of Cause), and several patterns related to recruitment[10] were identified:

- *Reduced Recruitment*[11] occurred during the 2017, 2018 and 2019 spawn years in the Harmer Creek population and in the 2018 spawn year in the Grave Creek population.
- The magnitude of Reduced Recruitment in the Harmer Creek population in the 2018 spawn year[12] was significant enough to constitute *Recruitment Failure*[13].
- Recruitment was *Above Replacement*[14] for the 2020 spawn year in both the Harmer and Grave Creek populations.

The recruitment patterns for the 2017, 2018 and 2019 spawn years in Harmer Creek are collectively referred to as Reduced Recruitment in this report. To the extent that there are specific nuances within 2017-2019 recruitment patterns that correlate with individual years, such as the 2018 Recruitment Failure, these are referenced as appropriate.

The Evaluation of Cause Project Team investigated one overarching question: **What potential stressors can explain changes in the Harmer Creek Westslope Cutthroat Trout population over time, specifically with respect to patterns of Reduced Recruitment?** To investigate this question, the Team evaluated trends in WCT population parameters, including size, condition, and recruitment, and in the potential stressors that could impact these parameters. They evaluated the trends in WCT population parameters based on monitoring data collected from 2017 to 2021 (reported in Thorley et al., 2022 and Chapter 4, Harmer Creek Evaluation of Cause Team, 2022). The Grave Creek population area was used as a reference area for this evaluation.

---

[9] "Grave Creek population area" includes Grave Creek upstream of the waterfall and Harmer Creek below Harmer Sedimentation Pond. "Harmer Creek population area" includes Harmer Creek and its tributaries (including Dry Creek) from Harmer Sedimentation Pond and upstream.

[10] Recruitment refers to the addition of new individuals to a population through reproduction.

[11] For the purposes of the Evaluation of Cause, Reduced Recruitment is defined as a probability of > 50% that annual recruitment was < 100% of that required for population replacement (See Chapter 4, Evaluation of Cause, Harmer Creek Evaluation of Cause Team, 2022).

[12] The spawn year is the year a fish egg was deposited, and fry emerged.

[13] For the purposes of the Evaluation of Cause, Recruitment Failure is defined as a probability of > 50% that annual recruitment is < 10% of that required for population replacement (See Chapter 4 Evaluation of Cause, Harmer Creek Evaluation of Cause Team, 2022).

[14] For the purposes of the Evaluation of Cause, recruitment Above Replacement is defined as a probability of > 50% that annual recruitment is > 100% of that required for population replacement (See Chapter 4 Evaluation of Cause, Harmer Creek Evaluation of Cause Team, 2022)

The approach for analyzing potential stressors for the Evaluation of Cause was to: (1) characterize trends in each stressor for the Harmer and Grave Creek populations, (2) compare the trends between the two population areas, (3) identify any changes in Harmer Creek during the period of Reduced Recruitment, including the Recruitment Failure of the 2018 spawn year where appropriate, and (4) evaluate how each stressor trended relative to the fish population parameters. The Team then identified mechanisms by which the potential stressors could impact WCT and determined if the stressors were present at a sufficient magnitude and duration to have an adverse effect on WCT during the period of Reduced Recruitment. Together, these analyses were used in the Evaluation of Cause report to support conclusions about the relative contribution of each potential stressor to the Reduced Recruitment observed in the Harmer Creek population area.

1.2. REPORT SPECIFIC BACKGROUND

This Subject Matter Expert (SME) report evaluating the Energetic Status of age-0 WCT was developed late in the Harmer Creek Evaluation of Cause process to address what was identified as an important causal effect pathway. The analysis of fish population monitoring data suggested that the recruitment patterns for the 2017 to 2019 spawn years were primarily caused by low survival of fish in their first winter, due to their small size at the onset of winter (Chapter 4, Harmer Creek Evaluation of Cause Team, 2022). Several stressors were evaluated that could affect the growth of fish [i.e., low growing season degree days (Hocking et al 2022) dietary selenium (de Bruyn et al 2022), food availability (Wiebe & Orr 2022) or energy use (e.g., Hocking et al 2022)]. The scope of the other SME reports was to consider each of these potential stressors individually. This report considers the energetic status of fish, as inferred from fish size. This approach allows the relative contribution of the energy related stressors, for which sufficient data is available, to changes in recruitment to be estimated. In the case of Dry Creek, the contribution of the maternal transfer of selenium acting directly on the egg to age-1 survival is also estimated (see Attachment A).

There were two primary objectives addressed by this SME report. The first objective was to evaluate the relationship between energetic status and egg to age-1 survival. The second objective was to estimate the contributions of the stressors for which sufficient data were available, in this case growing season degree days (GSDD) and dietary selenium, to the observed Reduced Recruitment and Recruitment Failure patterns through energetic status[15]. Energetic status, which is defined in this report as the ratio of the relative energy stores at the onset of winter to the energy requirements during winter, is important because it determines whether individuals have sufficient energy reserves to survive the winter. The energetic status of a cohort of age-0 salmonids at the start of winter is perhaps the most important predictor of recruitment success in systems with a short growing season (Coleman and Fausch 2007a). While stressors other than GSDD and selenium have the potential to affect a fish’s energy budget, a lack of data or information on the other stressors’ causal influence on any of the terms in the model prevented their inclusion in the analysis. Examples of other stressors that may influence energy stores or requirements include food availability, predation pressure and winter conditions.

[15] In this report the term Reduced Recruitment is used to refer to the difference in the estimated egg to age-1 survival in the Harmer Creek population relative to the Grave Creek population from 2017 to 2019 while the term Recruitment Failure refers to the difference in the estimated egg to age-1 survival in 2018 relative to 2017 and 2019 for the Harmer Creek population.

1.3. REVIEW OF RELEVANT WESTSLOPE CUTTHROAT TROUT BIOLOGY

There are conditions in the Harmer Creek population area that make it challenging for age-0 fish to attain the energetic status they need to survive winter. This section provides a review of key aspects of WCT biology needed to understand this relationship.

Spawning typically commences in both the Harmer Creek and Grave Creek populations by May 25, peaks around June 15 and continues to about July 15, although in colder years it may be delayed (Chapter 3, Harmer Creek Evaluation of Cause Team, 2022; Thorley et al 2022b). Based on the spawning and temperature data collected by Cope and Cope (2020) and detailed by Hocking et al (2022), it is estimated that in a typical year fry emergence would begin in the warmest section of Grave Creek below the confluence with Harmer Creek around the end of July but may not peak until late August in the mainstem of Harmer Creek. This leaves the newly emergent fry with a short window of time to accumulate enough energy prior to the onset of winter in early October.

The age-0 WCT emerge from the gravels with a fork length of approximately 20 mm (Coleman and Fausch 2007a) and begin primarily feeding on benthic invertebrates (Wiebe et al. 2022). Initially the young of year put their energy into growing longer (Biro et al. 2005) but as winter approaches they increase their lipid (fat) content (Giacomini and Shuter 2013; Biro et al. 2021). The pressure to accumulate energy to survive the winter is so strong that smaller young-of-year fish will risk being eaten by predators to get the food they need (Biro et al. 2005; Finstad et al. 2010). In fact, the resultant increase in predation associated with local reductions in food availability due to competition between individuals is considered to be one of the primary factors limiting the abundance of trout populations (van Poorten et al. 2018). Cannibalism by age-2 and older conspecifics may represent the most important predation pressure (Rosenfeld 2014). The young fish continue to grow until the mean daily water temperature drops below about 4 °C (Coleman and Fausch 2007b) which, in the Harmer system is typically the beginning of October.

Overwintering in cold high elevation and/or high latitude streams is energetically demanding (Huusko et al. 2007). Initially, the fry must expend a disproportionate amount of energy acclimatizing to the drop in water temperature (Cunjak et al. 1987). This transition is so physiologically taxing that a spike in mortality has been observed at the start of winter (Cunjak et al. 1987; Coleman and Fausch 2007b). Then the fry must survive four to six months until the mean daily water temperature rises above 5 °C (Coleman and Fausch 2007a). During this time a reduced gastric evacuation rate (Elliott 1972; Cunjak et al. 1987; Khan 2022) means that ingestion of benthic invertebrates provides insufficient energy to meet metabolic requirements (Cunjak and Power 1987). To prolong their energy reserves overwintering fish reduce their metabolic costs by minimizing movement (Speers-Roesch et al. 2018). In this context changes in flow and/or anchor/frazil ice that induce a fish to relocate require a relatively high energetic cost. It should, however, be noted that under surface ice fish are reported to lose less energy. This is because conditions tend to be more hydraulically and thermally stable which results in a lower metabolic expenditure (Hansen and Rahel 2015). Fish may also consume more food (Finstad et al. 2004) which is associated with a reduction in the predation risk from the reduced light levels (Metcalfe et al. 1999; Finstad 2004). For further discussion of ice and water temperature in the context of the Harmer Creek WCT population see Hocking et al. (2022).

The length of age-0 trout at the end of the fall strongly influences the probability of surviving through the winter (Huusko et al. 2007). For example, based on laboratory (Coleman and Fausch 2007b) and field studies Coleman and Fausch (2007a) concluded that the "data suggest that cutthroat trout fry need to reach a minimum of 30 - 35 mm TL [28 – 33 mm FL] by the onset of winter to allow recruitment to age 1 in temperature regimes like those of the streams we studied in the southern Rocky Mountains." They were able to predict fish length from the number of degree days available for egg incubation and fish growth which they quantified in terms of the GSDD. Coleman and Fausch (2007a) defined the start of the growing season as the beginning of the first week that average stream temperatures exceeded and remained above 5°C; and the end as the last day of the first week that average stream temperature dropped below 4°C. A key conclusion of Coleman and Fausch (2007a) was that the three subspecies[16] of Cutthroat Trout native to Colorado streams have a high probability of recruitment failure in streams with less than 800 GSDDs but may have adequate recruitment in some years in streams reaching about 800–900 degree days. Coleman and Fausch (2007a) considered 900 to 1,200 degree days to be optimal for recruitment for Cutthroat Trout native to Colorado in the southern Rocky Mountains. From 2017 to 2019, the average GSDD in Harmer Creek was 780 degree days below the confluence with Dry Creek, 910 GSDD above the Harmer Creek Sedimentation Pond at the lower limit of the Harmer Creek population and 1,080 below the Harmer Creek Sedimentation Pond where the Grave Creek population extends into Harmer Creek (Hocking et al. 2022).

The lipid content of age-0 trout is also a key predictor of overwintering survival (Biro et al. 2004, 2021; Berg et al. 2011). The body condition of a fish, which is its wet weight (mass) relative to its length (He et al. 2008), provides an index of how "fat" a fish is. Cunjak and Power (1987) reported an ~25% decline in body condition between late summer and early winter for trout in a temperate Canadian stream which persisted until the spring that the authors attributed to the energetic demands of acclimatization. Simpkins et al. (2003) reported that both lipid content and body condition declined linearly during fasting (the latter by ~20% over three months) and Alverez and Nicieza (2005) demonstrated that brown trout compensate for food restriction by rapidly gaining body condition (not length) and this gain reflects an increase in lipid content. More recently, Wilson et al. (2021), found that condition factor, rather than energetic variables, was the best predictor of swim performance in juvenile sockeye salmon (*Oncorhynchus nerka*) during food deprivation.

Selenium exposure is concerning from an energetic perspective because in parts of the Grave Creek population area it is at levels that can reduce the growth of salmonid fry (de Bruyn et al. 2022). An experiment has demonstrated that even moderate levels of selenium in food (~11 mg/kg dw) can reduce the growth of Chinook salmon (*Oncorhynchus tshawytscha*) fry by ~10% (DeForest et al 1999; Hamilton et al, 1990). As discussed by de Bruyn et al. (2022) and conceptually detailed by Hocking et al. (2022) a relatively small change in length could have a disproportionate effect on recruitment if a relatively high proportion of the population are close to an energetic threshold required to survive the winter. As discussed above, age-0 fish in the Harmer Creek population area are relatively small due to the short growing season and cold water temperatures in the Harmer Creek population area. Selenium also reduces the lipids (triglycerides) in the liver (Knight et al. 2016) – an important energy store. The fact that disruption of lipid metabolism is part of selenium's adverse outcome pathway (Ankley et al. 2010) raises the possibility that there may be additional energetic costs of dietary exposure beyond those captured by the reduction in length. For further information on possible pathways of action of selenium on the Harmer Creek population see de Bruyn et al. (2022).

[16] In addition to Colorado Cutthroat Trout (*Oncorhynchus clarkii pleuriticus*), Greenback (*Oncorhynchus clarkii virginalis*) and Rio Grande Cutthroat Trout (*Oncorhynchus clarkia stomias*) are also native to Colorado.

2. METHODS

2.1. STUDY AREA

The study area, which is mapped in Figure 1, is described in Chapter 2 and the Grave Creek and Harmer Creek fish populations in Chapters 3 and 4 in the Evaluation of Cause Report (Harmer Creek Evaluation of Cause Team 2022). For the purposes of this report it is important to be aware that: 1) almost all spawning and subsequent age-0 growth occurs in Harmer Creek downstream of the confluence with Dry Creek; 2) selenium undergoes speciation and is converted into a bioavailable form – primarily in the Dry Creek and Harmer Creek Sedimentation Ponds – resulting in increased downstream dietary selenium concentrations (de Bruyn et al. 2022); and 3) based on lineal distance, approximately 6% (Table 1) of the age-0 fish belonging to the Grave Creek population inhabit Harmer Creek below the Harmer Creek Sedimentation Pond (HRM-R1) where, like the age-0 Harmer Creek population fish, they are exposed to elevated dietary selenium levels. For additional information on the study area and fish populations see Cope and Cope (2020) and Thorley et al. (2022b).

Table 1. The lineal fish habitat by population, creek and reach.

Population	Creek	Reach	Length (km)
Grave	Grave Creek	GRV-R2	2.3
Grave	Grave Creek	GRV-R3	4.8
Grave	Grave Creek	GRV-R4	3.8
Grave	Harmer Creek	HRM-R1	0.5
Harmer	Harmer Creek	HRM-R2	0.3
Harmer	Harmer Creek	HRM-R3	2.6
Harmer	Harmer Creek	HRM-R4	2.1
Harmer	Harmer Creek	HRM-R5	0.8

2.2. DATA COLLECTION

The data used in these analyses were collected as part of Teck Coal's aquatic monitoring program. A data summary and description of methods used is provided in those reports (Golder 2022; Hocking et al. 2022; Thorley et al. 2022b; Brooks and Robinson 2022).

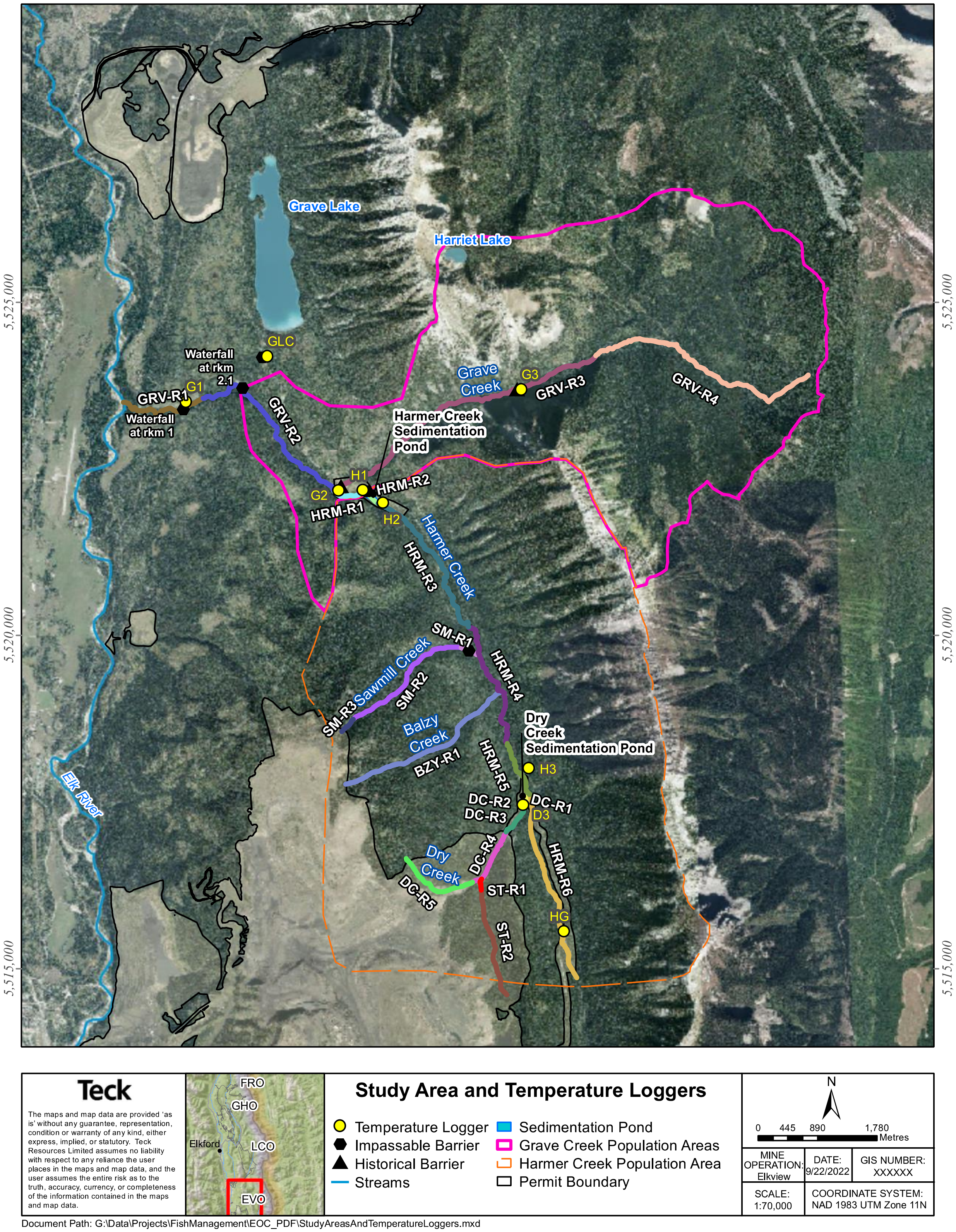


Figure 1. A map of the Grave-Harmer Watershed indicating reaches, barriers and water temperatures loggers.

2.2.1. Fork Lengths

Following Thorley (2022b), fish < 50 mm FL in the Grave Creek population and < 45 mm FL in the Harmer Creek population were considered to be age-0 based on length-frequency distributions. Age-0 fish were incidentally captured[17] while backpack electrofishing for age-1 and older fish in all years except 2020 for the Grave Creek population and except 2019 and 2020 for the Harmer Creek population (Thorley et al. 2022b). The fork lengths of all fish were recorded to the nearest 1 mm. In 2021 bank walks were also conducted in early October resulting in the capture by dip-netting of age-0 fish (Thorley et al. 2022b). Forks lengths were once again measured to ± 1 mm. The individual fish lengths for the Harmer Creek population (HRM-R3-R5) and the Grave Creek population below the Harmer Creek Sedimentation Pond (HRM-R1) were input into the integrated model to provide information on the length of age-0 fish at the onset of winter[18] (Figure).

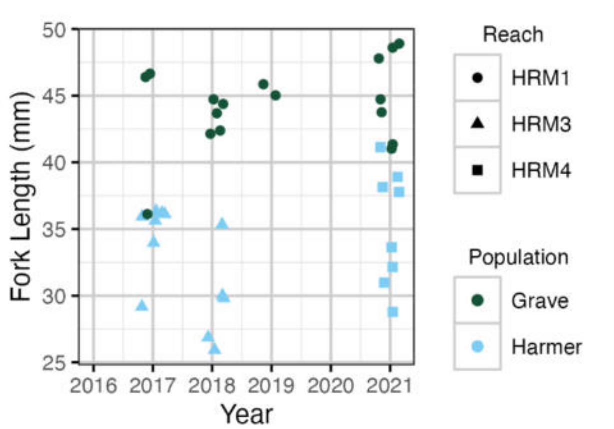


Figure 2. The individual age-0 fish length data by year, population and reach from Thorley et al. (2022b).

2.2.2. Wet Weights

Wet weight (mass) was recorded to the nearest ± 0.1 g for age-0, and older, fish. However, these data were not considered to be accurate for age-0 fish due to the measurement error (± 0.1 g) associated with weighing a very small wetted fish in the field relative to its actual body weight (Thorley et al. 2022b).

2.2.3. Body Condition

Body condition is calculated as weight relative to length. Because weight data were not reliable for age-0 fish (see above), we were not able to calculate body condition directly for age-0 fish. Instead, the body condition of juvenile fish (i.e., 65 to 169 mm) captured by backpack electrofishing were used to estimate the body condition of age-0s (Figure 3).

---

[17] The backpack electrofishing did not target age-0 fish because due to their small size, delayed emergence and patchy distribution it is not possible to produce a reliable abundance estimate (Thorley et al. 2022b).

[18] All of the measured lengths of the fish from the Grave Creek population are above the threshold of 28-33 mm FL suggested by Coleman and Fausch (2007) for Cutthroat Trout native to Colorado in the southern Rocky Mountains. However, rather than simply assume that a length threshold of the same magnitude applies to Westslope Cutthroat Trout in the Grave-Harmer watershed, the relationship between length and body condition was estimated based on the available data. As discussed below a correction factor of 0.8 was also applied to the estimated fork lengths for the Grave population to account for the fact that HRM-R1 was substantially warmer than GRV-R3.

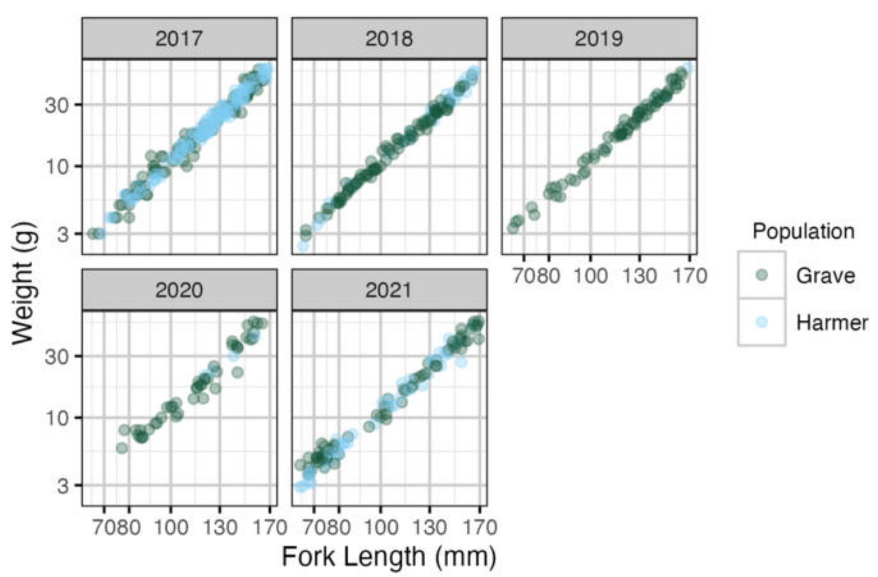


Figure 3. The weight and length data for individual fish between 65 and 169 mm from Thorley et al (2022b) by year and population.

2.2.4. GROWING SEASON DEGREE DAYS

Growing season degree days are the accumulated thermal units between the beginning of the first week of the year that average stream temperatures exceed and remain above 5 °C and the last day of the first week that average stream temperature drop below 4 °C (Coleman and Fausch 2007a). The GSDD data from 2017 to 2019 for station H1 in Harmer Creek below the Harmer Creek Sedimentation Pond and stations H2 and H3 in Harmer Creek above the Harmer Creek Sedimentation Pond were provided by Hocking et al. (2022). The GSDD data for 2021 for station H1 were provided by Brooks and Robinson (2022). The GSDD data for station H1 and the annual mean of H2 and H3 (Figure 4) were input into the model where available to provide information on the relationship between GSDD and the fork length at the onset of winter. The GSDD data for the other Grave Creek temperature stations (G2 and G3) were not used because few age-0 fish were captured within their vicinity.

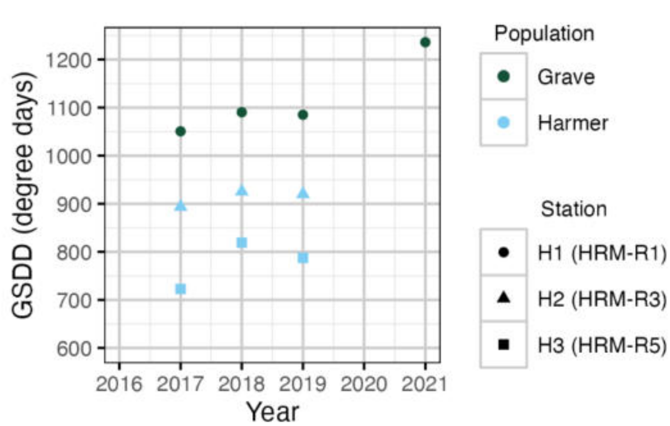


Figure 4. The Growing Season Degree Days (GSDD) data by year, population and station (reach) from Hocking et al. (2022) and Brooks and Robinson (2022).

2.2.5. SELENIUM

Selenium dry weight (dw) concentrations for benthic invertebrates (dietary) and fish muscle tissue were extracted from the raw data (Teck Coal 2022) for the Harmer Creek population below the confluence with Dry Creek and the Grave Creek population in HRM-R1 (Harmer Creek below the Harmer Creek Sedimentation Pond). The selenium concentration data were input into the model to provide information on selenium exposure in each population (Figure 5). Data from these sampling areas were selected because they were the only ones where GSDD, selenium and age-0 length data were consistently collected. The model accounted for the difference between the invertebrate (dietary) and fish muscle concentrations using a trophic transfer factor (TTF). Following Kuchapski and Rasmussen's (2015) study on TTFs for WCT in nine streams in the Elk Valley including Harmer Creek, the TTF was assumed to be 1.24 ± 0.07. This is consistent with de Bruyn et al. (2022) who cite Presser and Luoma (2010) for a trophic transfer factor of ~1 – 2 among a wide variety of fish species.

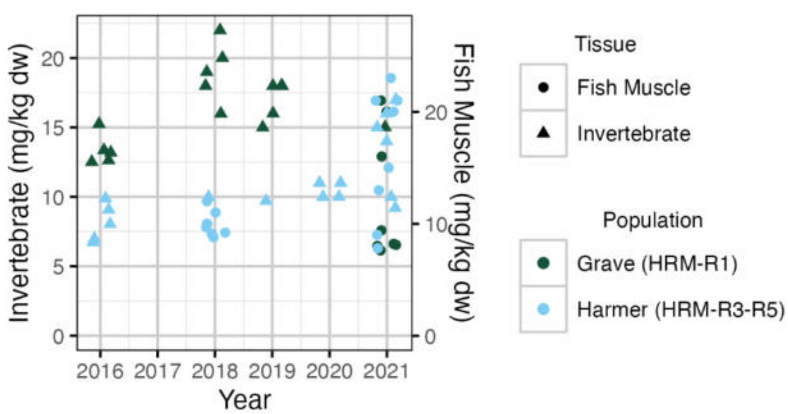


Figure 5. The selenium concentration data for the Harmer Creek population below Dry Creek (HRM-R3-R5) and the Grave Creek population below the Harmer Creek Sedimentation Pond (HRM-R1) by year, population and tissue type. For plotting purposes the fish muscle concentrations data are divided by the trophic transfer factor from benthic invertebrates to fish muscle tissue of 1.24 estimated by Kuchapski and Rasmussen (2015).

2.2.6. GROWTH

The effect of selenium on growth (increase in length) following emergence was estimated by the integrated model using dietary selenium concentrations, mean lengths and associated standard errors reported by Hamilton et al. (1990). The mean lengths and associated standard errors were converted into the equivalent change in length (Figure 6) assuming newly emergent Chinook salmon have a fork length of 37 mm (Fuhrman et al. 2018) using the following equation:

$$\text{change in length} = \frac{\text{length} - \text{length at emergence}}{\text{length at emergence}}$$

Based on Coleman and Fausch (2007a), the integrated model assumed that the newly emergent Cutthroat Trout have a fork length between 18 and 22 mm.

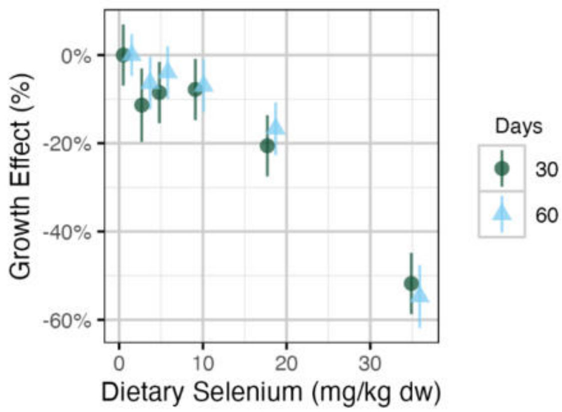


Figure 6. The growth effect data for Chinook salmon fry from Hamilton et al. (1990) by dietary selenium concentration and days since emergence with 95% confidence intervals. The reported mean lengths and standard errors were converted into mean growth effects and standard errors under the assumption that Chinook salmon fry emerge at 37 mm (Fuhrman et al. 2018).

2.3. Statistical Methods

To understand the details of the data analysis it is necessary to be familiar with the following statistical concepts: log and log odds transformations; allometric relationships; normal and truncated probability distributions; and varying (or random) effects. These are described briefly below.

2.3.1. Log Transformation

The log transformation maps positive numbers, which range from 0 to ∞ (infinity), on to the unbounded real number scale, which ranges from -∞ to ∞ (Figure 7). Example of values which must be positive are fish lengths and weights and selenium concentrations. The log transformation ensures negative relative changes on the log values always result in positive absolute values (McElreath 2020). The pH scale is a commonly used example of a log scale where an increase of 1 unit represents a 10x increase in the concentration of hydrogen ions in the solution.

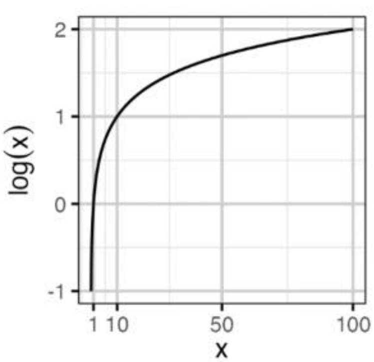


Figure 7. The mapping between values on the log scale and the real probability scales.

2.3.2. Log Odds Transformation

The log odds or logistic transformation maps probabilities, which are bounded between 0 and 1, onto the unbounded real number scale. The log odds transformation is used in logistic regression to link the predicted response based on the independent variables to the probability of an event. The log odds of a probability is given by Equation 1.

$$\text{Log odds } p = \log\left(\frac{p}{1-p}\right)$$

Equation 1. The log odds or logistic transformation.

Thus, for example a probability of 0.5 is equivalent to a log odds of 0 while a probability of 0.125 corresponds to log odds of approximately -2 (Figure 8).

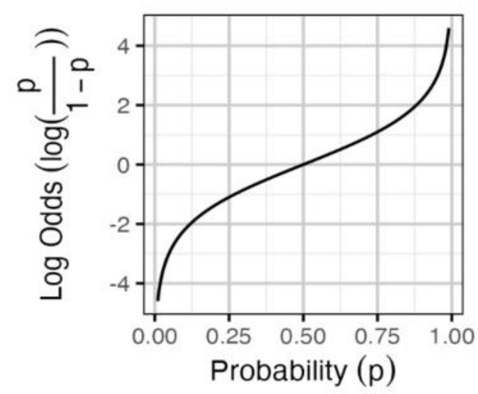


Figure 8. The mapping between values on the log odds and probability scales.

As its name suggests the log odds is the log of the odds where the odds is the probability of an event occurring divided by the probability of an event not occurring. Odds *against* an event are used by British bookmakers where, ignoring bookkeepers' margins, an odds of 3 to 1 indicates that an event is considered to be three times more likely to not occur than occur and thus is equivalent to a probability of 0.25 or log odds of -1.

This mapping allows changes in probabilities to be modeled as changes in the log odds while ensuring the resultant values are also probabilities, i.e. remain between 0 and 1 (McElreath 2020). The integrated model estimates the effect of log energy on the log odds egg to age-1 survival (see below).

2.3.3. Allometric Relationships

Many biological processes scale non-linearly with the size of an organism (Calder 2001).
For example, if the shape and tissue density remain constant, the weight (W) of a fish is expected to increase by a factor of eight (2^3) for every doubling of the length (L) as indicated by Equation 2 where $\propto$ is the 'proportional to' operator.

$$W \propto L^3$$

Equation 2. The expected relationship between weight (W) and length (L) for fish within the same life-stage from Calder (2001).

Conversely the standard metabolic rate (SMR) of salmonids tends to decrease by about 9% for every doubling of the weight (W).

$$\text{SMR} \propto \frac{W^{0.87}}{W}$$

Equation 3. The expected relationship between standard metabolic rate (SMR) and weight (W) for salmonids from Steingrimsson and Grant (1999).

When related to body size or physiology, such non-linear power relationships are called allometric relationships (Calder 2001)

$$Y = \alpha X^{\beta}$$

Equation 4. The general allometric relationship from Calder (2001).

and are often modeled using the log transformation such that

$$\log(Y) = \log(\alpha) + \beta \log{(X)}$$

Equation 5. The general allometric relationship as a simple linear regression on the log scale.

which is equivalent to a simple linear regression where $\log(\alpha)$ is the intercept and β the slope.

2.3.4. NORMAL DISTRIBUTION

The normal (or Gaussian) distribution, which is fully defined by its mean (centre) value and standard deviation (spread), is a bell-shaped curve (Figure 9). This curve describes the probability density of all possible real values. The normal distribution provides a useful tool for describing the uncertainty in many unbounded biological parameters or outcomes (McElreath 2020). Almost exactly 95% of the probability mass (i.e., the area under the curve) falls within two standard deviations of the mean.

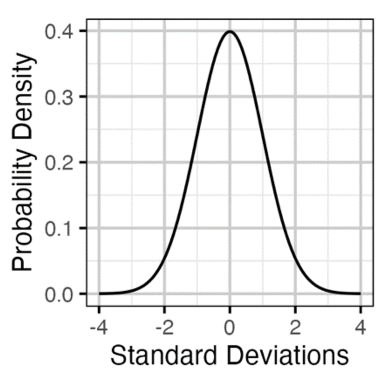


Figure 9. The normal probability density function by standard deviations from the mean.

2.3.5. TRUNCATED DISTRIBUTIONS

Truncated distributions assign zero probability to values outside the truncation limits. They are useful tools to provide limits to informative priors or in the case of truncated half-normal distributions (Figure 10) to provide positive values for standard deviations while ensuring most of the probability mass is close to 0 (Stan Development Team 2017).

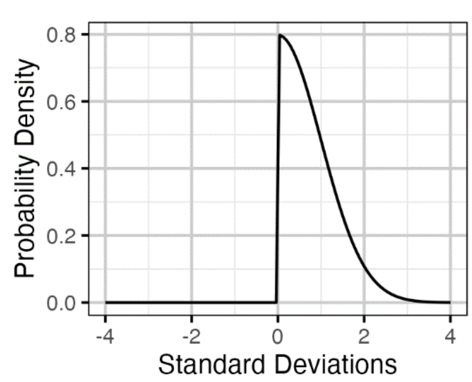


Figure 10. The truncated half-normal probability density function by standard deviations from the mean.

2.3.6. VARYING EFFECTS

Hierarchical (also known as multilevel or mixed effects models) are so named because they include multiple varying (also known as random) effects (McElreath 2020). A varying effect improves predictions by finding the appropriate balance between no variation and total independence. Thus, for example, a varying effect of year allows the values from years where there is data to inform those where there is not while still permitting inter-annual variation (Kéry and Royle 2016). This is possible because the values from years with data provide information on the expected value as well as the variation among years.

2.3.7. EGG TO AGE-1 SURVIVAL

The point estimates of the egg to age-1 survival from Thorley et al.'s (2022b) integrated life-cycle model were converted into log odds (Figure 11) and input into the model described in Section 2.5 below to estimate the relationship, if any, between energetic status and early life-stage survival.

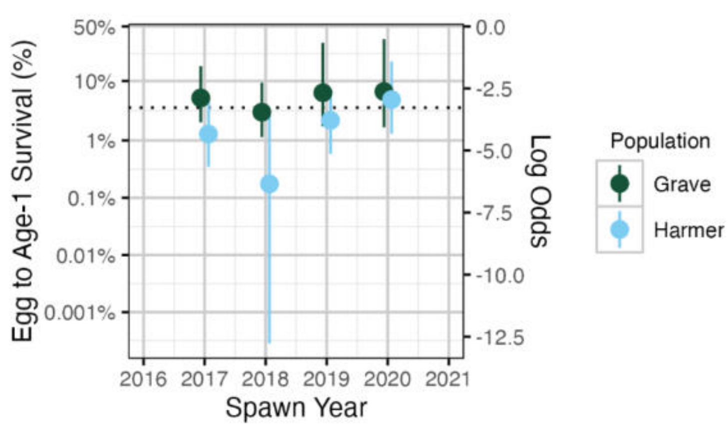


Figure 11. The egg to age-1 survival estimates from Thorley et al. (2022b) by spawn year and population (with 95% CIs). The estimates are plotted on the log odds scale. The dotted horizontal black line indicates the estimated population replacement rate of 3.7% based on the integrated lifecycle model.

2.4. DATA ANALYSIS

A hierarchical Bayesian Integrated Network (hBIN) model was used to estimate the effect of energetic status on the egg to age-1 survival. hBIN models (Kéry and Royle 2016; Carriger et al. 2016; McElreath 2020; Schaub and Kery 2022) have multiple advantages over standard Maximum Likelihood-based (Millar 2011) Generalized Linear Models (GLMs; Dobson and Barnett 2018). The incorporation of a hierarchical (varying effects) structure correctly accounts for non-independence in the data (Hurlbert 1984) and as discussed above allows years with lots of data to inform those with little or no data (Kéry and Royle 2016). A Bayesian framework permits the incorporation of existing knowledge (Liedloff et al. 2013; Kaikkonen et al. 2021), does not require a minimum sample size in order to produce valid estimates and readily handles missing values (McElreath 2020). In addition, integrated models allow information from multiple, diverse data sets to inform key uncertainties (Schaub and Kery 2022). Finally, causal network (as opposed to purely correlative) models (Kaikkonen et al. 2021) allow the contributions of particular variables to an outcome of interests to be quantified via a counterfactual approach (Pearl 2009; McElreath 2020).

Except where stated otherwise in the model description below, the hBIN model used weakly informative normal or truncated 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 $\hat{R} \leq 1.05$ and (Kery and Schaub 2011) the effective sample size was ≥ 150 (Brooks et al. 2011) for each of the monitored parameters (Kery and Schaub 2011).

The parameters are summarized in terms of the point *estimate*, *lower* and *upper* 95% compatibility limits (Rafi and Greenland 2020) and the surprisal *s-value* (Greenland 2019). The estimate is the median (50th percentile) of the MCMC samples while the 95% compatibility interval (CI) is the 2.5th and 97.5th percentiles. The s-value indicates how surprising it would be to discover that the true value of the parameter is in the opposite direction to the estimate (Greenland 2019). An s-value of $>$ 4.3 bits, which is equivalent to a significant p-value $<$ 0.05 (Kery and Schaub 2011; Greenland and Poole 2013), indicates that the surprise would be equivalent to throwing at least 4.3 heads in a row.

The sensitivity of the parameters to the choice of prior distributions was evaluated by increasing the standard deviations (SDs) of all the priors by an order of magnitude while preserving any truncation and then using $\hat{R}$ to evaluate whether the samples were drawn from the same posterior distribution (Thorley and Andrusak 2017).

The analyses were implemented using R version 4.2.0 (R Core Team 2022) and the estimates produced using JAGS (Plummer 2003).

2.5. Model Description

The hBIN model consists of an integrated network of hierarchical Bayesian submodels linking the expected GSDDs, dietary selenium concentrations, fork lengths and wet weights to the data and an allometric energetic submodel linking the expected fork lengths and weights to the egg to age-1 survival (see Section 2.3.7 above). The submodels are described verbally and mathematically below. For additional information on the model, including the model definition in JAGS code (Plummer 2017), see *https://www.poissonconsulting.ca/f/418102047*.

2.5.1. Energetic Submodel

The energetic submodel was based on the assumptions that 1) the structural (lipid requiring) tissue varies linearly by expected (mean) weight (Calder 2001); 2) the SMR (lipid requirements of the structural tissue per gram) varies by the structural tissue to the power of ~0.87 (Steingrímsson and Grant 1999); and 3) the total storage (available lipid) tissue varies linearly by the wet weight above a minimum length specific threshold at which an individual is expected to die of starvation (Cunjak and Power 1987; Simpkins et al. 2003; Álvarez and Nicieza 2005; Wilson et al. 2021). We define the energetic status of an individual at the onset of winter (E) as

$$E \propto \frac{\text{relative energy stores}}{\text{relative metabolic requirement}}$$

Equation 6. The relationship between energetic status, energy stores and metabolic requirement.

it follows from the above assumptions[19] that

$$E \propto \frac{W - W_{\text{min}}}{W_{\text{average}}^{\beta_{\text{SMR}}}}$$

Equation 7. The relationship between energetic status and the actual, minimum and average weight.

where W is the actual weight, W_{average} is the expected weight in an average year given the length of the fish, W_{min} is the length specific weight at starvation and β_{SMR} (~0.87) is the allometric scaling of the standard metabolic rate to weight.

[19] The initial formulation of energetic status included the duration of the winter based on the end and start of the growing season as a variable. However, winter duration was not supported as an informative predictor.

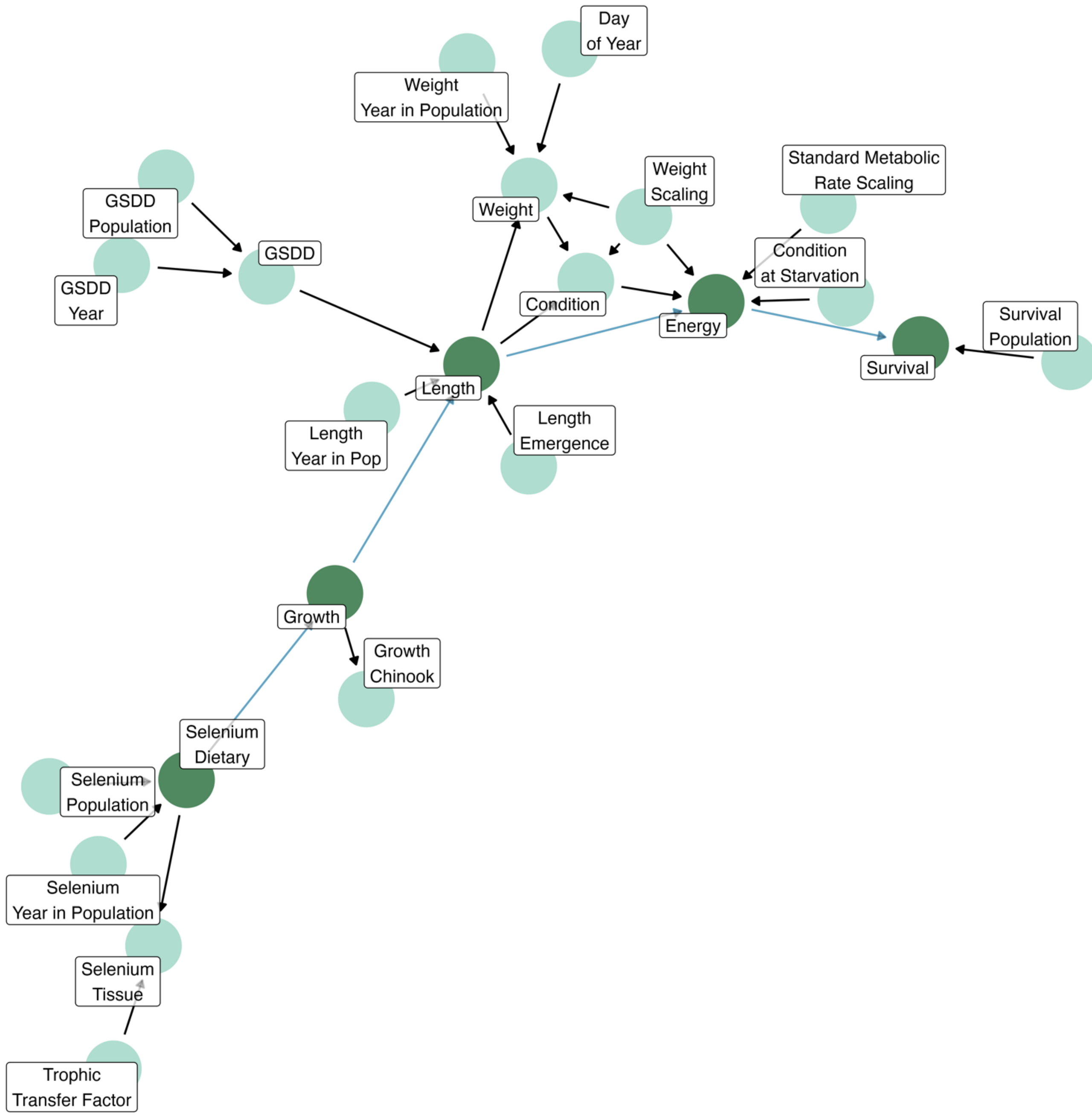


Figure 12. The Directed Acyclic Graph (DAG) of the relationships between variables. where 'Condition' is the body condition at the onset of winter, 'Condition at Starvation' is the body condition at starvation, 'Day of Year' is the day of the year, 'Energy' is the energetic status at the onset of winter, 'Growth' is the change in length, 'Growth Chinook' is the change in length of Chinook salmon fry in the Hamilton et al. (1990) data, 'GSDD' is the growing season degree days, 'Length' is the fork length at the onset of winter, 'Length Emergence' is the fork length at emergence, 'Population' is the population (Harmer or Grave), 'Selenium Dietary' is the selenium dietary concentration, 'Selenium Tissue' is the selenium tissue concentration, 'Standard Metabolic Rate Scaling' is the allometric scaling from weight to the standard metabolic rate, 'Trophic Transfer Factor' is the trophic transfer factor, 'Weight' is the wet weight, 'Weight Scaling' is the allometric scaling from length to weight, 'Year' is the year as a discrete variable and 'Year in Population' is the year within population as a discrete variable. The modelled relationships between variables are indicated by arrows. The arrows on the pathway from dietary selenium concentration to egg to age-1 survival are colored light green.

Given that $C = W/W_{\text{average}}$ where C is the body condition, defined as actual weight as a percentage of average weight for a fish of the same length (He et al. 2008), the previous equation can be reformulated as

$$E \propto \frac{(C - C_{\text{min}})W_{\text{average}}}{W_{\text{average}}^{\beta_{\text{SMR}}}}$$

Equation 8. The relationship between energetic status and body condition, minimum body condition and average weight.

As $W_{\text{average}} \propto L^{\beta_W}$, where β_{W} ($\sim$3) is the allometric scaling term for the weight to length (Calder 2001), it can be restated as

$$E \propto \frac{(C - C_{\text{min}})L^{\beta_{\text{W}}}}{L^{\beta_{\text{W}}\beta_{\text{SMR}}}}$$

Equation 9. The relationship between energetic status and body condition, minimum body condition and fork length.

which simplifies to

$$E \propto \frac{(C - C_{min})}{L^{\beta_{\text{W}}\beta_{\text{SMR}} - \beta_{\text{W}}}}$$

Equation 10. A simplified form of the relationship between energetic status and body condition, minimum body condition and fork length.

Under the assumption that an increase in energetic status has more effect on the egg to age-1 survival (S) at lower energy status (McElreath 2020) then

$$\text{log odds }(S) \propto \log\,(E)$$

Equation 11. The relationship between the log odds egg to age-1 survival and the energetic status at the onset of winter.

Based on Steingrimsson and Grant (1999), the prior uncertainty in the metabolic scaling constant (β_{SMR}) was assumed to be an informative normal distribution with a mean of 0.87 and SD of 0.035 truncated at 0.8 and 0.94. To cover a wide range of possibilities the prior uncertainty in the body condition at starvation (C_{min}) was assumed to be an normal distribution with a mean of 0.4 and a SD of 0.4 truncated at 0 and 0.8 (Cunjak and Power 1987; Simpkins et al. 2003; Álvarez and Nicieza 2005; Wilson et al. 2021). The energetic submodel also included an effect of population on the egg to age-1 survival (α_{S_P}) to account for additional sources of mortality unrelated to condition ($C_{p,y}$) or fork length ($L_{p,y}$).

Mathematically the survival part of the energetic submodel was defined as follows:

$$\text{logit}(S_{\text{p,y}}) \sim \text{Normal}(\mu_{S_{p,y}}, \sigma_S)$$
$$\mu_{S_{p,y}} = \alpha_{S_0} + \beta_E(\log(E_{p,y}) - \log(E_v)) + \alpha_{S_P} \cdot \begin{cases} 1 \text{ if Grave} \\ -1 \text{ if Harmer} \end{cases}$$
$$\sigma_S \sim \text{Normal}(0, 2)\ \text{T}(0,)$$
$$\alpha_{S_0} \sim \text{Normal}(-4, 2)$$
$$\beta_E \sim \text{Normal}(0, 100)$$
$$\alpha_{S_P} \sim \text{Normal}(0, 2)$$

where $S_{\text{p,y}}$ is the probability of survival for the p^{th} population in the y^{th} year, $\mu_{S_{p,y}}$is the expected survival, σ_S is the SD of the residual variation in $S_{\text{p,y}}$, α_{S_0} is the expected survival of a 37.5 mm FL fish of average body condition, β_E is the effect of energetic status on α_{S_0}, $E_{p,y}$ is the energetic status at the onset of winter for the p^{th} population in the y^{th} year, E_v is the energetic status for a 37.5 mm FL fish of average body condition and α_P is half the difference in the effect of population on α_{S_0}.

The energetic part of submodel was:

$$
\begin{gathered}
\log\,(E_{p,y}) = \log\big(C_{p,y} - C_{\min}\big) - (\beta_W \beta_{\text{SMR}} - \beta_W) \cdot \log\big(L_{p,y}\big) \\
\log\,(E_v) = \log(1 - C_{\min}) - (\beta_W \beta_{\text{SMR}} - \beta_W) \cdot \log(37.5) \\
C_{\min} \sim \text{Normal}(0.4, 0.4)\ \text{T}(0, 0.8) \\
\beta_{\text{W}} \sim \text{Normal}(3, 1) \\
\beta_{\text{SMR}} \sim \text{Normal}(0.87, 0.035)\ \text{T}(0.8, 0.94)
\end{gathered}
$$

where $C_{\text{p,y}}$ is the body condition at the onset of winter for the p^{th} population in the y^{th} year, $C_{\min}$ is the body condition at starvation, β_W is the length to weight allometric scaling exponent, β_{SMR} is the weight to standard metabolic rate allometric scaling exponent and $L_{p,y}$ is the fork length at the onset of winter for the p^{th} population in the y^{th} year.

2.5.2. GSDD SUBMODEL

To allow the missing GSDD values (Figure 4) to be efficiently estimated in the absence of repeat sampling or any predictor variables (McElreath 2020), the GSDD submodel assumed that all the uncertainty was in the varying effect of year (α_{GSDD_y}) and the difference between the populations (α_{GSDD_P}).

Mathematically the submodel was defined as follows:

$$
\begin{gathered}
\text{GSDD}_{\text{p,y}} \sim \text{Normal}(\mu_{\text{GSDD}_{p,y}}, 1) \\
\mu_{\text{GSDD}_{p,y}} = \alpha_{GSDD_0} + \alpha_{\text{GSDD}_P} \cdot \begin{cases} 0 \text{ if Grave} \\ 1 \text{ if Harmer} \end{cases} + \alpha_{GSDD_y} \\
\alpha_{GSDD_0} \sim \text{Normal}(1100, 10)\ \text{T}(1090, 1110) \\
\alpha_{\text{GSDD}_P} \sim \text{Normal}(0, 200) \\
\alpha_{GSDD_y} \sim \text{Normal}(0, \sigma_{GSDD_Y}) \\
\sigma_{GSDD_Y} \sim \text{Normal}(0, 200)\ \text{T}(0,)
\end{gathered}
$$

where $\text{GSDD}_{\text{p,y}}$ is the GSDD for the p^{th} population in the y^{th} year, $\mu_{\text{GSDD}_{p,y}}$ is the expected GSDD for the p^{th} population in the y^{th} year, α_{GSDD_0} is the GSDD in HRM-R1 in an average year, α_{GSDD_P} is the difference between HRM-R1 and HRM-R3-R5, α_{GSDD_y} is the varying effect of year, and σ_{GSDD_Y} is the SD of the varying effect of year.

2.5.3. Growth Effect of Selenium Submodel

The growth effect submodel assumed that the effect of dietary selenium on growth (increase in length since emergence) is the same for WCT as that for Chinook salmon fry in the experiments of Hamilton et al. (1990).

Mathematically the submodel was:

$$G_i \sim \mathrm{Normal}(\mu_{G_i}, \sigma_{G_i})$$
$$\mu_{G_i} = 1/(1 + 10\string^(\alpha_{\mathrm{Se}} * (\log(\alpha_{\mathrm{EC50}})/\log(10) - \log(\mathrm{Se}_i - 1)/\log(10)))) * -1$$
$$\alpha_{\mathrm{EC50}} \sim \mathrm{Normal}(30, 5)\ \mathrm{T}(0,)$$
$$\alpha_{\mathrm{Se}} \sim \mathrm{Normal}(2,1)$$

where G_i is the mean growth in the i^{th} experiment, μ_{G_i} is the expected growth in i^{th} experiment, σ_{G_i} is the standard error of the mean growth in the i^{th} experiment, α_{Se} is the intercept, α_{EC50} is the dietary selenium concentration with a 50% effect on growth, and Se_i is the dietary selenium concentration in the i^{th} experiment.

2.5.4. Dietary Selenium Submodel

To analyse the benthic invertebrate and fish muscle tissue selenium data together, the dietary selenium submodel assumed that the prior uncertainty in the trophic transfer factor from benthic invertebrate to fish muscle tissue (β_{TTF}) was a normal distribution with a mean of 1.24 and a SD of 0.07 truncated at 1.10 and 1.38 (Kuchapski and Rasmussen 2015). The model allowed the dietary selenium concentration to vary by population (α_{Se_P}) and randomly by population within year ($\alpha_{Se_{p,y}}$).

Mathematically the submodel was:

$$\log(Se_{p,y,s,i}) \sim \mathrm{Normal}\left(\log\left(\mu_{Se_{p,y,s}}\right), \sigma_{\mathrm{Se}}\right)$$
$$\log\left(\mu_{Se_{p,y,s}}\right) = \alpha_{\mathrm{Se}_0} + \alpha_{\mathrm{TTF}} \cdot \begin{cases} 0 \text{ if Dietary} \\ 1 \text{ if Tissue} \end{cases} + \alpha_{\mathrm{Se}_P} \cdot \begin{cases} 0 \text{ if Grave} \\ 1 \text{ if Harmer} \end{cases} + \alpha_{Se_{p,y}}$$
$$\sigma_{Se} \sim \mathrm{Normal}(0,2)\ \mathrm{T}(0,)$$
$$\alpha_{Se_0} \sim \mathrm{Normal}(-4,2)$$
$$\alpha_{\mathrm{TTF}} \sim \mathrm{Normal}(1.24, 0.07)\ \mathrm{T}(1.10, 1.38)$$
$$\alpha_{\mathrm{Se}_P} \sim \mathrm{Normal}(0,2)$$
$$\alpha_{Se_{p,y}} \sim \mathrm{Normal}(0, \sigma_{Se_{PY}})$$
$$\sigma_{Se_{PY}} \sim \mathrm{Normal}(0,2)\ \mathrm{T}(0,)$$

where $Se_{p,y,s,i}$ is the selenium concentration of the i^{th} sample of the s^{th} substrate (benthic invertebrate kick sample or fish muscle tissue plug) in the p^{th} population in the y^{th} year, $\mu_{Se_{p,y,s}}$ is the expected selenium concentration of the s^{th} substrate in the p^{th} population in the y^{th} year, σ_{Se} is the SD of the residual variation in $Se_{p,y,s,i}$, α_{Se_0} is the expected selenium concentration of benthic invertebrates in HRM-R1 in an average year, α_{TTF} is the TTF from benthic invertebrate to fish muscle tissue, α_{Se_P} is the difference between HRM-R3-R5 and HRM-R1, $\alpha_{Se_{p,y}}$ is the varying effect of year within population, and $\sigma_{Se_{PY}}$ is the SD of the varying effect of year within population.

2.5.5. Fork Length Submodel

The fork length submodel assumed that the length at the onset of winter varies by dietary selenium exposure and randomly by population within year and varies positively with GSDD (Coleman and Fausch 2007a, 2007b; Brooks and Robinson 2022). The prior uncertainty in the fork length of the WCT at emergence (α_{EMERGE}) was a normal distribution with a mean of 20 and a SD of 1 mm truncated at 18 and 22 mm (Coleman and Fausch 2007).

Mathematically the submodel was:

$$\log(L_{p,y,i}) \sim \text{Normal}(\log(\mu_{L_{p,y,i}}), \sigma_L)$$
$$\log(\mu_{L_{p,y,i}}) = ((\log(\alpha_{L_0}) + \beta_{\text{GSDD}}(\text{GSDD}_{p,y} - 900) + \alpha_{L_{p,y}}) - \alpha_{\text{EMERGE}})(G_{p,y} + 1) + \alpha_{\text{EMERGE}}$$
$$\sigma_L \sim \text{Normal}(0,1)\ \text{T}(0,)$$
$$\alpha_{L_0} \sim \text{Normal}(37.5, 5)$$
$$\beta_{\text{GSDD}} \sim \text{Normal}(0,0.1)\ \text{T}(0,)$$
$$GSDD_{p,y} = \alpha_{GSDD_0} + \alpha_{\text{GSDD}_P} \cdot \begin{cases} 0 \text{ if Grave} \\ 1 \text{ if Harmer} \end{cases} + \alpha_{GSDD_y}$$
$$\alpha_{L_{p,y}} \sim \text{Normal}(0, \sigma_{L_{PY}})$$
$$\alpha_{\text{EMERGE}} \sim \text{Normal}(20,1)\ \text{T}(18,22)$$
$$G_{p,y} = 1/(1 + 10\text{\^{}}(\alpha_{\text{Se}} * (\log(\alpha_{\text{EC50}})/\log(10) - \log(\text{Se}_{p,y} - 1)/\log(10)))) * -1$$
$$\log(\text{Se}_{p,y}) = \alpha_{Se_0} + \alpha_{\text{Se}_P} \cdot \begin{cases} 0 \text{ if Grave} \\ 1 \text{ if Harmer} \end{cases} + \alpha_{Se_{p,y}}$$
$$\sigma_{L_{PY}} \sim \text{Normal}(0,1)\ \text{T}(0,)$$

where $L_{p,y,i}$ is the fork length of the i^{th} fish in the p^{th} population in the y^{th} year, $\mu_{L_{p,y,i}}$ is the expected fork length of the i^{th} fish in the p^{th} population in the y^{th} year, σ_L is the SD of the residual variation in $L_{p,y,i}$, α_{L_0} is the expected fork length of a fish at the onset of winter at 900 GSDD, β_{GSDD} is the effect of GSDD on α_{L_0}, $\text{GSDD}_{p,y}$ is the GSDD in the p^{th} population in the y^{th} year, $\alpha_{L_{p,y}}$ is the varying effect of year within population on α_{L_0}, α_{EMERGE} is the length at emergence, $G_{p,y}$ is the growth effect of dietary selenium in the p^{th} population in the y^{th} year, $\sigma_{L_{PY}}$ is the SD of $\alpha_{L_{p,y}}$ and $\text{Se}_{p,y}$ is the dietary selenium concentration in the p^{th} population in the y^{th} year.

2.5.6. Weight (Condition) Submodel

The weight submodel assumed that the weight varied by fork length, day of the year and randomly by population within year (He et al. 2008). The weight submodel was used to estimate the body condition by dividing the expected weight of a 37.5 mm FL fish for each population in each year by its expected weight in an average year. As weight to length allometric scaling term (β_{W}) was close to 3 the estimated body conditions are insensitive to the length of the fish used for standardization. A condition value of 1.05 indicates that fish are on average 5% heavier for their length at the onset of winter than in an average year.

Mathematically the submodel was:

$$\log(W_{p,y,i}) \sim \text{Normal}(\log(\mu_{p,y,i}), \sigma_W)$$

$$\log(\mu_{p,y,i}) = \alpha_{W_0} + \beta_W \log(L_{p,y,i}) + \beta_{\mathrm{DOY}}(DOY_i - 275) + \alpha_{W_{p,y}}$$
$$\sigma_W \sim \mathrm{Normal}(0,1)\ \mathrm{T}(0,)$$
$$\alpha_{W_0} \sim \mathrm{Normal}(-11,2)$$
$$\beta_{\mathrm{DOY}} \sim \mathrm{Normal}(0, 0.01)$$
$$\alpha_{W_{p,y}} \sim \mathrm{Normal}(0, \sigma_{W_{PY}})$$
$$\sigma_{W_{PY}} \sim \mathrm{Normal}(0,0.1)\ \mathrm{T}(0,)$$
$$C_{p,y} = \frac{\exp\left(\alpha_{W_0} + \beta_W \log(37.5) + \alpha_{W_{p,y}}\right)}{\exp\left(\alpha_{W_0} + \beta_W \log(37.5)\right)}$$

where $W_{p,y,i}$ is the wet weight of the i^{th} fish in the p^{th} population in the y^{th} year, $\mu_{p,y,i}$ is the expected wet weight of the i^{th} fish in the p^{th} population in the y^{th} year, σ_W is the SD of the residual variation in $W_{p,y,i}$, α_{W_0} is the expected wet weight of a 1 mm FL fish in an average year at the onset of winter, β_W is defined in the energetic submodel above, $L_{p,y,i}$ is the length of the i^{th} fish in the p^{th} population in the y^{th} year, β_{DOY} is the effect of day of the year on α_{W_0}, DOY_i is the day of the year the i^{th} fish was caught, $\alpha_{W_{p,y}}$ is the varying effect of year within population, $\sigma_{W_{PY}}$ is the SD of $\alpha_{W_{p,y}}$ and $C_{\mathrm{p,y}}$ is the body condition at the onset of winter for the p^{th} population in the y^{th} year.

2.5.7. CORRECTION FACTORS

2.5.8. Grave Creek Population

Two correction factors were introduced to the model to account for the fact that the selenium exposure and length data for the Grave Creek population were for HRM-R1 which is only ~6% of the Grave population area based on length. Following Thorley et al. (2022b), the correction factors were calculated assuming that the number of fish in each reach was directly proportional to the length of the reach (Table 1). The selenium exposure correction factor of 0.15 for the Grave Creek (κ_{Se}) population was then calculated under the further assumptions that, based on approximate watershed areas, dietary selenium concentrations in GRV-R1 and GRV-R2 were 50% of those in HRM-R1 and that due to the absence of any mine influence dietary selenium concentrations in GRV-R3 and GRV-R4 were negligible[20]. The length correction factor for the Grave Creek population (κ_L) of 0.8 assumed that fish in GRV-R3 grew 50% less than those in the other reaches based on a GSDD of between 580 and 730 degree days at temperature station G3 (Hocking et al. 2022; Brooks and Robinson 2022). Both Grave Creek population correction factors included uncertainty via their prior distributions. More specifically, the prior uncertainty in the Grave Creek population selenium exposure correction factor was a normal distribution with a mean of 0.15 and a SD of 0.05 truncated at 0.05 and 0.25. The prior uncertainty in the length correction factor for Grave Creek was a normal distribution with a mean of 0.8 and a SD of 0.1 truncated at 0.7 and 0.9.

[20] For the purposes of the calculation the dietary selenium concentrations in GRV-R3 and GRV-R4 were conservatively assumed to be 0 mg/kg dw. However, Figure 13 in Golder (2022) and Figure 4 in de Bruyn et al. (2022) suggests that concentrations of selenium in benthic invertebrates in the control reaches of GRV-R3 and HRM-R6 are between 3 and 8 mg/kg dw. The consequences of this assumption for estimation of the effects of dietary selenium on the recruitment patterns are described in the Discussion.

2.5.9. Harmer Creek Population

GSDD and dietary selenium concentrations are substantially higher in Dry Creek than the Harmer Creek mainstem (de Bruyn et al. 2022; Golder 2022; Hocking et al. 2022). However, almost all egg incubation and rearing to age-1 for the Harmer Creek population occurs in the Harmer Creek mainstem (Thorley et al. 2022b). Consequently, dietary selenium and GSDD correction factors were not required. Nonetheless, the possibility that the egg to age-1 survival rate for the Harmer Creek population may have been lowered due to exposure of adults in Dry Creek to selenium and other constituents of concern (Golder 2022) is explored in Attachment A and placed in context in the Evaluation of Cause report (Harmer Creek Evaluation of Cause Team 2022).

2.5.10. Counterfactual Analysis

The counterfactual analysis (Ferraro 2009) evaluates the extent to which fork length and GSDD and dietary selenium (through their influence on fork length) as well as body condition and energetic status (based on fork length and body condition) may have contributed to the Reduced Recruitment and Recruitment Failure patterns. The Reduced Recruitment in the Harmer Creek population from 2017 to 2019 and the Recruitment Failure in the Harmer Creek population in 2018 were quantified in terms of the difference in the log odds in the egg to age-1 survival as estimated by the hBIN model. More specifically the Reduced Recruitment was quantified in terms of the mean of the annual differences in the log odds survival for the Harmer Creek population versus the Grave Creek population from 2017 to 2019. The Recruitment Failure was the difference in 2018 versus the mean of 2017 and 2019 for the Harmer Creek population. The counterfactual estimates the percent contribution by using the hBIN model to estimate what the percent change in the log odds survival differences would have been if the fish in both populations in all years were typical length (37.5 mm FL) and/or GSDD was 950 degree days and/or dietary selenium was 5 mg/kg dw (within background levels) and/or body condition was 1 (the estimated value for an average year) in both populations in all years[21].

3. Results

The results suggest that the energetic status at the onset of winter, based on length and body condition, is an important predictor of the age to age-1 survival explaining an estimated 65% (29-85% 95% CI) of the Reduced Recruitment and 90% (76-96% 95% CI) of the Recruitment Failure. The results also confirm the findings from previous studies that the juvenile body condition in 2018 was low in both populations (Thorley et al. 2022b; Wiebe et al. 2022); the length of age-0 WCT was shorter than expected given the GSDD in 2018 in the Harmer Creek population (Thorley et al. 2022b); GSDD influences length of age-0 Cutthroat Trout at the onset of winter (Coleman and Fausch 2007a, 2007b; Brooks and Robinson 2022); and dietary selenium influences growth in Chinook salmon fry (Hamilton et al. 1990; DeForest et al. 1999; de Bruyn et al. 2022). Each of these results is described in more detail below starting with the effect of dietary selenium on growth. The parameters estimates are tabulated below (Table 2). For additional results see *https://www.poissonconsulting.ca/f/418102047*.

---

[21] The estimated contributions are relatively insensitive to the value of the constants because the counterfactual analysis is simply estimating the percent change in the difference in the estimated log odds survival if the length, GSDD, dietary selenium and/or body condition were the same. From this perspective the use of values that are typical as opposed to specific to one year or population is preferable in the sense that they represent intermediate values between the extremes.

3.1. GROWTH EFFECT OF SELENIUM

For the effect of dietary selenium on growth (increase in length from emergence) based on the data from Hamilton et al. (1990) as shown in Figure 6, the integrated model estimated that the EC_{10} (concentration with a 10% effect) was 11 (9-14 95% CI) mg/kg dw and the EC_{50} was 33 (31-37 95% CI) mg/kg dw (Figure 13). The estimated EC_{10} is consistent with the Elk Valley Water Quality Plan Level 1 Dietary Selenium Benchmark of 11 mg/kg dw (Teck Coal Limited 2014).

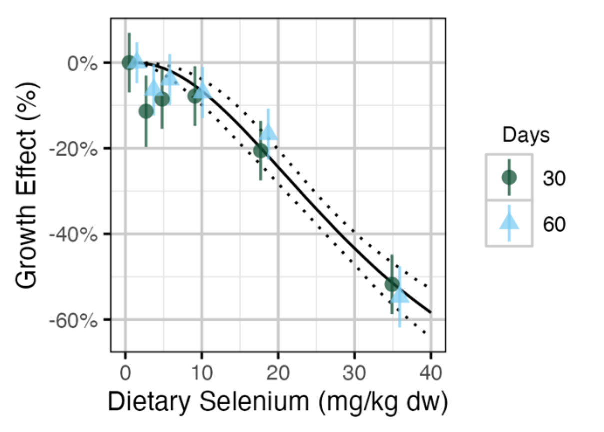


Figure 13. The estimated average effect of dietary selenium on age-0 WCT growth based on the data from Hamilton et al. (1990) (with 95% CIs as dotted lines).

Table 2. The parameter estimates, lower and upper 95% CLs and s-values.

Parameter	Description	Estimate	Lower 95% CL	Upper 95% CL	SValue
β_{SMR}	Allometric scaling of SMR to weight	0.872	0.81	0.929	10.6
C_{min}	Body condition at starvation	0.322	0.0162	0.744	10.6
α_{GSDD_0}	Expected value of GSDD in HRM-R1 in an average year	1100	1090	1110	10.6
α_{GSDD_P}	The effect of population on α_{GSDD_0}	-231	-232	-229	10.6
κ_L	Length correction factor for the Grave Creek population	0.789	0.704	0.889	10.6
α_{Se}	The intercept for selenium survival effect	2.03	1.63	2.56	10.6
α_{EC50}	Selenium concentration with a 50% effect on growth	33.1	30.6	36.6	10.6
α_{L_0}	Expected fork length at the onset of winter at 900 GSDD	36.6	33	41.2	10.6
α_{EMERGE}	Fork length of the WCT at emergence	20	18.3	21.6	10.6
β_{GSDD}	The effect of GSDD on α_{L_0}	0.000562	7.23E-05	0.00125	10.6
α_{Se_0}	Expected selenium in HRM-R1 in average year	0.868	0.0943	1.34	5.13
κ_{Se}	Selenium exposure correction factor for Grave population	0.167	0.0802	0.241	10.6
α_{Se_P}	Effect of population on α_{Se_0}	1.41	0.881	2.2	10.6
α_{TTF}	TTF from benthic invertebrate to fish muscle tissue	1.19	1.11	1.31	10.6
α_{S_0}	Survival of a 37.5 mm FL fish of average body condition	-3.66	-4.4	-2.79	10.6
β_E	The effect of energetic status on α_{S_0}	13.5	3.15	33	5.19
α_{S_P}	Effect of population on the egg to age-1 survival	0.267	-0.831	0.912	0.888
α_{W_0}	Expected weight of a 1 mm FL fish at the onset of winter	-11.4	-11.6	-11.2	10.6
β_{DOY}	Effect of day of the year on α_{W_0}	-0.00262	-0.0053	-8.90E-05	4.57
β_W	Allometric scaling term for the weight to length	2.99	2.95	3.03	10.6
σ_{GSDD_Y}	SD of the varying effect of year on α_{GSDD_0}	90.5	47	220	10.6
σ_L	SD of the residual variation in $L_{p,y,i}$,	0.101	0.08	0.134	10.6
$\sigma_{L_{PY}}$	SD of $\alpha_{L_{p,y}}$	0.102	0.0406	0.232	10.6
σ_{Se}	SD of the residual variation in $Se_{p,y,s,i}$	0.272	0.223	0.335	10.6
$\sigma_{Se_{PY}}$	SD of the effect of year within population on α_{Se_0}	0.243	0.125	0.527	10.6
σ_S	SD of the residual variation in $S_{\text{p,y}}$	0.386	0.0185	1.55	10.6
σ_W	SD of the residual variation in $W_{p,y,i}$	0.109	0.102	0.116	10.6
$\sigma_{W_{PY}}$	SD of $\alpha_{W_{p,y}}$	0.0339	0.0151	0.0706	10.6

3.2. DIETARY SELENIUM

The estimates of the average annual population dietary selenium exposure for age-0 fish based on measurements of benthic invertebrate and fish muscle tissue from the Harmer Creek population (Figure 5) varied from a low of 1.8 (0.8-2.7 95% CI) mg/kg dw in HRM-R1 in the Grave Creek population area in 2021 to a high of 13 (11-15 95% CI) mg/kg dw in the Harmer Creek population in 2021 (Figure 14).

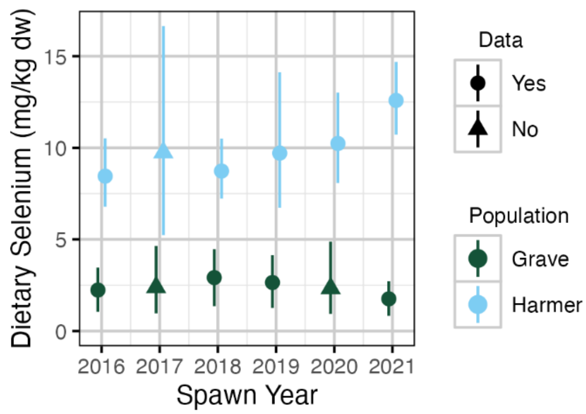


Figure 14. The estimated average dietary selenium exposure by spawn year, population and whether the estimates are informed by population and year specific dietary and tissue selenium data (with 95% CIs).

3.3. GSDD

The hBIN estimated that the GSDD ranged from ~800 to ~900 in all years except 2021 in the Harmer Creek population when it was ~1,000 degree days (Figure 15). In the Grave Creek population area GSDD was estimated to range between ~1,050 and ~1,150 for all years except 2021 when it was just over 1,200. The estimates of the GSDD were uncertain in 2016 and 2020 for both populations because there were no measured data for those years.

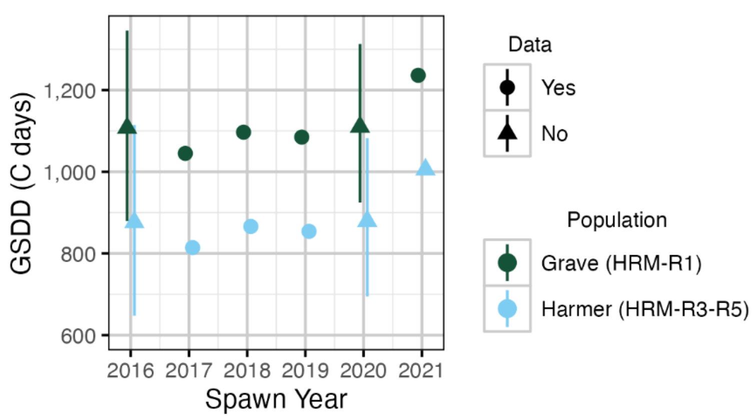


Figure 15. The estimated Growing Season Degree Days (GSDD) by spawn year and population (reach) and whether the estimates are informed by population and year specific temperature data (with 95% CIs).

The model also estimated that expected fork length increased with GSDD from 35 (30-40 95% CI) mm at 800 GSDD to 43 (38-52 95% CI) mm at 1,200 GSDD (Figure 16). The estimated relationship is less steep than that estimated by Brooks and Robinson (2022; Figure 7) for multiple systems in the Elk Valley including upper Fording River and Grave, Greenhills, Harmer, Lizard and Michel Creeks. One possible explanation for this discrepancy is that dietary selenium has more effect on growth, and therefore fork length, of WCT than Chinook salmon in Hamilton et al.'s (1990) study although due to the limited current dataset sampling error cannot be excluded.

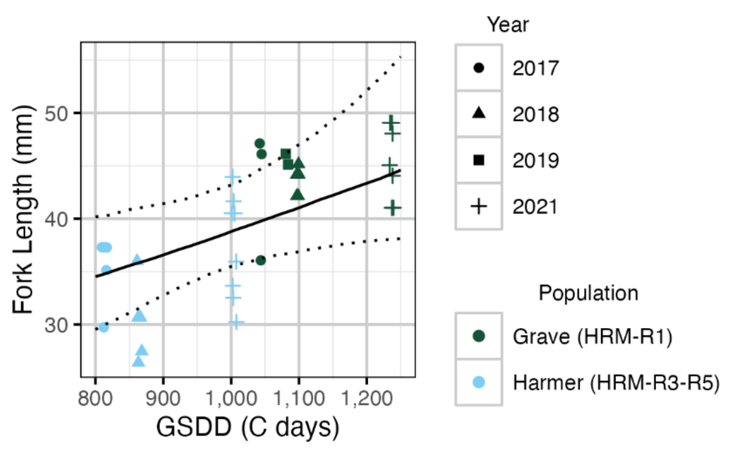


Figure 16. The estimated relationship between the average fork length at the onset of winter and the GSDD (with 95% CIs as dotted lines). The individual data points are the lengths of individual fish corrected for the estimated effect of dietary selenium.

3.4. Fork Length

The model estimated that across all years the mean fork length of age-0s was between 41 and 43 mm in the Grave Creek population and between 30 and 37 mm in the Harmer Creek population (Figure 17). The biggest difference was in 2018 when the age-0 fish in the Grave Creek population were estimated to be 43 (39 – 48 95% CI) mm FL compared to 30 (28 – 33 95% CI) mm FL in the Harmer Creek population (Figure 17).

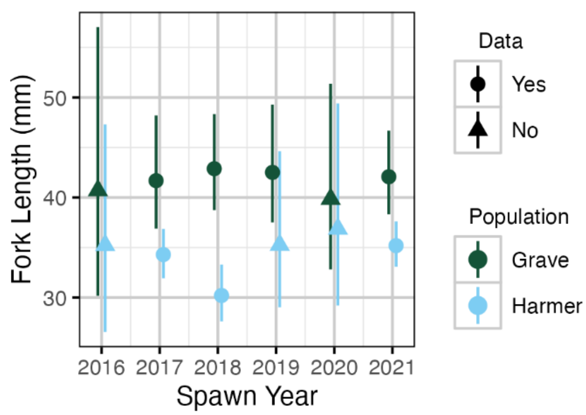


Figure 17. The estimated average fork length of age-0s by population and whether the estimates are informed by population and year specific length data (with 95% CIs).

3.5. BODY CONDITION

Consistent with Thorley et al. (2022b) and Wiebe et al. (2022), the model estimated that the body condition of juveniles was lower in 2018 in both systems than the other years presented in Figure 18. The model estimated that the average body condition in 2018 was 97% (93 – 100% 95% CI) and 95% (90 – 99% 95% CI) lower than in an average year for the Grave Creek and Harmer Creek populations, respectively.

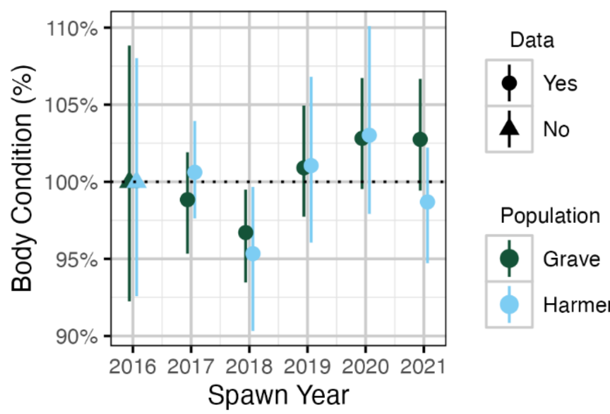


Figure 18. The estimated average body condition (weight corrected for length based on a 37.5 mm FL fish) by spawn year and population and whether the estimates are informed by population and year specific weight and length data (with 95% CIs).

3.6. ENERGETIC STATUS

The hBIN model estimated that the energetic status at the onset of winter was a strong positive predictor of the egg to age-1 survival (Figure 19). The associated surprisal value of ~5 bits indicated that discovering that energetic status based on body condition and fork length did not have a positive effect on egg to age-1 survival would be at least as surprising as throwing 5 heads in a row on a fair coin.

The plot of the egg to age-1 survival on the log odds scale indicates that the egg to age-1 survival for the Harmer Creek population in 2018 was substantially lower than predicted based on the fork length and body condition (Figure 20). The egg to age-1 survival values for the Grave Creek population are all higher than predicted based on energetic status and all but one (2020) of the Harmer Creek population values are lower than predicted. This difference is fully accounted for by the model which estimated that unrelated to energetic status (based on fork length and wetted weight) the egg to age-1 survival is 0.5 (-1.7-1.8) log odds units higher in the Grave Creek population than the Harmer Creek population although the surprisal value is less than 1 bit.

The hBIN model estimated that the WCT in the Grave Creek and Harmer Creek populations die of starvation at a body condition of 0.32 (0.02-0.74). The estimate which seems implausibly low should not be taken at face value because it represents an extrapolation under the assumption that energy storage declines linearly with wet weight. In reality the lipid content (g/g wet weight) can more than half over the course of the winter (Biro et al. 2004, 2021).

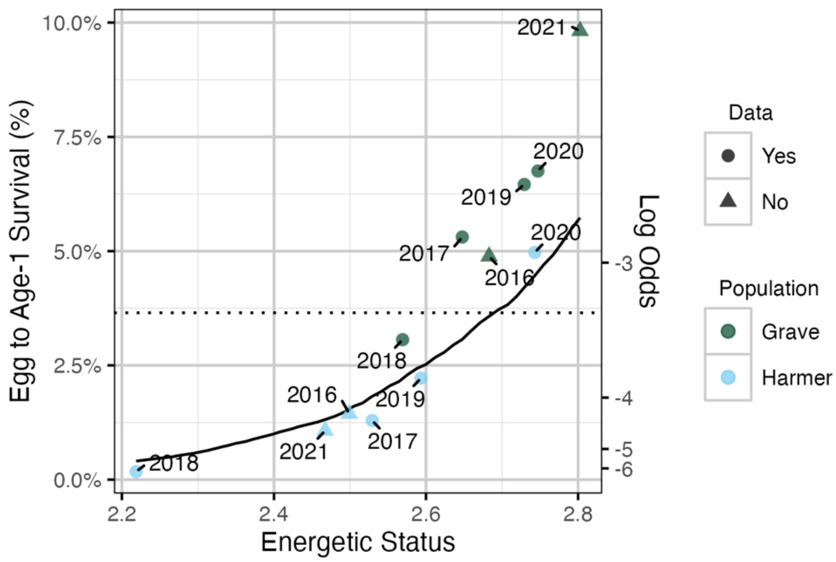


Figure 19. The estimated relationship between the egg to age-1 survival and energetic status at the onset of winter based on the mean fork length and mean body condition by population and spawn year and whether the survival estimates are informed by population and year specific density data. The individual points represent the egg to age-1 survival as measured by Thorley et al. (2022a) or estimated by the current analysis. The horizontal dotted line indicates the estimated egg to age-1 survival of 3.7% required for population replacement based on the life-cycle model.

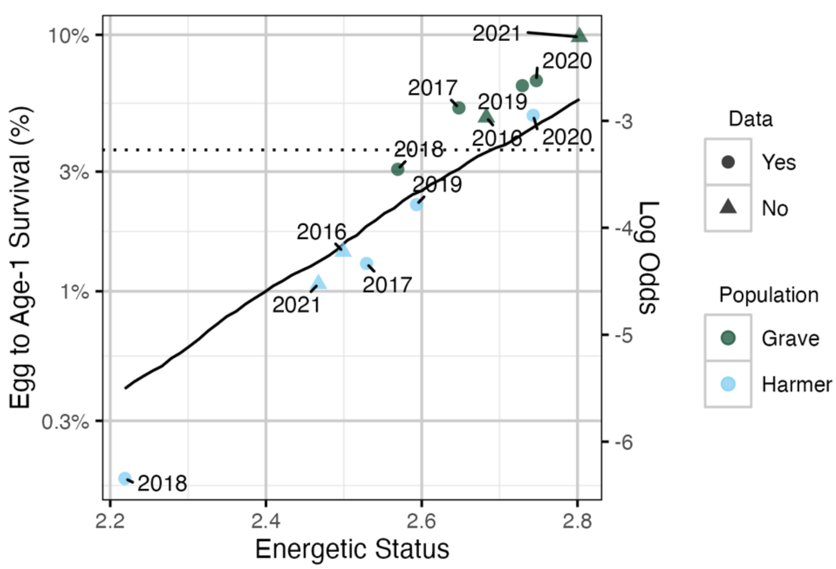


Figure 20. The estimated relationship between the egg to age-1 survival on the log odds scale and the energetic status at the onset of winter based on the fork length and body condition by population and spawn year and whether the survival estimates are informed by population and year specific density data. The individual points represent the egg to age-1 survival as measured by Thorley et al. (2022a) or estimated by the current analysis. The horizontal dotted line indicates the estimated egg to age-1 survival of 3.7% required for population replacement based on the life-cycle model.

3.7. COUNTERFACTUALS

The hBIN model estimated that the actual Reduced Recruitment difference was -1.8 log odds units and the actual Recruitment Failure difference was -2.2 log odds units (Figure 21).

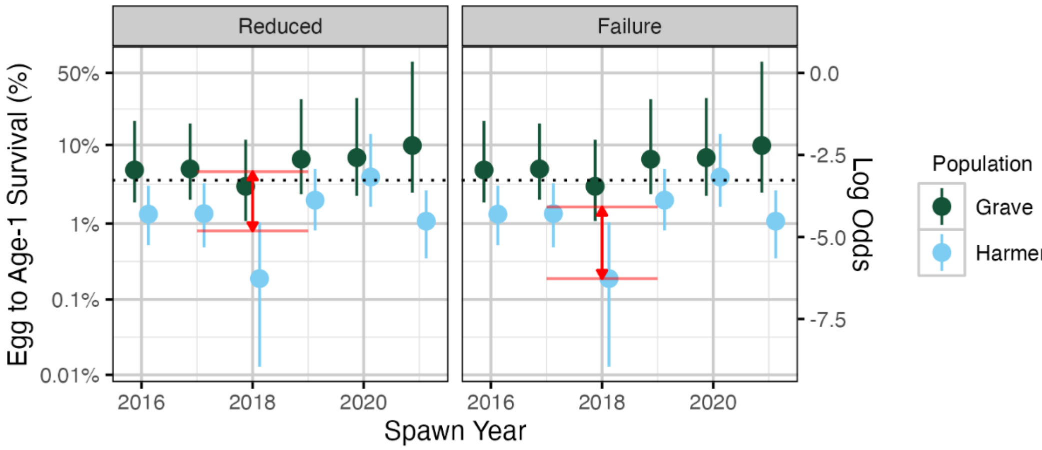


Figure 21. The actual egg to age-1 survival as estimated by the hBIN model (with 95% CIs) by spawn year and recruitment pattern (Reduced Recruitment vs Recruitment Failure). The red horizontal lines indicate the estimated recruitment difference for each pattern. The horizontal dotted line indicates the egg to age-1 survival of 3.7% required for population replacement as estimated by the life-cycle model.

The counterfactual analysis estimated that energetic status at the onset of winter explained approximately two-thirds of the Reduced Recruitment because when the hBIN model was used to predict the egg to age-1 survival with the same energetic status in both populations in all years (achieved by setting the fork length to be 37.5 mm and the body condition to be 1) the Reduced Recruitment difference was just -0.6 log odds units as opposed to the estimated actual value of -1.8 (Figure 22). This can be seen by comparing the estimated difference in the Energy panel to the Actual panel in Figure 22.

For the Recruitment Failure, the counterfactual analysis estimated that energetic status at the onset of winter explained approximately 90% of the pattern because with a constant energetic status the Reduced Recruitment difference was just -0.2 log odds units as opposed to the estimated actual value of -2.2 (Figure 23).This can be seen by comparing the estimated difference in the Energy panel to the Actual panel in Figure 23.

As discussed above and represented graphically in Figure 24, the counterfactual analysis estimated that energetic status at the onset of winter based on length and body condition explained 65% (29-85% 95% CI) of the Reduced Recruitment and 90% (76-96% 95% CI) of the Recruitment Failure. With respect to the Reduced Recruitment, the difference in fork length between the two populations, of which ~50% was explained by GSDD and ~12% was explained by dietary selenium, fully explained the difference in energetic status. In the case of the 2018 Recruitment Failure, the difference in body condition explained ~62% of the difference in the energetic status with fork length accounting for the remaining ~38%. However, neither GSDD or dietary selenium explained any of the reduction in fork length in 2018 indicating that other environmental variables and/or pathways were influencing growth (Figure 24). Overall, dietary selenium was estimated to have contributed 8% (3-16% 95% CI) to the Reduced Recruitment and diminished[22] the Recruitment Failure by -3% (-1--5% 95% CI).

[22] The model estimated that dietary selenium was slightly lower in the Harmer Creek population in 2018 than 2017 and 2019 which means that based on the pathway considered it would have had a positive effect on energetic status of the fish in the Harmer Creek population in 2018 *relative* to 2017 and 2019.

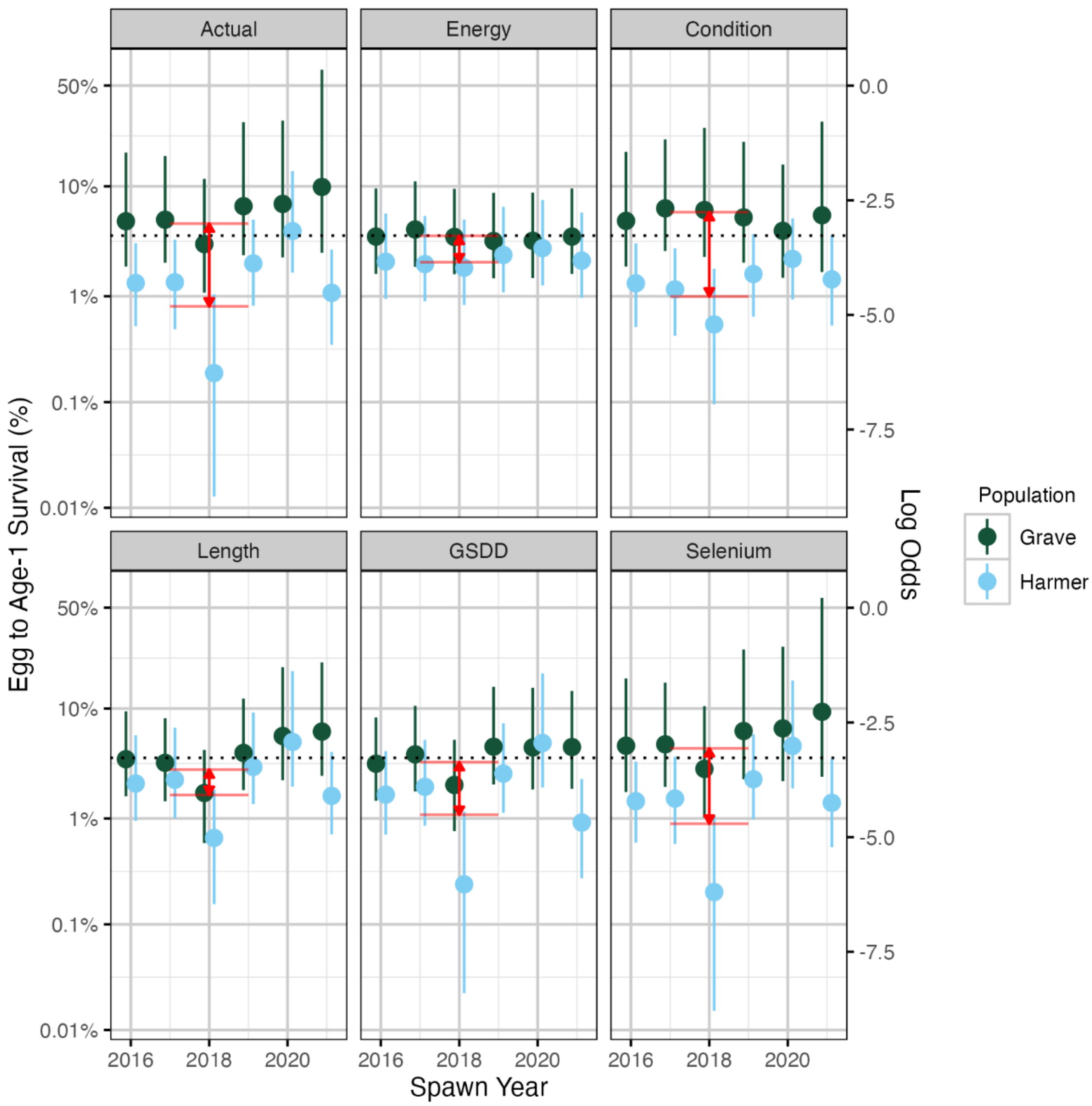


Figure 22. The egg to age-1 survival (with 95% CIs) and Reduced Recruitment differences as estimated by the hBIN model by spawn year and counterfactual scenario. Actual indicates the estimated actual values, energy indicates the estimated values with a constant energetic status at the onset of winter in both populations in all years (fork length of 37.5 mm and body condition of 1), condition indicates the values with a constant body condition of 1, length indicates with a constant fork length of 37.5 mm, GSDD indicates with a growing season of 950 degree days and selenium indicates with a dietary selenium concentration of 5 mg/kg dw. The red horizontal lines indicate the estimated Reduced Recruitment difference for each scenario. The horizontal dotted line indicates the egg to age-1 survival of 3.7% required for population replacement as estimated by the life-cycle model.

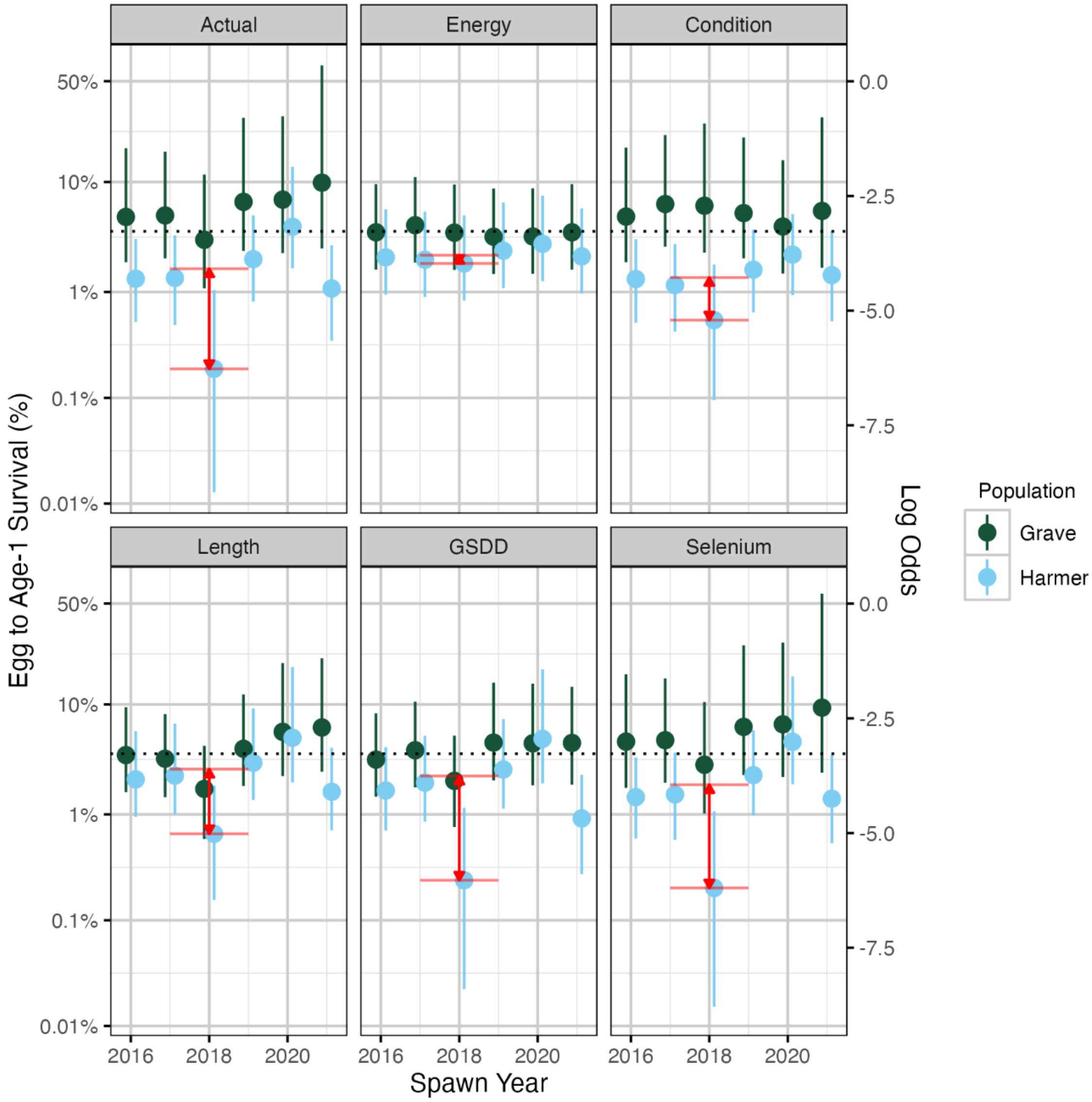


Figure 23. The egg to age-1 survival (with 95% CIs) and Recruitment Failure differences as estimated by the hBIN model by spawn year and counterfactual scenario. Actual indicates the estimated actual values, energy indicates the estimated values with a constant energetic status at the onset of winter in both populations in all years (fork length of 37.5 mm and body condition of 1), condition indicates the values with a constant body condition of 1, length indicates with a constant fork length of 37.5 mm, GSDD indicates with a growing season of 950 degree days and selenium indicates with a dietary selenium concentration of 5 mg/kg dw. The red horizontal lines indicate the estimated Recruitment Failure difference for each scenario. The horizontal dotted line indicates the egg to age-1 survival of 3.7% required for population replacement as estimated by the life-cycle model.

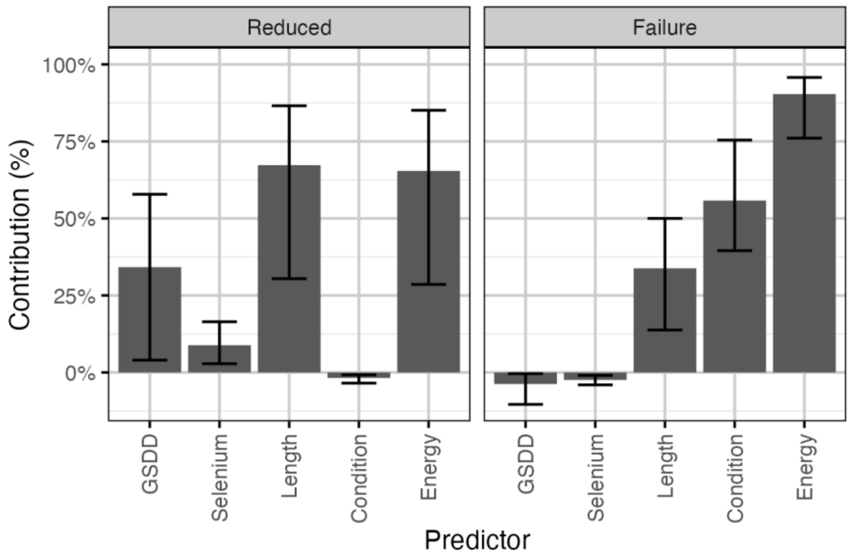


Figure 24. The estimated percent contributions to the Reduced Recruitment and Recruitment Failure patterns by the predictors of Growing Season Degree Days, dietary selenium, fork length, body condition and energetic status ("energy") at the onset of winter (with 95% CIs).

4. DISCUSSION

Early in the process the Harmer Creek Evaluation of Cause Team (2022) concluded that the Reduced Recruitment and Recruitment Failure patterns were primarily due to low survival of fish in their first winter, likely due to their small size. A strong negative relationship between the size of young of year trout and overwintering survival is well documented in the literature (Coleman and Fausch 2007a, 2007b) and likely reflects the fact that size is a key indicator of energetic status. More specifically, length indicates the efficiency of energy use while body condition is an indicator of lipid storage. Although fish can feed in winter, they must store most of the energy they require throughout the winter during the short growing season. The ratio between energy stores at the onset of winter and energy requirements was calculated as energetic status for this report. We used a hierarchical Bayesian Integrated Network model (Kéry & Royle, 2016; Carriger et al., 2016; McElreath, 2020; Schaub & Kéry, 2022) to quantify the effect of energetic status on the egg to age-1 survival for the Harmer Creek and Grave Creek populations, based on length, body condition and the scaling of standard metabolic rate to the size observed in salmonids. This was used to estimate the relative contributions of GSSD, dietary selenium, fork length, body condition and energetic status to the observed recruitment patterns. Key assumptions in the model development are discussed below followed by a discussion of other environmental variables that could be explanatory for the differences in recruitment not explained by energetic status.

4.1. MODEL ASSUMPTIONS

Models use what is known (the data) to inform what is unknown (the questions) by making assumptions about the inter-relationships between the knowns and the unknowns. Models are simplifications of reality: rather than attempting to describe all possible inter-relationship, models simply describe the most important relationships. As is the case with all models the utility of the results depends on the extent to which the model's assumptions adequately represent the system (Box 1976; McElreath 2020). The advantage of statistical models over professional judgement is that all the underlying assumptions can be identified and quantified allowing others to evaluate their validity. In the following paragraphs we consider the model's key assumptions with a focus on the implications for the estimates of the contribution of the variables to the two recruitment patterns. Where the assumptions are not met, we provide an explanation of how that could influence the results.

A key assumption of the current analysis is that **there is a difference in the egg to age-1 survival between the Grave Creek and Harmer Creek populations (α_{S_P}) that is unrelated to energetic status**. This assumption is only weakly supported by the available data (s-value of just 0.89 bits). Removing this assumption, which explains ~25% of the Reduced Recruitment, substantially increases the contribution of fork length, and as a result dietary selenium (and GSDD), to the Reduced Recruitment. However, as much of the increase is likely to be correlative (as opposed to causal) the assumption is considered reasonable (McElreath 2020).

A second key assumption is that **the contribution of the unquantified stressors such as anomalous winter conditions to the egg to age-1 survival in 2018 is negligible**. To the extent that this assumption is violated, the current analysis overestimates the proportion of the Recruitment Failure explained by body condition as well as the effect of energetic status on the egg to age-1 survival.

A third key assumption is that **the resultant effect of dietary selenium on the increase in length from emergence is the same for WCT as it is for Chinook salmon**. As discussed in the selenium report (de Bruyn et al. 2022) this is probably a reasonable or at the very least potentially conservative assumption in the sense that any violations would decrease the contribution of dietary selenium.

A fourth key assumption is that **the effect of selenium on length occurs solely via the dietary pathway**. As discussed by de Bruyn et al. (2022), maternal transfer could result in elevated selenium concentrations from spawning until emergence. Maternal transfer may also result in elevated selenium concentrations into the free-living fry stage although depuration is expected to result in a decline in body tissue concentrations once feeding commences (de Bruyn et al. 2022). Bioaccumulation causes fish muscle tissue concentrations to be ~ 1.24 times dietary concentrations (Kuchapski and Rasmussen 2015) and egg tissue concentrations to be ~1.6 times fish muscle tissue concentrations (Nautilus Environmental and Interior Reforestation 2011). Taken together these two TTFs result in a total benthic invertebrate to egg TTF of ~ 2. Given the capacity of dietary selenium to bioaccumulate in eggs it is possible that maternal transfer explains some of the remaining length difference between the two populations. And as benthic invertebrate or fish tissue selenium data are not available for 2017, it is also possible that the exceptionally short length of the fry in Harmer Creek in 2018, which accounted for ~33% of the Recruitment Failure, may have been partially due to maternal transfer of selenium (de Bruyn et al. 2022).

A fifth key assumption is that **selenium only affects the length of the fry**. This assumption is false as maternal transfer of selenium can increase mortality in WCT embryos prior to emergence (Nautilus Environmental and Interior Reforestation 2011). However, the estimated relationship is extremely non-linear with the EC_{10} (concentration at which mortality is 10% higher than controls) not occurring until an egg concentration of 25 (12-31 95% CI) mg/kg dw is reached. Based on the estimated benthic invertebrate selenium concentrations and a total TTF of ~2 it is likely that the EC_{10} was not reached until 2021 although embryo mortality may have made a small (<5%) contribution to the Reduced Recruitment as a 10% increase in the mortality is equivalent to a change in the log odds of ~0.1 (with the overall difference being ~1.9 log odds units).

A sixth key assumption is that **the background concentrations of dietary selenium in Grave Creek above the confluence with Harmer Creek are negligible**. This assumption is also false. Dietary selenium values in Grave Creek above Harmer Creek and Harmer Creek above Dry Creek both indicate background concentrations between 3 and 8 mg/kg dw (de Bruyn et al. 2022; Golder 2022) which are consistent with the upper limit of the reference area normal selenium range of 8.74 mg/kg dw (Ings and Weech 2020). The fact that the estimated mean dietary selenium concentrations in the Grave Creek population are likely biased low means that the estimated contribution of dietary selenium to the Reduced Recruitment is likely biased high.

A seventh assumption is that **each population consists of a cohort of fish that are exposed to similar environmental conditions**. This assumption is not fully met because for example fish in the lower end of HRM-R3 experience a GSDD ~ 100 degree days warmer than those in HRM-R5. There is also substantial variation in GSDD and/or selenium exposure for fish in the Grave population in GRV-R2, HRM-R1, GRV-R3 and GRV-R4. To account for this variation, which may or may not bias the estimates of the contributions depending on the distribution of fish and conditions, reach specific egg to age-1 survival rates would have to be developed.

An eighth key assumption is that **the average environmental conditions are indicative of the average population-level exposure**. Although related to the previous assumption, this assumption concerns the variation about the modal value(s) as opposed to the existence of a single modal value. The assumption is violated when individual variation in environmental conditions is high and the response is strongly non-linear. In the current analysis, there is substantial individual variation (Forsythe et al. 2021) in selenium muscle tissue concentrations and fork length and the effects of selenium on growth and fork length on egg to age-1 survival are both non-linear. As the effect of selenium on growth is disproportionately stronger at higher concentrations the estimated contribution of dietary selenium to the Reduced Recruitment is expected to be biased slightly low. There was insufficient data to switch to an individual-based model (Johnston et al. 2019).

4.2. ADDITIONAL ENVIRONMENTAL VARIABLES

The Evaluation of Cause, and underlying SME reports, considered predictors of egg to age-1 survival other than GSDD, selenium, length and body and energetic status. In the case of small population size (Thorley et al. 2022a), calcite, and dissolved oxygen in the mainstem the differences between populations and among years were too small to substantially contribute to the recruitment patterns[23]. The data for food availability (Wiebe et al. 2022) and total suspended solids (TSS) were relatively sparse. Finally, although the winter of 2018/2019 was anomalous, there were no direct observations of ice and the contributions of the differences in ice or stream flow could not be quantified (Hocking et al. 2022). It is therefore possible that if food availability, TSS, stream flow, ice and/or some other unknown environmental variable(s) were included in the model then one or more of the estimated contributions might change in one of three ways depending on the inter-relationships. If the other variables simply explained some of the residual variation in the egg to age-1 survival, then the uncertainty in the estimated contributions would be reduced. Alternatively, if the other variables explained some of the additional mortality in 2018 that is currently accounted for by energetic status, then the estimated contributions would decrease. Finally, if the other variables interact with energetic status then they might increase or decrease the estimated contributions depending on the context (McElreath 2020).

[23] Although density-dependence is a key determinant of recruitment (van Poorten et al. 2018) it was not included in the model as the differences in the egg densities between populations and among years were relatively small (Thorley et al. 2022c, 2022b).

4.3. CONCLUSIONS

The results of our analysis indicate that energetic status at the onset of winter based on fork length and wet weight is an important predictor of the egg to age-1 survival and that GSDD and dietary selenium have both contributed to the Reduced Recruitment in the Harmer Creek population through their effects on fork length. More specifically the results suggest that energetic status explains 65% (29-85% 95% CI) and 90% (76-96% 95% CI) of the Reduced Recruitment and Recruitment Failure, respectively. The results also suggest that GSDD contributed 34% (4-58% 95% CI) and dietary selenium contributed 8% (3-16% 95% CI) to the Reduced Recruitment. However, growing season degree days and selenium were similar in 2018 compared to 2017 and 2019 therefore did not explain the Recruitment Failure that occurred over and above the observed Reduced Recruitment.

By evaluating the relationship of energetic status to egg to age-1 survival, we were able to consider the role of more than one stressor that could impact WCT through a common mechanism. This led us to a better understanding of the relative role of the different stressors. From an ecological perspective the finding that energetic status is an important predictor of egg to age-1 survival provides a framework for understanding the dynamics of WCT populations in colder systems.

5. REFERENCES

Álvarez, D., and Nicieza, A.G. 2005. Compensatory response 'defends' energy levels but not growth trajectories in brown trout, *Salmo trutta* L. Proc. R. Soc. B Biol. Sci. **272**(1563): 601–607. doi:10.1098/rspb.2004.2991.

Ankley, G.T., Bennett, R.S., Erickson, R.J., Hoff, D.J., Hornung, M.W., Johnson, R.D., Mount, D.R., Nichols, J.W., Russom, C.L., Schmieder, P.K., Serrano, J.A., Tietge, J.E., and Villeneuve, D.L. 2010. Adverse outcome pathways: A conceptual framework to support ecotoxicology research and risk assessment. Environ. Toxicol. Chem. **29**(3): 730–741. doi:10.1002/etc.34.

Berg, O.K., Rød, G., Solem, Ø., and Finstad, A.G. 2011. Pre-winter lipid stores in brown trout Salmo trutta along altitudinal and latitudinal gradients. J. Fish Biol. **79**(5): 1156–1166. doi:10.1111/j.1095-8649.2011.03097.x.

Biro, P.A., Morton, A.E., Post, J.R., and Parkinson, E.A. 2004. Over-winter lipid depletion and mortality of age-0 rainbow trout (*Oncorhynchus mykiss*). Can. J. Fish. Aquat. Sci. **61**(8): 1513–1519. doi:10.1139/f04-083.

Biro, P.A., Post, J.R., and Abrahams, M.V. 2005. Ontogeny of energy allocation reveals selective pressure promoting risk-taking behaviour in young fish cohorts. Proc. R. Soc. B Biol. Sci. **272**(1571): 1443–1448. doi:10.1098/rspb.2005.3096.

Biro, P.A., Post, J.R., and Beckmann, C. 2021. Autumn lipid reserves, overwinter lipid depletion, and high winter mortality of rainbow trout in experimental lakes. Can. J. Fish. Aquat. Sci. **78**(6): 738–743. doi:10.1139/cjfas-2020-0276.

Box, G.E.P. 1976. Science and Statistics. J. Am. Stat. Assoc. **71**(356): 791–799. doi:10.1080/01621459.1976.10480949.

Brooks, J., and Robinson, M. 2022. A Preliminary Investigation into Water Temperature as a Predictor of Westslope Cutthroat Trout Fry Growth. A Lotic Environmental Report, Teck Coal Limited, Sparwood, BC.

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

de Bruyn, A., Bollinger, T., and Luoma, S. 2022. Subject Matter Expert Report: Selenium Assessment. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population. Teck Coal Limited, Sparwood, BC.

Calder, W.A. 2001. Ecological Consequences of Body Size. *In* eLS, 1st edition. *Edited by* John Wiley & Sons, Ltd. Wiley. doi:10.1038/npg.els.0003208.

Carriger, J.F., Barron, M.G., and Newman, M.C. 2016. Bayesian Networks Improve Causal Environmental Assessments for Evidence-Based Policy. Environ. Sci. Technol. **50**(24): 13195–13205. doi:10.1021/acs.est.6b03220.

Coleman, M.A., and Fausch, K.D. 2007a. Cold Summer Temperature Regimes Cause a Recruitment Bottleneck in Age-0 Colorado River Cutthroat Trout Reared in Laboratory Streams. Trans. Am. Fish. Soc. **136**(3): 639–654. doi:10.1577/T05-288.1.

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

Cope, S., and Cope, A. 2020. Harmer and Grave Creek Westslope Cutthroat Trout Habitat and Population Assessment. A Westslope Fisheries Ltd. report, Teck Coal Limited, Sparwood, BC.

Cunjak, R.A., Curry, A., and Power, G. 1987. Seasonal Energy Budget of Brook Trout in Streams: Implications of a Possible Deficit in Early Winter. Trans. Am. Fish. Soc. **116**(6): 817–828. doi:10.1577/1548-8659(1987)116<817:SEBOBT>2.0.CO;2.

Cunjak, R.A., and Power, G. 1987. The feeding and energetics of stream-resident trout in winter. J. Fish Biol. **31**: 493–511.

DeForest, D.K., Brix, K.V., and Adams, W.J. 1999. Critical Review of Proposed Residue-Based Selenium Toxicity Thresholds for Freshwater Fish. Hum. Ecol. Risk Assess. Int. J. **5**(6): 1187–1228. doi:10.1080/10807039.1999.10518886.

Dobson, A.J., and Barnett, A.G. 2018. An introduction to generalized linear models. *In* Fourth edition. CRC Press, Taylor & Francis Group, Boca Raton.

Elliott, J.M. 1972. Rates of gastric evacuation in brown trout, Salmo trutta L. Freshw. Biol. **2**(1): 1–18. doi:10.1111/j.1365-2427.1972.tb01575.x.

Ferraro, P.J. 2009. Counterfactual thinking and impact evaluation in environmental policy. New Dir. Eval. **2009**(122): 75–84. doi:10.1002/ev.297.

Finstad, A.G. 2004. Energy-related juvenile winter mortality in a northern population of Atlantic salmon (Salmo salar).

Finstad, A.G., Berg, O.K., Forseth, T., Ugedal, O., and Næsje, T.F. 2010. Adaptive winter survival strategies: defended energy levels in juvenile Atlantic salmon along a latitudinal gradient. Proc. R. Soc. B Biol. Sci. **277**(1684): 1113–1120. doi:10.1098/rspb.2009.1874.

Finstad, A.G., Forseth, T., Naesje, T.F., and Ugedal, O. 2004. The importance of ice cover for energy turnover in juvenile Atlantic salmon: Ice cover and energetics of juvenile salmon. J. Anim. Ecol. **73**(5): 959–966. doi:10.1111/j.0021-8790.2004.00871.x.

Forsythe, A.B., Day, T., and Nelson, W.A. 2021. Demystifying individual heterogeneity. Ecol. Lett. **24**(10): 2282–2297. doi:10.1111/ele.13843.

Fuhrman, A.E., Larsen, D.A., Steel, E.A., Young, G., and Beckman, B.R. 2018. Chinook salmon emergence phenotypes: Describing the relationships between temperature, emergence timing and condition factor in a reaction norm framework. Ecol. Freshw. Fish **27**(1): 350–362. doi:10.1111/eff.12351.

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.

Giacomini, H.C., and Shuter, B.J. 2013. Adaptive responses of energy storage and fish life histories to climatic gradients. J. Theor. Biol. **339**: 100–111. doi:10.1016/j.jtbi.2013.08.020.

Golder. 2022. Subject Matter Expert Report: Surface Water Quality. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population. Teck Coal Limited, Sparwood, BC.

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. 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.

Hamilton, S.J., Buhl, K.J., Faerber, N.L., Bullard, F.A., and Wiedmeyer, R.H. 1990. Toxicity of organic selenium in the diet to chinook salmon. Environ. Toxicol. Chem. **9**(3): 347–358. doi:10.1002/etc.5620090310.

Harmer Creek Evaluation of Cause Team. 2022. Evaluation of Cause - Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population. Teck Coal Limited, Sparwood, BC.

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:10.1577/T07-012.1.

Hocking, M., Whelan, C., and Hatfield, T. 2022. Subject Matter Expert Report: Water Temperature and Ice. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population. An Ecofish Research Ltd. Report, Teck Coal Limited.

Hurlbert, S.H. 1984. Pseudoreplication and the Design of Ecological Field Experiments. Ecol. Monogr. **54**(2): 187–211. doi:10.2307/1942661.

Huusko, A., Greenberg, L., Stickler, M., Linnansaari, T., Nykänen, M., Vehanen, T., Koljonen, S., Louhi, P., and Alfredsen, K. 2007. Life in the ice lane: the winter ecology of stream salmonids. River Res. Appl. **23**(5): 469–491. doi:10.1002/rra.999.

Ings, J., and Weech, S. 2020. Study Design for the Regional Aquatic Effects Monitoring Program, 2021 to 2023. A Minnow Environmental Inc. Report, Teck Coal Limited, Sparwood, BC.

Johnston, A.S.A., Boyd, R.J., Watson, J.W., Paul, A., Evans, L.C., Gardner, E.L., and Boult, V.L. 2019. Predicting population responses to environmental change from individual-level mechanisms: towards a standardized mechanistic approach. Proc. R. Soc. B Biol. Sci. **286**(1913): 20191916. doi:10.1098/rspb.2019.1916.

Kaikkonen, L., Helle, I., Kostamo, K., Kuikka, S., Törnroos, A., Nygård, H., Venesjärvi, R., and Uusitalo, L. 2021. Causal Approach to Determining the Environmental Risks of Seabed Mining. Environ. Sci. Technol. **55**(13): 8502–8513. doi:10.1021/acs.est.1c01241.

Kéry, M., and Royle, J.A. 2016. 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.

Khan, U. 2022. Temperature, meal size and body size effects on the gastric evacuation of rainbow trout: modelling optimum and upper thermal limits. J. Fish Biol. **100**(6): 1388–1398. doi:10.1111/jfb.15049.

Knight, R., Marlatt, V.L., Baker, J.A., Lo, B.P., deBruyn, A.M.H., Elphick, J.R., and Martyniuk, C.J. 2016. Dietary selenium disrupts hepatic triglyceride stores and transcriptional networks associated with growth and Notch signaling in juvenile rainbow trout. Aquat. Toxicol. **180**: 103–114. doi:10.1016/j.aquatox.2016.09.014.

Kuchapski, K.A., and Rasmussen, J.B. 2015. Food chain transfer and exposure effects of selenium in salmonid fish communities in two watersheds in the Canadian Rocky Mountains. Can. J. Fish. Aquat. Sci. **72**(7): 955–967. doi:10.1139/cjfas-2014-0484.

Liedloff, A.C., Woodward, E.L., Harrington, G.A., and Jackson, S. 2013. Integrating indigenous ecological and scientific hydro-geological knowledge using a Bayesian Network in the context of water resource development. J. Hydrol. **499**: 177–187. doi:10.1016/j.jhydrol.2013.06.051.

McElreath, R. 2020. Statistical rethinking: a Bayesian course with examples in R and Stan. *In* 2nd edition. Taylor and Francis, CRC Press, Boca Raton.

Metcalfe, N.B., Fraser, N.H.C., and Burns, M.D. 1999. Food availability and the nocturnal vs. diurnal foraging trade-off in juvenile salmon. J. Anim. Ecol. **68**(2): 371–381. doi:10.1046/j.1365-2656.1999.00289.x.

Millar, R.B. 2011. Maximum likelihood estimation and inference: with examples in R, SAS, and ADMB. Wiley, Chichester, West Sussex.

Nautilus Environmental, and Interior Reforestation. 2011. Evaluation of the Effects of Selenium on Early Life Stage Development of Westslope Cutthroat Trout from the Elk Valley, BC. Teck Coal Limited.

Pearl, J. 2009. Causal inference in statistics: An overview. Stat. Surv. **3**(none). doi:10.1214/09-SS057.

Plummer, M. 2003. JAGS: a program for analysis of Bayesian graphical models using Gibbs sampling. *In* Proceedings of the 3rd International Workshop on Distributed Statistical Computing (DSC 2003). *Edited by* K. Hornik, F. Leisch, and A. Zeileis. Vienna, Austria.

Plummer, M. 2017, June 28. JAGS version 4.3.0 user manual. Available from http://sourceforge.net/projects/mcmc-jags/files/Manuals/4.x/jags_user_manual.pdf.

van Poorten, B., Korman, J., and Walters, C. 2018. Revisiting Beverton–Holt recruitment in the presence of variation in food availability. Rev. Fish Biol. Fish. **28**(3): 607–624. doi:10.1007/s11160-018-9521-6.

Presser, T.S., and Luoma, S.N. 2010. A methodology for ecosystem-scale modeling of selenium. Integr. Environ. Assess. Manag. **6**(4): 685–710. doi:10.1002/ieam.101.

R Core Team. 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. Available from https://www.R-project.org/.

Rafi, Z., and Greenland, S. 2020. Semantic and cognitive tools to aid statistical science: replace confidence and significance by compatibility and surprise. BMC Med. Res. Methodol. **20**(1): 244. doi:10.1186/s12874-020-01105-9.

Rosenfeld, J.S. 2014. Modelling the effects of habitat on self-thinning, energy equivalence, and optimal habitat structure for juvenile trout. Can. J. Fish. Aquat. Sci. **71**(9): 1395–1406. doi:10.1139/cjfas-2013-0603.

Schaub, M., and Kery, M. 2022. Integrated population models: theory and ecological applications with R and JAGS. Academic Press.

Simpkins, D.G., Hubert, W.A., Del Rio, C.M., and Rule, D.C. 2003. Physiological Responses of Juvenile Rainbow Trout to Fasting and Swimming Activity: Effects on Body Composition and Condition Indices. Trans. Am. Fish. Soc. **132**(3): 576–589. doi:10.1577/1548-8659(2003)132<0576:PROJRT>2.0.CO;2.

Speers-Roesch, B., Norin, T., and Driedzic, W.R. 2018. The benefit of being still: energy savings during winter dormancy in fish come from inactivity and the cold, not from metabolic rate depression. Proc. R. Soc. B Biol. Sci. **285**(1886): 20181593. doi:10.1098/rspb.2018.1593.

Stan Development Team. 2017, September 5. Stan Modeling Language User's Guide and Reference Manual.

Steingrímsson, S.Ó., and Grant, J.W.A. 1999. Allometry of territory size and metabolic rate as predictors of self-thinning in young-of-the-year Atlantic salmon. J. Anim. Ecol. **68**: 17–26.

Teck Coal Limited. 2014. Elk Valley Water Quality Plan. A Teck Coal Plan, Teck Coal Limited, Sparwood, BC.

Thorley, J.L., and Andrusak, G.F. 2017. The fishing and natural mortality of large, piscivorous Bull Trout and Rainbow Trout in Kootenay Lake, British Columbia (2008–2013). PeerJ **5**: e2874. doi:10.7717/peerj.2874.

Thorley, J.L., Hussein, N., and Amish, S.J. 2022a. Subject Matter Expert Report: Small Population Size. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population. A Poisson Consulting Ltd. Report, Teck Coal Limited.

Thorley, J.L., Kortello, A.K., Brooks, J., and Robinson, M. 2022b. Grave and Harmer Creek Westslope Cutthroat Trout Population Monitoring 2021. A Poisson Consulting, Grylloblatta Consulting and Lotic Environmental Report, Teck Coal Ltd, Sparwood, BC.

Thorley, J.L., Kortello, A.K., Brooks, J., and Robinson, M. 2022c. Grave and Harmer Creek Westslope Cutthroat Trout Population Monitoring 2021. A Poisson Consulting, Grylloblatta Consulting and Lotic Environmental Report, Teck Coal Ltd, Sparwood, BC.

Wiebe, A., Orr, P., and Ings, J. 2022. Subject Matter Expert Report: Food Availability. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population. A Minnow Environmental Inc. Report, Teck Coal Limited.

Wilson, S.M., Robinson, K.A., Gutzmann, S., Moore, J.W., and Patterson, D.A. 2021. Limits on performance and survival of juvenile sockeye salmon (*Oncorhynchus nerka*) during food deprivation: a laboratory-based study. Conserv. Physiol. **9**(1): coab014. doi:10.1093/conphys/coab014.